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

May 12, 2014

Manufacturing Data and Manufacturing Cell Group Factual Report

A. INCIDENT: DCA13IA037

LOCATION: Boston, Massachusetts

DATE/TIME: January 7, 2013, about 10:21 AM EST[1]

AIRCRAFT: Japan Airlines Boeing 787, JA829J, Line Number 84

B. GROUP MEMBERS:

Co-Group Chairman: Pocholo Cruz
National Transportation Safety Board
Washington, DC

Co-Group Chairman: Erik Mueller
National Transportation Safety Board
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Member: Joseph Panagiotou
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[1] Eastern Standard Time

Member:	Michael Bramble Federal Aviation Administration Seattle, WA
Member:	Richard Anderson Boeing Commercial Airplanes Seattle, WA
Member:	Johan Condette BEA Paris, France
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Member:	Yoshiaki Namikawa GS Yuasa Kyoto, Japan

C. <u>ADDITIONAL PARTICIPANTS:</u>

Participant:	Brian Barnett TIAX, LLC. Boston, MA
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Participant:	James A. Barnes U.S. Department of Energy Washington, DC

D: SUMMARY

On January 7, 2013, about 1021 EST, 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. 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.

E: DETAILS OF THE INVESTIGATION

1.0 787 Main and APU Battery Engineering Design and Verification

The 787 Power Conversion System includes two identical lithium-ion batteries. One battery was dedicated to starting the APU (APU Battery) and was located in the aft equipment bay (just aft of the wings). The other battery (Main Battery) provides back up power to the flight instruments in case of a complete power loss. It was located in the main equipment center just in front of the forward cargo bay. In 2003, Boeing created a Statement of Work for the design and manufacture of the 787 Dreamliner Power Conversion System. A Request for Proposal (RFP) was issued to suppliers and consequently a contract was awarded to Thales Avionics Electrical Systems (AES) in May 2004. Thales AES subcontracted the design and manufacture of the 787 Battery Charging System to Securaplane Technologies, Inc. and the design and manufacture of the 787 Main and APU Batteries to GS Yuasa Corporation (GSY) in 2004. Per the agreements between Boeing and the contractors, each contractor retained ownership of the associated intellectual property. Initially Boeing created the Specification Control Drawings (SCD) and Interface Control Drawings (ICD) with Thales participation. The amended and validated SCD became the Boeing document in which Thales were to develop and manufacture the battery and battery charging system for the airplane. Boeing's contract required Thales would develop a power conversion system that would meet all the requirements specified in the SCD and ICD.

In addition, Boeing required Thales to manage their sub-tier suppliers for the battery and the battery charger system. In their efforts to support Boeing's application for certification by FAA for the sub-system battery/battery charger, Thales, GS Yuasa, and Securaplane were responsible for providing necessary testing and analysis to support FAA regulatory requirements. Only Boeing had contact with the FAA for certification activities for the 787 Power Conversion System. Boeing was responsible for showing compliance and the FAA was responsible for finding compliance to all the applicable regulatory requirements.

Thales selected sub-tier suppliers for the battery and battery charger with concurrence from Boeing. Thales was responsible for flowing down the battery and battery charger specifications to its chosen sub-tier suppliers. The means of compliance were jointly developed by Boeing, Thales, and GS Yuasa. Thales and its suppliers provided Boeing with testing and analysis results required by Boeing. The requirements were verified and validated by Boeing, Thales and sub-tiers throughout the various phases of the design.

The basic design of the battery began in 2005. As part of the design, GS Yuasa contracted Kanto Aircraft Instruments (KAI) to design and manufacture the Battery Management Unit (BMU). As the evolution of the battery designs began to mature, Preliminary Design Reviews (PDR) and Critical Design Reviews (CDR) were conducted by Boeing with active participation of Thales and GS Yuasa. There were approximately 38 subtier suppliers for the manufacturing of the 787 battery.

Qualification testing was witnessed by delegated representatives from Boeing. There were limited and specific areas of direct FAA oversight—conformity, for example. However, in 2009 the FAA acceptance was delegated to the Boeing Organizational Delegation Authority.

In addition, Boeing contractually required its suppliers, including their sub-tiers, to perform First Article Inspection (FAI) per AS9102 standard on first production runs of any article. The FAI was one of the primary methods for the inspection and testing of vendor components. The testing of a pre-production sample was considered essential in the process of approving an order or contract. The first article inspection should determine if the product meets acceptance requirements and quality control requirements. The purpose of the First Article Inspection was to give objective evidence that all engineering, design and specification requirements are correctly understood, accounted for, verified, and recorded. This testing was performed in addition to system integration and flight testing.

Further, Boeing had an additional internal process called the Boeing First Article Inspection (BFAI) which was a formal review of suppliers' FAIs. A BFAI was performed on battery S/N 178 on November 25, 2010, at GS Yuasa by a Boeing Supplier Quality Representative.

In 2006, after the Securaplane Incident[2], a design change was incorporated by adding the internal contactor and an additional BMU Board (sub BMU). Qualification testing was completed in June 2007. In October 2009 (after APSIF incident[3]), a second design change was implemented to improve the active material, sealing and incorporation of the latching function in the BMU. In addition, a Battery Diode Module was added so that the Main Battery was charged only by the dedicated charger and not inadvertently by the airplane electrical system. The critical design review for this design version was conducted by Boeing and completed in January 2010, and qualification testing completed in June 2010.

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[2] See Airworthiness Factual Report and/or Addendum for more information on the Securaplane Incident

[3] See Airworthiness Factual Report and/or Addendum for more information on the APSIF Incident.

2.0 Main and APU Battery Manufacturing Process

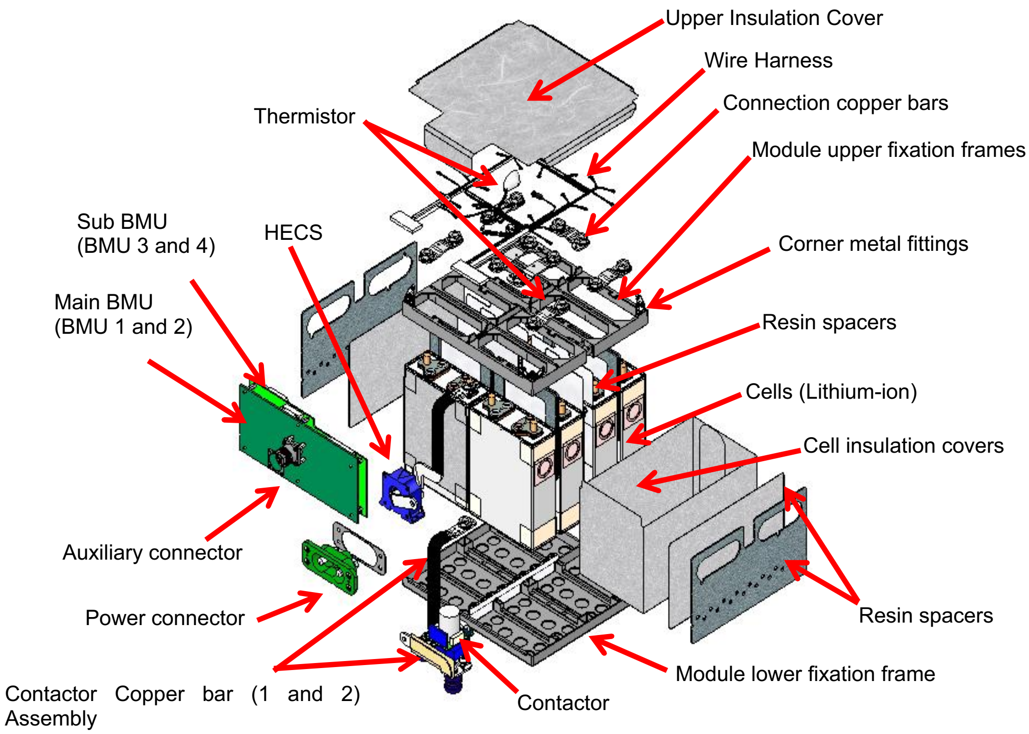

Figure 1 - Exploded view diagram of the GS Yuasa battery.

GS Yuasa was originally founded in 1895 and traditionally made lead acid batteries. GS Yuasa was #3 in worldwide market share for auto batteries and #1 for motorcycle batteries. The company also made nickel metal hydride (NiMH) batteries. GS Yuasa began commercialized lithium ion battery production in the 1990s. These batteries are used in satellite applications, backup systems for railcars, main supply for many auto applications, and deep sea diving equipment. GS Yuasa currently has three US business units. GS Yuasa employs 11,000 people worldwide with 41 business units in 19 countries. The -901[4] batteries were manufactured at GS Yuasa's Technologies Facility in Kyoto, Japan.

The GS Yuasa design group had subgroups that designed the cell, the mechanical parts, and the battery assembly. Each group had its own goals with discrete design objectives, and the groups collaborated on the final overall design at the end. Based on the specifications for this particular battery, GS Yuasa assigned approximately eight engineers to the development of the -901 battery design. When the -901 development ended, six of the eight engineers became involved in other projects. As of May 2013, there were three engineers collaborating on the new -902[5] design. The

[4] -901 was the configuration of the GSY LVP-65 battery in the JAL Boston and ANA Takamatsu incidents.
[5] -902 was the configuration of the GSY LVP-65 battery developed after the -901 incidents to achieve airworthiness. Changes were made at the battery level, however, the cell design and configuration remained the same as the -901.

number of engineers in each subset of the -901 design project was an approximation by GS Yuasa, because many of the engineers cross-worked on each subset. While these engineers worked some time on other projects, the majority of their time was spent on the battery development. All the design engineers had chemistry backgrounds. As is common in Japan, the engineers receive their battery and cell design knowledge from years of on-the-job technical and engineering training.

According to GS Yuasa, the cell design engineers were knowledgeable about the cell manufacturing process. They worked with the manufacturing engineers on how to make the parts during the design process.

Simulation work was performed by GS Yuasa to determine current and voltage evolution during charging and discharging during battery normal operation of the -901 battery. This computer analysis was used to assist in the design work. Thales requested simulation, not for validating performance of battery, but rather for checking the behavior of the design as it was incorporated into the system. These simulations did not include specific failure conditions like overcharging and overdischarging, since they were only incorporated after the Failure Design Analysis (FDA) and Failure Modes and Effects Analysis (FMEA) were developed. The simulation procedure was a risk-based analysis using the FMEA to develop the failure probabilities. The FMEA, created by Thales and approved by Boeing, determined each failure mode would be between 10^{-7} and 10^{-9} depending on the failure mode. The requirements for these rates came from the Boeing's SCD based on the Special Conditions, whereas the values were developed from data the proposal originally drafted to Thales (from GS Yuasa) by Boeing based in requirements for each type of failure event. Thales' data only related to integration of the battery with the battery charger system. GS Yuasa's knowledge of the failure conditions were limited once incorporated into the entire aircraft system—once on the plane, the failure conditions probability was initially computed by Thales and then verified by Boeing. However, GS Yuasa was requested to reduce the probabilities of failure as much as possible.

3.0 GS Yuasa Factory Tour of Cell Manufacturing Process

From May 29 to May 31, 2014, the NTSB Manufacturing Group visited the GS Yuasa facilities in Kyoto, Japan. The tours included inspection of the cell manufacturing buildings and battery assembly areas.

3.1 Cell Manufacturing Tour

The groups entering the cell manufacturing areas were required to change shoes before entering as required per internal procedures. GS Yuasa presented the manufacturing flow chart briefly describing the overall process of coating, winding, assembly, and final production of the cell. GS Yuasa also presented some display satellite battery cells, which were larger than those used in the 787 battery. Even though GS Yuasa makes cylindrical cells, the majority of cells manufactured at this facility were prismatic. GS Yuasa Technology makes over 3,000 cells per year at their Kyoto facility, which mostly manufactures specialized batteries for satellites, aircraft, and rockets. The aircraft batteries were completely assembled on sight, whereas the satellite batteries were finished at the prime customer. Most of the rooms were humidity controlled with the humidity level continuously monitored. GSY employs a target level dew point, but also employs alarm safeties at higher levels below what the required threshold in case of an unexpected rise in humidity levels. The total number of humidity sensors was not disclosed and differed from room to room based on the needed level of control.

A sample of the aluminum and copper foils were shown; these are used for the cathode and anode electrodes, respectively. There was a white polyolefin separator used between the aluminum and copper foils. (b) (4) [redacted] The only cathode active material used in this facility was lithiated cobalt dioxide ($LiCoO_2$). The anode active material was carbon, but different types were used depending on the individual cell design application (airplane, satellite, or rocket). (b) (4) [redacted]

In the Mixer Room, cathode and anode pastes were mixed in batch processes in dedicated mixing machines that were located in the same room approximately 2 meters apart. None of the group visitors was able to enter the room unless they changed shoes and walked over a sticky mat. (b) (4) [redacted] Each mixing machine was identical, from the same manufacturer, holding up to 25 L. (b) (4) [redacted] One member of the team was permitted to inspect the mixing vessel when it was open (b) (4) [redacted] On the day of the tour, a cathode slurry was being prepared. The mixing process began with an as-supplied polyvinylidene difluoride (PVDF) binder solution in a solvent. The cathode active material was used (b) (4) [redacted]

The various powders used in each slurry were manually weighed and filled in a container on a scale (which was calibrated once per year) and then charged into the mixer container. This information was recorded into a computer database. (b) (4) [redacted] The time in process was the primary determinant of each successive step and its completion. Viscosity of the mixture and viscosity as a function of shear were not measured. (b) (4) [redacted]

The mixer was automated, but an operator was present to monitor for any problems, such as unusual noise. (b) (4) [redacted] During maintenance or non-use of a mixer, the mixing chamber was kept sealed under vacuum. The solvent and binder come directly from the supplier and were checked for conformity before use. Each mixer was dedicated to either the anode or the cathode slurry during the visit.

The operator was observed standing and monitoring the machine. At regular intervals, the operator would scrape the blades with a plastic spatula to remove slurry adhering to the blades. He was wearing a waste-length coat, mask, gloves, and hat. He did not have any specific expertise related to the chemicals used. The room had fluorescent lighting and had an air conditioner with dehumidifier. The room was maintained below a prescribed threshold temperature and humidity. After the mixing was completed, the operator performed a visual check of the particle size. The cathode slurry was transferred from the blender to a stainless steel container using a stainless steel scoop for transport to the coating room. [redacted] GS Yuasa stated that the shelf life of the paste was limited by the specification and stored in the mixer room in a tightly sealed steel container.

The powders were typically stored in a local warehouse prior to use. During the visit, GSY Yuasa employees stated that no additional processing of the powders, such as ball milling, was performed before mixing. Since the visit, GS Yuasa has indicated they do perform ball milling. The cathode paste involves mixing the solvent and binder with the carbon (called mill paste). The definition of a well-mixed powder was defined in the drawing by a specific predetermined mixing time. The in situ mixing particle size was measured using a manual analog method with a pass/fail criterion. The operator stated that he had never encountered powder mixing issues such as agglomeration or foaming. Adding a solvent to adjust the appropriate viscosity was permitted without involving engineering level change, according to the manufacturing procedure. Engineering level changes do not need to be approved by Thales. In case of an engineering level change, the batch would be scrapped. The operator stated that batches of the same recipe were commonly combined since they were generally small relative to the amount required for the coating process. The first two batches were typically combined at the start of the coating process, with additional batches being added as necessary. The combined batches were considered as one coating. Each batch weight was recorded in the computer database by name, operator, weight, date, lot number, and particle size of the supply powder.

The Coating Room was the location where the cathode and anode foils were coated on separate coating machines. [redacted] The room was lit with fluorescent lighting and maintained at a set temperature; there was no humidity requirement, although the humidity was monitored. Typically, the coating occurs the day following mixing of a batch.

The coating machine in operation was coating the cathode foil for a different model battery. The foil being coated was the same as that used for the 787 battery. The foil roll was placed on a reel in an enclosed case and as it unrolled, it was coated with the cathode slurry via a reverse comma coating head as depicted in Figure 2. The coating width was as used in the cell, relatively narrow. The slurry was delivered to the coating head through a series of metal and plastic connections from a stainless container. The reservoir of slurry at the coating head was in a small tray that was open to the air and was equipped with a "slow speed" mixer. As slurry was used from the reservoir, an additional dose of material was added to the reservoir. Coating was continuous, with no gaps.

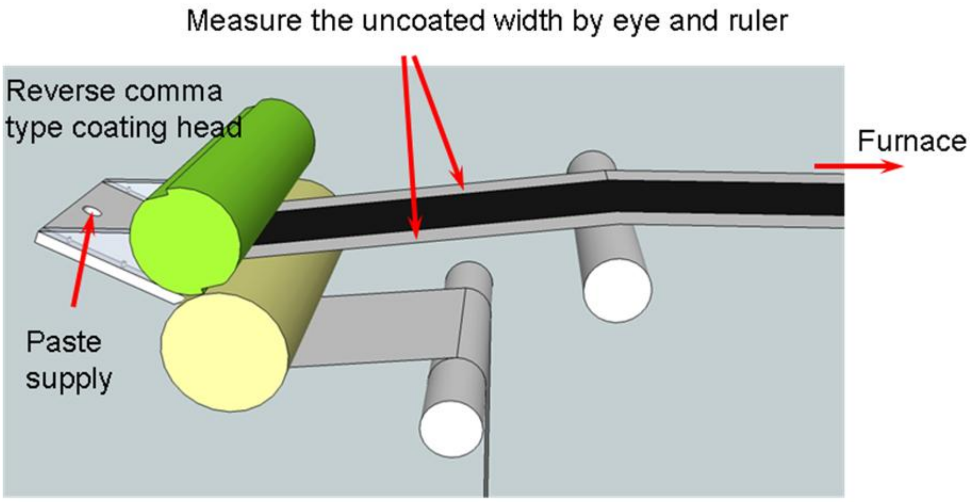

Figure 2 – Sketch drawing of the coating process.

The line speed was kept constant, as was the gap between the coating roll and the reverse comma knife, past what was supplied on the aluminum foil because no back roll was used. The coating width was monitored by eye and measured by ruler periodically. The operator measured the thickness periodically by micrometer—the micrometers were calibrated once per year by and external vendor. The cathode coater and anode coater had different total drying zone lengths (the anode coater was not operating on the day of the tour). During the coating process, an operator stood near the coating head monitoring the process. Once one side of the roll was coated and wound, it was returned to the front of the coater, inverted and coated on the opposite side. The thickness of the coating was adjusted manually by the operator through a doctor blade process whereby the slurry was gravity fed onto the foil. The operator monitored the roll for wrinkles[6] and any other defects. Occasionally he would use a hand ruler to measure the uncoated foil along each edge of the electrode as it exited the coating head. The coating head was enclosed by a set of shields; the door to this shielded area must be opened for the operator to reach into the enclosure and over the coated area to make alignment measurements.

The coater/dryer system consisted of multiple drying zone [redacted] (b) (4) At this time, the operator would check the thickness of the coating using a hand held micrometer periodically. No specific checks on electrochemical capacity as a function of coating length were carried out. No slitting of the foil was performed during any stage of the coating and drying process. Winding sensors were in place to prevent misalignment, which was stressed repeatedly by the operator as a chief concern. The operator was also trained to look visually for burrs and wrinkles. [redacted] (b) (4) The coater/dryer was inspected annually by an in-house maintenance team. The operator was required to perform a daily sound and visual inspection of

[6] GS Yuasa defined *wrinkles* as visible longitudinal or diagonal surface creases in the electrode coating on the foil that occur after the coating process. For the purposes of this report, *wrinkles* will be defined in this manner.

the machine before use, and clean all contact surfaces with rubbing alcohol at the end of the shift.

From the oven, the roll would be placed on the Clearance Calendar Roll Press where it was unrolled while being fed through the machine and pressed to achieve a reduction in thickness and re-rolled. (b) (4) [redacted] The electrode on the mandrel was pulled off by hand and pushed down into the bin by hand. During the calendaring process, an operator would monitor the foil as it exited the press, checking thickness periodically by micrometer (calibrated once per year, externally) during the process and at finish. Thickness sensors were observed after calendaring. (b) (4) [redacted] Both cathode and anode shared the same calendaring machine. The operator would observe 2 - 3 rolls per shift and would perform other various tasks when not monitoring the press. The calendared and rolled electrodes were placed in bubble wrap and temporarily stored in a vacuum dryer at a prescribed temperature for a maximum set time per specification. Both cathode and anode shared the same procedure.

The Winding Room—contained inside a large dry room that included several other operations—consisted of the large winding machine that merges the cathode and anode foils with separator to create a jellyroll. A separate operation in the same room involved a flattening jig for assembly of three flattened jellyrolls in an assembly preceding the header attachment. (b) (4) [redacted] he separator was a single layer polyolefin material made by a wet process.

The winding room temperature was required to stay within a designated humidity range below a set threshold. An alarm will activate if the humidity approaches that threshold, and the lot would be scrapped with mandatory quality checks given to Thales. The operator was wearing a mask, gloves, and hat. During the cell manufacturing subgroup's visit, the humidity alarm went off in the winding room. The operator and engineering staff immediately evacuated everyone from the room until the alarm subsided. It should be noted that the weather in Kyoto had been rainy and humid that day, with standing water still present outside on the day of the tour. After the alarm was cleared, only three members of the group were allowed back into the room with the operator and engineer.

The winding was automated but the operator manually performed a variety of tasks before and after this step. The operator took a plastic sleeve from a supply of previously prepared parts, which was made from heavy plastic sheet held in a cylindrical shape with tape. The operator slid the cylinder over large winding mandrel and visually aligned plastic cylinder on mandrel. The operator used a battery-powered screwdriver to tighten three or four bolts at ends of a mandrel to expand the mandrel against cylinder. The mandrel was fixed in a holder during this step. The mandrel, socket head screws, and motor-driven power tools are all metal-based. The operator then installed the mandrel into fittings on the winder (b) (4) [redacted] he automatic winding was executed, with a certain length of each roll being wound together and then cut off. Extra separator was wrapped around on the final step, and then cut and taped into place by the operator. (b) (4) [redacted] Several turns of separator were wound at the outer jellyroll and taped after cutting. The mandrel was removed from winder and put into the holder. The operator again used the electric screwdriver to loosen the mandrel and remove the sleeve. The winding process took less than 1 minute, but it took about (b) (4) [redacted] for the operator to prepare the winder and perform a post-wind inspection.

After winding, the operator would measure the alignment and weight of the each roll, applied a number on a piece of tape, and placed the completed wind into open box on a shelf near winder. This data would be inputted into a computer, and the weight was measured as pass/fail, as an indication given on the computer screen. The rolls were kept on a shelf in the room. Another table in the room was used to bundle three rolls (a compression jig). The compression jig consisted of two flat plates on each side of a base with handles connected to plates through cams. (b) (4) [redacted]—the jig was configured for assembly of three jellyrolls for the LVP65 cells on that day. (b) (4) [redacted] The operator then took one cylindrical wound jellyroll and, by gripping the jellyroll with his hand, partially flattened it in his hand, placing it into the jig.

This process was repeated for two more jellyrolls. He adjusted the three jellyrolls in the jig by hand and visual inspection and hand adjustment. The operator then moved both handles at the same time to move the flat plates together to complete the flattening process for all three winds. The operator put a block on one handle and released and retightened it two or three additional times.

The hand flattening pre-forming process created what appeared to be perturbations[7] of the electrode foil in the manner depicted in Figure 3 during the assembly, which captures the observations of the final three jellyroll flattening process.

[7] For the purposes of this report, electrode *perturbations* are defined as changes in the electrode foil nominal form due to compressive buckling.

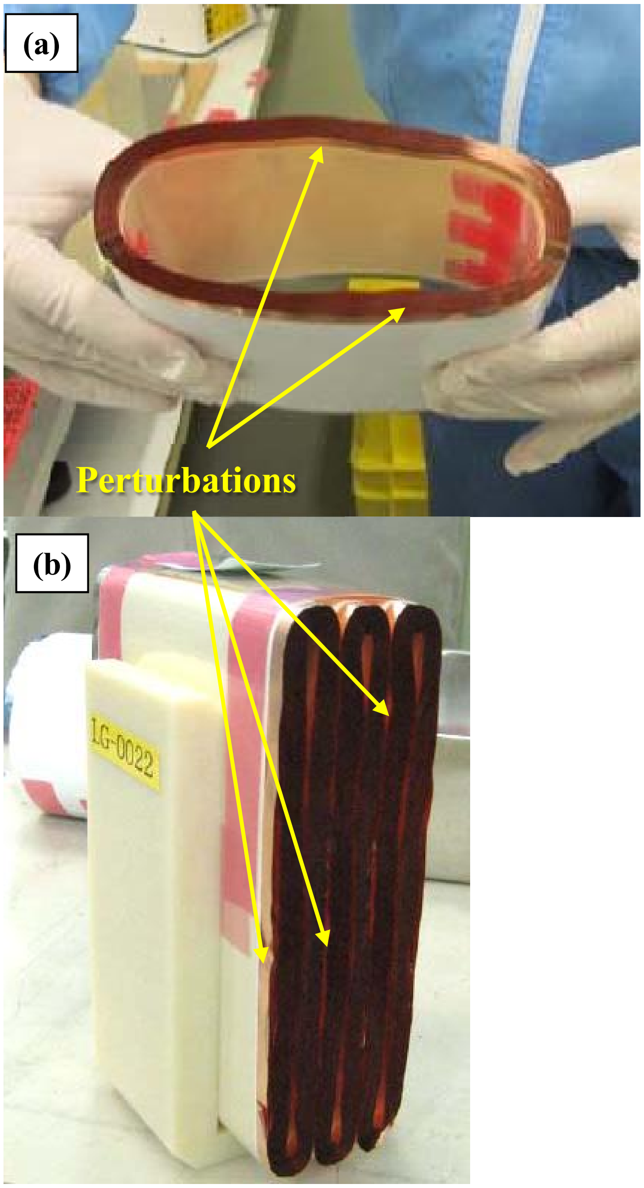

Figure 3 – Images of the jellyroll flattening process showing (a) hand flattening and (b) the three-electrode assembly after final flattening and taping.

Following the squeezing operation, the operator then manually taped plastic pieces on ends of cell where the curves of the winds were located and taped around the assembly. This resulted in three flat winds with four plastic pieces taped to enclose them on four sides with the metal edges of the winds still exposed. This assembly was put aside in an open box. The individual rolls were not serialized; rather receiving serial numbers after the three rolls were assembled in the next room. It was not clear whether the jellyrolls were pre-matched in any way. There was currently only one operator working in that area during the shift, and his primary focus was on winding the rolls.

The Cell Assembly room was a main staging area with a number of stations that focused on various stages of the cell assembly process. This room connected to the winding room, electrolyte-filling room, and coating/drying room, being isolated with double door airlock equipped with air showers. The room had fluorescent lighting and was noisy when the ultrasonic welding machine was in operation. Operators wore masks, gloves, and hats. Numerous steps to the assembly process were performed manually. Due to the precision needed to assemble some parts, metallic tweezers were used. There was no significant separation of the various operations carried out in the main staging area (e.g., the operations were not shrouded or carried out in enclosed spaces). Operators typically worked on 20 cells per shift. If a cell was dropped, it would be recorded in the system, and the engineering and quality control (QC) departments would determine what to do with that cell.

In the assembly room, the header assembly was attached to the flattened triple winding assembly. The header assembly [redacted] (b) (4) consisted of the cell header cover with two sets of current collectors riveted to the cover with insulators in between and two threaded terminals. First, manually using a rubber/plastic spatula and a pair of metallic tweezers, the operator separated the metal foil ends of the windings into bundles, which were pinched together. The cell header was carefully slid over one end of the set of three winds from the top and tapped into place with a mallet. Then each of the conducting fingers was manually fitted over one bundle of exposed foil ends and manually pinched into place. The bundle was then moved to the ultrasonic welding station at an adjacent table where two operators welded each of the conducting fingers to the edges of the foil. The ultrasonic welding was a manual process in which the operator welds the assembly on each side three times—[redacted] (b) (4) One operator performed the process using a foot pedal that actuated the automatic ultrasonic welder and vacuum attachment, while the other observed/directed. The vacuum (suction) and separate vacuum brush on the machine were in place to remove Foreign Object Damage (FOD) generated by the ultrasonic welding. After welding, the assembly would then be visually inspected to identify potential defects. If any issue were identified, this would be recorded into a database and discussed with engineering.

The welded bundles, with header in place, moved to the next table where additional insulating tape was wrapped around bundle. The cell would then be wrapped with an insulating film and heat-resistant tape. The wrapped bundle was slid into a stainless steel prefabricated case, and the top cover was set into place. A bar code was assigned to each cell which included serialized information such as lot number and components used. [redacted] (b) (4) the next process: manual tungsten inert gas (TIG) welding of the header cover to the cell case. The TIG weld station was a workbench in the corner of the assembly room. The operator used visual protection and a brace to rest his wrist during the welding. The welded cell was inspected by an inspector who used a magnifying glass to identify potential defects. The TIG weld process would be repeated as above if a possible defect was identified. The cell would also be inspected for potential damage to the insulation, excessive heat, and other defects. There was a small open hole in the cell case, which would be used for filling with the liquid electrolyte—an air leak test was performed to determine air tightness [redacted] (b) (4) If there was no leakage (pressure drop), the cell moved on to the electrolyte filling operation. Near the

TIG welder were four programmable laser welding machines—GS Yuasa indicated these were used for manufacture of other battery cell types.

The electrolyte filling was performed in a separate humidity-controlled room attached to the main assembly room. The groups did not witness the filling procedure being performed during the visit. The room had two electrolyte filling stations with hoods on one side, two precharging stations farther down on the same side, and the resistance welding station and electrolyte storage area on the other side. The electrolyte filling was an iterative manual operation. The cell was placed on its side on flat surface, fill hole facing upward. With a fitting over the hole with a gasket (pressure) fit, the cell was gravity filled under vacuum. The fill valve was actuated to allow a specific amount of electrolyte to flow into the cell during each step. The amount of electrolyte needed was measured by weight. The cell received a rest interval between each of the three iterative fill steps–the three steps were used to prevent overflow. After an applied precharge that results in a state-of-charge (SOC) of 2 - 3%, the cell was returned to the filling station, re-evacuated, and filled with more electrolyte. The cell received a one-hour precharge to a state-of-charge of about 20%. The cell was returned to fill station for the final evacuation/filling step with the goal of adding the remainder of desired electrolyte.

(b) (4) [redacted]

The fill hole on the side of the filled cell was plugged with a spherical metal ball that was resistance welded in place. This resistance welding was performed in the filling room next to the electrolyte storage area. (b) (4) [redacted]

The cell would then be moved to the Formation and Inspection area where a number of inspections were performed in a variety of smaller rooms—visual inspection (damage, scratches), weight, AC/DC resistance, capacity of cell, charge/discharge and open circuit voltage (OCV) change measurement check. DC resistance was measured at 100% SOC. GS Yuasa indicated that the DC resistance test was an in-process test, meaning that all cells are measured during production. Since DC resistance was measured at 100% SOC, then the only available position was the charge step after the third electrolyte fill. The charge/discharge was used as a standard solid electrolyte interface (SEI) layer formation procedure and the OCV check was performed to check for internal soft shorts. The cell would be attached to wiring that would record data on a computer. The cells would be monitored for 2 - 3 weeks every hour to look for a voltage decrease. If the voltage decreased beyond a certain amount, the cell could not be used. This information was stored in a data logger supplied by Boeing, with visible charts used to track trends in recent lots. Approximately 2% of the cells were rejected after the OCV testing.

Last, the cells were taken to the CT Inspection room, where a cell would be placed in the machine to produce a digital photograph of the inside of each cell. An operator would view the image on the computer to identify ultrasonic weld potential defects on the current collectors and enclosed FOD. The resolution of the scans produced from the CT scanner did not produce features consistent with those found during CT scanning performed as part of the NTSB investigation of the incident and exemplar batteries[8]. If a defect was identified, a Material Review Board (MRB) would be submitted and the cell would be subject to further assessment. The operator stated that approximately one or two cells in 500 were typically rejected by this criteria and were opened afterwards (most opened cells would not produce obvious defects). CT scanning was performed on 100% of the cells, with measured data saved to the database and traceable to cell numbers. No dimensional numbers were made. It was unclear what other information was saved to the database other than pass/fail and images. The operator would view 6 cells per hour, or about 40 cells per shift. There were no breaks specified to be taken by operators beyond the two 15-minute (morning and afternoon) breaks and a lunch break. However, if an operator felt tired, he could take a break because doing so would not affect the production line.

Once all inspections were completed, the cells would be grouped according to capacity grading for assembly into the battery. The operator was provided training and education on the procedure but there was no test to determine if he was qualified. He would receive on the job training and when deemed capable, he would be signed off to do the work.

4.0 GS Yuasa Factory Tour of Battery Manufacturing Process

4.1 Battery Manufacturing Tour

The other area of the tour started in the Receiving Room where raw materials were received and inspected. (b) (4) [redacted] All incoming material was 100% inspected, and the engineering drawings state what to inspect and verify, under standardized overall inspection procedure. (b) (4) [redacted] GS Yuasa stated that their suppliers package all materials properly with no contamination, so the direct transfer to the dry room when needed was appropriate. (b) (4) [redacted]

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[8] See NTSB DCA13IA037 *Computed Tomography Specialist's Factual Report*.

(b) (4)

[redacted] The demands on the suppliers were customer driven (example: some customers demand full ISO 9001 testing). The 787 battery materials were checked for each lot to develop a range. Suppliers submit a certificate of acceptance (COA) and other quality assurance paperwork. GS Yuasa confirms the COA and QA paperwork from each supplier for each lot. Since attaining "black label[9]" status, the incoming material was checked 100%. GS Yuasa posted a clearly visible graph on the inside door of the number of non-conformance items per supplier for the month. This data helped GS Yuasa determine which supplier to audit. This chart was updated monthly. For those suppliers requiring an audit, GS Yuasa would implement a 1-year improvement program for them.

Tooling also came to the receiving room and was checked for calibration. Once calibrated, a label would be affixed indicating how long the calibration was valid. If a non-conformance was found, the item was placed in a locked box. A rejection tag processed by MRB would be issued and GS Yuasa would discuss with Thales whether to scrap the item.

The tour proceeded to the Inventory Warehouse, which was next door to the Receiving Room. The items were stored on moveable steel shelves with tracking numbers. [redacted]

(b) (4)

The Battery Manufacturing area housed a number of phases of the battery manufacturing assembly process. Four to five operators were observed in the room with one inspector. Operators were assigned to one of the phases. All operators were wearing a coat, hat, gloves, and a mask. The inspector was not wearing a mask. GS Yuasa later stated that inspectors are supposed to don masks. The room only needed to be at the ambient air temperature and humidity (which was checked daily) but the room did have air conditioning for the comfort of operators. Lighting consisted of hanging fluorescent lighting from the ceiling. There were manuals located in three locations in the room that operators would reference when manufacturing the battery. GS Yuasa was currently manufacturing (b) (4) per day, which was full capacity. The previous battery production was (b) (4) per day.

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[9] "Black Label" batteries are batteries installed on production aircraft delivered to operators.

The cells for the -901 and -902 battery designs were identical, and the assembly process for the -902 battery was comparable to the -901 assembly. The operators were working on the -902 battery assembly at the time of the NTSB visit. Any cells manufactured before the -902 changeover retained their old -901 cell serial numbers. Each battery cell was installed at less than 10% SOC. The cells were installed in the battery based on similar charge capacities. These values were written down in an engineering communication document that also contained the battery S/N and individual cell S/Ns. This run sheet showed variances overall in battery cell capacity, but the eight cells in each battery exhibited a much tighter tolerance. (b) (4) [redacted]

The BMU was installed in the battery box followed by the lower fixation tray and other accessories. An operator would remove the cells from a plastic bin for insertion in the battery casing. GS Yuasa stated that the first step was to attach high temperature tape to the -902 cells around welded header and attach a prefabricated plastic insulator around the header terminals (the -901 battery cell case had not been covered with tape). An inspector would inspect the cells after taping and the results were documented in the computer. After the cells were taped, they were placed into a plastic bin. More robust glass-reinforced polymer material cell separators were used between the cells to aid in cell positioning, electrical isolation and reducing heat transfer. The bus bar nuts were initially hand torqued and then tightened to a specific set torque value that would click. This process was monitored by an inspector who confirmed proper torque on a controlled document. The parts used in the assembly process were not kitted but were taken as needed from bins. Wiring bundles were used to connect the cells and BMU to the external battery leads. (b) (4) [redacted] The operator uses a wiring diagram to confirm the proper placement of each wire lead. An inspector watches the operator during this process. The -902 battery box was developed with holes in the battery box to allow for cell venting, with the cells aligned opposite the corresponding vent holes.

(b) (4) [redacted]

The Pre-shipment Inspection Room was the area where the enhanced acceptance test procedure (ATP) was performed. Tests performed included: dimensional check, standard appearance, functional inspection, charge/discharge test, voltage check, AC/DC resistance test, and BMU functional check. Boeing authorized two qualified GS Yuasa operators to perform the inspections. The dimension check involved using digital calipers that register the measurement into a Microsoft Excel spreadsheet software. Soft short tests were performed at 0% SOC for 2 weeks. The battery charge/discharge testing was performed in a chamber where the battery box would be opened (top removed) and an infrared camera was used to monitor the temperature during the enhanced ATP test. This test was required by Boeing described in a Thales document.

The battery then underwent a final AC/DC testing. If the battery passed all tests, it would be shipped. There was a zero reject rate, although some batteries would require 1-2 minor changes or adjustment (e.g., pitting of paint), which would be corrected and the battery would be tested again. These changes or adjustments performed would not be related to the cell or battery functioning properly. The temperature and humidity range in this room was monitored and was checked daily. [redacted] (b) (4)

GS Yuasa was currently operating at full capacity, [redacted] (b) (4) If they were not shipped immediately, they would be stored in the refrigerator with the cells. [redacted] (b) (4)

5.0 Kanto Aircraft Instruments

Kanto Aircraft Instruments was founded on December 29, 1952, and currently had an annual capital of $6 million (¥480 million) with 224 employees. Kanto's focus was designing and developing instrumentation for precision aircraft, electronics, controls, testing and measurement hardware. Much of Kanto's business was for the Japanese Ministry of Defense. They had an authorization for JIS Q9100: 2009; JIS Q9001:2008 (ISO 9001:2008); and JIS Q14001: 2004. They did not have JCAB manufacturing authorization. However, they did have authorization from the Ministry of Economy, Trade, and Industry (MET) for military applications.

The commercial or civil aviation product produced at KAI was the 787 Main and APU Battery BMU. The production of the BMU accounted for only a small percent of KAI's total production. KAI did not produce any other monitoring interfaces for battery applications.

KAI explained that JIS Q9001 was an authorization not only for airborne materials but also for broad manufacturing. JIS Q9100 was an authorization for airborne equipment only.

GS Yuasa holds the authority for any acceptance engineering corrective action to products noncompliance through GS Yuasa's MRB process[10]. Additionally, GS Yuasa also had the ultimate design authority; however, KAI owns the design of the BMU.

KAI was hired by GS Yuasa to develop the BMU in 2005. This was the first time that KAI and GS Yuasa did business together. According to the company, KAI received the SCD from GS Yuasa, whereupon KAI developed the design specification based on the SCD. After receiving confirmation and approval for the BMU design from GS Yuasa, KAI would make BMUs.

[10] GS Yuasa's nomenclature for a MRB was an Engineering Order (EO).

[redacted] Part of the tooling used to make the BMU was also used to make other products not associated with civil aviation.

5.1 Tour of KAI production facility

On May 28, 2014, KAI provided the Manufacturing Group with a tour of the production facility. Upon entering the facility, members of the group were required to remove their shoes and to put on a pair of grey slippers. The group walked to another room where they were required to remove the grey slippers and to put on a pair of white slippers, a static-free coat, and hat. The process of changing shoes was to prevent static build up. KAI had no prescribed limit to the number of visitors allowed at one time.

The manufacturing room had fluorescent ceiling lighting, with temperature and humidity controls. There were two workers assigned to the Boeing 787 BMU and typically worked from 0830 until 1720, Monday through Friday. The workers were assigned an emergency shift at the time of the visit due to increased production of BMUs. The workers were on duty from about 0830 until 2100 – 2200 local time, Monday through Friday. Normal production of BMUs was [redacted], but they during emergency shifts, KAI can produce [redacted]. To perform work on the BMU, each worker completed and passed an annual soldering test, which included classroom training and demonstrated capability.

[redacted]

(b) (4)

[redacted]

[redacted] *Temperature test*. At this stage, the main and sub BMU were combined and the masking was removed. The BMU was tested from -30 ºC to +70 °C. (b) (4) [redacted] No discrepancies had been found by this system. If a discrepancy were to be found, the BMU would be repaired and the process repeated from the beginning.

- *Function test*. A final function test was completed. If the BMU passed this test, it was ready to be released and was stored in an environmental cabinet until it was sent to GS Yuasa for further production. The COTS component reels and the finished BMUs were stored in a dry cabinet.

6.0 Human Performance in the Manufacturing Process

The following information was obtained by GS Yuasa and KAI personnel during the NTSB's visit to their facilities on May 28-30, 2013, unless otherwise noted.

6.1 GS Yuasa operator work schedule and training

Operators in the battery manufacturing facility worked 0800 – 1800 and this included 2 hours of overtime. These hours were worked Monday, Tuesday, Thursday, and Friday. Wednesday was considered a no overtime day and operators worked 0800 – 1635. They received three breaks—15 minute breaks from 1000 – 1015, lunch breaks from 1200 – 1245, and 15 minute breaks from 1400 – 1415. The times could be adjusted slightly based on the work being performed. Operators typically worked 7.83 hours in the shops. The operators work at one station each day and then rotate to a different station the next day depending on the individual skill sets. There were no specific qualification tests for the different skill levels, although GSY implements qualification tests for soldering and TIG welding operators. Operators in the cell manufacturing facility worked one of two shifts—0800 – 2000 or 2000 – 0800, Monday through Friday, unless production demands required more.

The operators were unionized and the union contract determined the breaks required. There were a number of trade unions, and GSY worked with one specific to metal and machinery. During the visit to GSY in May 2013, GSY management was negotiating with the trade union regarding the next month's production schedule.

Overtime could be worked after normal working hours and required that operators take a 15-minute break before starting their overtime work. There was a maximum amount of overtime that could be worked—2 hours per day, 45 hours per month and 360 hours per year. If these amounts were to be exceeded, management would negotiate with the trade union or create a mutual agreement, for example to increase the daily overtime limit to 4 hours. If an operator worked until midnight, he would be given the next day off. Monthly and yearly overtime data was collected and assessed by GSY. GSY did not negotiate for additional overtime hours for the lithium ion battery production.

Regarding training, all operators received supervised on-the-job training (OJT). GSY used a skill map to assess the skills needed of each operator. The amount received was dependent on the task. Some tasks required 3 – 7 days of OJT while others required more. Inspectors required at least 2 months of OJT in order to be considered qualified and "get the stamp." Inspectors sometimes required the approval of the "boss." There was no specific classroom training but a lecture was provided to all operators once per month regarding basic scientific knowledge of batteries with the purpose of deepening their understanding. Some tasks required operators to be checked for their competence and skill level, such as soldering and welding. This was judged by a qualified and skilled inspector. Records were kept and maintained as a part of the training and education of the operator.

The NTSB requested all training manuals and documents related to training for battery and cell manufacturing. The GS Yuasa "Education and Training Plan" scope stated "this regulation shall apply to education and training for all employees of manufacturing (manufacturing, quality control and production control), engineering, quality assurance, sales and project for special batteries and large-scale lithium-ion batteries." The document discussed who should plan, approve, implement, and evaluate the education and training. Some personnel would be provided with "education from time to time for qualification," including qualified personnel of design and development, checker of drawing, operator and inspection personnel engaged in special process, and internal quality auditors.

The GS Yuasa "Special Process Control Regulation" scope stated, "This regulation shall apply to special processes in the production of the large lithium-ion battery. The special processes mean such processes specified in Section 5 and needed to verify the effectiveness to assure the production process and quality but difficult to ensure quality of the applicable product by the normal method of product inspection." Section 5 of this document stated, "The special process shall be designated on the list of drawings or drawing itself by Design Section with consideration to the specifications requested by the customer, or customer requirements agreed to in the contract, and the significance of quality assurance."

A list of training procedures was also provided:

- General education procedures
    - Acceptance Education
- Training procedure for battery
    - FOD
    - Static electricity
    - Manufacturing procedure
    - Precaution statement for battery assembly process
- Training procedure for cell
    - Special process – TIG welding
    - Special process – Ultrasonic welding
    - Key process – Electrode; on the job training
    - Key process – Element (jelly roll); on the job training

6.2 KAI operator work schedule and training

Production line operators had been working the "emergency shift" since March 2013 and were expected to continue that shift until the end of June 2013 when production was expected to slow down. [redacted] (b) (4)

Regulations dictated that production line operators must take a lunch break of 50 minutes. It was at the individual operator's discretion as to when to take rest or other breaks during their shift. If an operator must work past 1720, it was KAI's rule that the operator must be given a break from 1720 until 1730 and a longer break from 1930 until 2000. Production line operators were unionized and per the union contract, operators could work a maximum of 360 hours of overtime each year.

KAI did not have a document specifying the training or education required for initial hires or training when being assigned to working on the BMU. The soldering test was a top priority to determine if an operator begin work or continue work on the BMU. If an operator passed the test, he would be put on the line. There was also support type work apart from soldering, but if an operator did not pass the soldering test, he would not work on soldering.

Following recognition that operators had used alternative parts contrary to the parts listed on the approved drawings, KAI provided one-time training to current employees to make sure they would not use any other part with a part number different from what was stated in the drawings. The training provided was documented as performed but there was no documentation indicating that training for use of parts was required training. No additional training was scheduled at this time for current employees; however, new employees would receive this training if they would be working on the BMU.

7.0 Quality System

7.1 Boeing

Because the 787 Dreamliner has about 2.3 million parts and assemblies per airplane that are built all over the world by numerous suppliers and partners, Boeing, the production certificate holder, was required by FAA regulations to ensure the parts and assemblies being built for the airplane conform to the approved designs and are manufactured in a condition for safe operation. Boeing developed and maintained the Boeing Commercial Airplanes (BCA) Quality Manual to ensure compliance to the rule.

According to the Boeing's Quality Manual, Boeing uses their internal Supplier Management Organization to oversee all aspects of the production supply chain (i.e. definition of requirements, selection, negotiation/award of contracts, supplier performance, product conformance, etc.). As part of the Boeing supplier selection process, Boeing suppliers must certify that their production systems meet Boeing Quality Management System requirements, and their systems must be approved by Boeing, the Federal Aviation Administration (FAA) and an independent third party. Further, one key criteria was the suppliers' ability to manage a subtier supply chain. Subtier suppliers are the suppliers who provide sub-systems raw materials and other items to First-Tier Boeing suppliers[11].

Boeing personnel are embedded at supplier factories around the world to monitor quality, work with suppliers on process improvements, and ensure adherence to Boeing standards and schedules. Boeing also performs audits of supplier operations.

[11] First Tier suppliers are those who supply the finished component directly to Boeing. These suppliers have direct contracts with Boeing and have primary contractual responsibility for function and reliability of the component.

For regulatory requirements, Boeing's external supplier network was an extension of Boeing factories. Suppliers must meet or exceed established performance measures for quality, capability, and compliance. External suppliers must adhere to Boeing standards and practices, including deployment of a rigorous quality management system.

Boeing supplier quality oversight relies on oversight by Certification Bodies (CB) in the scope of AS/EN9100 certification and Boeing specific Supplier Quality Surveillance (SQS) activities at suppliers.

The Boeing SQS was a proactive approach to improve partnership with Suppliers, combining business surveillance activities and improvement reporting of Supplier health. The SQS consists of three tools (1) Product Assessment (2) Quality Process Assessment and (3) Manufacturing Process Assessment. According to Boeing, the tools support Boeing in monitoring suppliers in a planned/scheduled manner without impeding product delivery. Surveillance activity was determined based on supplier performance and risk to Boeing. SQS activities are performed by Boeing's Supplier Quality Representatives at the Supplier or Supplier's subcontractor facility under the contractual General Provisions addressing Boeing's right of surveillance and review of goods and related procedures, practices and processes.

Prior to the incident, besides its own periodic surveillance of Thales, Boeing also relied on Bureau Veritas Certification (BVC) in performing twice a year surveillance assessments of Thales AES France (see Table 1).

Table 1 - The Boeing Surveillance Records on Thales

	Assessment Type	Scope of Assessment	Date	Location	Minor Findings	Major Findings	Total Findings
2010	BVC	EN9100:2003	April 20-21	Thales	0	0	0
	Boeing	First Article Inspection	June 18	Thales	0	0	0
	BVC	EN9100:2003	Sep 15-16	Thales	0	0	0
	Boeing	Auto Transformer Rectifier Unit	Oct 10	Thales	0	0	0
2011	BVC	EN9100:2003	April 4-5	Thales	0	0	0
	Boeing	Power Conversion Panel	May 19	Thales	0	0	0
	BVC	EN9100:2003	Oct 3-6	Thales	2	0	2
	Boeing	Electrical Brake Power Supply Unit	Nov 4	Martek Power, sub tier to Thales	4	0	4
2012	Boeing	MTRU	Feb 14	Thales	0	0	0
	Boeing	Receiving Inspection	Feb 23	Thales	2	0	2
	Boeing	Auto Transformer Unit	Mar 14	Thales	0	0	0
	BVC	EN9100:2009	Mar 19-22	Thales	0	0	0
	Boeing	Equipped Frames for Power Conversion Panels	Mar 30	NSE, subtier to Thales	3	0	3
	Boeing	Auto Transformer Rectifier Unit	Apr 3	Thales	0	0	0
	BVC	EN9100:2009	Oct 15-19	Thales	0	0	0

After the incident, Boeing sent a Supplier Quality Team to Thales, GS Yuasa, and Kanto Aircraft Instruments to accomplish further audits specific to the manufacturer, quality, and management of subtier supply chain, business processes, and adherence to Boeing standards. Until the recent activities involving direct Boeing audits of GS Yuasa's facilities and manufacturing capability, Boeing had not conducted any manufacturing capability specific visits to GS Yuasa or Kanto Aircraft Instruments. According to the contract between Boeing and Thales, Thales owned this responsibility.

Boeing maintains a specific set of requirements for actions associated with a Supplier Quality Audit. These focus on noted items of non-complaint items and are documented in Supplier Evaluation Reports (SER). The supplier was required to submit documentation associated with immediate correction action, a corrective action plan, a root cause plan which outlines long term corrective action, and a verification methodology outlining how effective the corrective action has been to be completed after a given amount of time passage.

The audit of Thales, GS Yuasa, and Kanto Aircraft Instruments found 17 items of non-compliance per Boeing requirements. Most of the compliance issues found at GS Yuasa involve administrative adherence to written procedures and communication with Thales and Boeing regarding authorization for proposed procedural and testing changes for the battery. Compliance issues found at Thales likewise involve adherence to contractual requirements for Boeing approval on drawing or procedure changes. Compliance issues noted at KAI involve data collection for repairs to production components, storage requirements for circuit board tooling, and equivalent electronic component (resistor) substitution documentation.

As of December 2013, all but one of the above 17 findings from the audit have been closed meaning that interim and long-term action was identified and actioned by the appropriate vendor. In addition, Boeing has determined that the long-term action for each closed finding has been verified as being responsive toward rectification of the original finding. The remaining open audit finding regarding final Boeing approval for the latest battery configuration documentation was verified in May 2014.

7.2 Japan Civil Aviation Bureau (JCAB)

JCAB had performed audits of GS Yuasa, but not in relation to B787 program. GS Yuasa was audited once every 2 years related to other lithium ion battery and other battery programs, which was part of the type certification process. GS Yuasa had a type certificate issued by JCAB for Japanese defense application and lifesaving equipment, not civilian applications. This was not a manufacturing authority.

7.3 The French Direction Générale de l'Aviation Civile (DGAC) and Organisme pour la Sécurité de l'Aviation Civile (OSAC)

DGAC delegates OSAC surveillance on the behalf of organizations that provide parts and appliances to aerospace companies. The DGAC has production oversight for French companies. Therefore, the OSAC delegated audits are based on production, maintenance, and continuing airworthiness of their products. According to EU regulation (748/2012), audits are conducted on a two-year basis with a yearly check for those who released with airworthiness tags—additional audits could be performed, if warranted. OSAC audits are forwarded to the companies for compliance. OSAC then validates the corrective actions proposed by the production organization. Based on a sample-check basis and dedicated management audits, DGAC controls the OSAC processes ensuring that they are in accordance with EU regulation.

According to DGAC/OSAC, audits of Thales' supplier GS Yuasa was conducted yearly per its audit criteria. The last two such audits were reviewed from October 2011 and September 2012. The September 2012 audit revealed two minor findings (Shop document procedures and change control documents) which were both corrected.

7.4 Thales

Thales developed a Quality Assurance Requirements for Suppliers (QARS) document to be met by suppliers of Thales AES during the whole life cycle of the units for the Boeing 787 Power Conversion System. The document was to ensure the quality of the products supplied by Thales partners and suppliers.

Thales requires each supplier maintain an effective quality system to ensure product and process integrity that was based on AS9100. Thales also requires development partners maintain an accredited aerospace industry certification/registration to AS9100. Further, to ensure suppliers meet the Thales QARS, Thales requires suppliers develop its own Quality Assurance Plan (QAP). The QAP provides a description of the supplier's continuous improvement. According to Thales representatives, audits of suppliers are conducted annually and periodically throughout the year. Supplier Quality Records show Thales accomplished the surveillance of GS Yuasa on three occasions, as shown in Table 2.

Table 2 - GS Yuasa audits by Thales

	Assessment Type	Scope of Assessment	Date	Location	Minor	Major	Total
2010	Thales	Battery B3856-901	April 6-7	GS Yuasa	1	0	1
2011	Thales	Battery B3856-901	June 22-23	GS Yuasa	3	0	3
2012	Thales	Battery B3856-901	Sep 11-12	GS Yuasa	7	1	8

Thales had audited GS Yuasa twice since the battery release: one in June 2011 and the other in September 2012, which were reported to Boeing. In June 2011 audit, there were three minor findings, all of which have been corrected and closed. These were:

1) No requalification frequency was defined concerning special processes that were subcontracted. No qualification documents and test result performed on the test bars were available the day of the audit.

2) The day of the audit there was no authorized list of people who were trained and authorized to sign the Certificate of Conformance (CoC).

3) The day of the audit there was no training procedure to qualify people who were authorized to sign CoC.

In the September 2012 audit there were 12 findings. Most were minor, with at least one major; all have been closed. GS Yuasa indicated it was unable to disclose the list of specific findings due to contractual and copyright restrictions, but provided the following summary:

1) Some items in the previous action plan (further audits in 2011) were still open and specifically concerned special process requalification.

2) First article inspection was not yet signed by Thales (GS Yuasa was waiting for the Thales approval).

3) The major finding was administrative in nature: Thales PO#230102677 the contract review was not realized and not systematically formalized. Not all the documents notified in the Purchase Order (PO) were held by GS Yuasa (Y13-5425 as an old part number). GS Yuasa had not sent acknowledgment of PO to Thales.

4) GS Yuasa archiving system of 10 years was not compliant with Thales 30 year standard.

7.5 GS Yuasa

Before 787 battery development, GS Yuasa was required to create a quality system specific to the 787 battery in accordance with JIS Q9100[12]. This was equivalent to AS9100 and EN9100 and had JIS Q9100:2009 / ISO 9001:2008 approval. It was a Boeing requirement to obtain the applicable certificate in order to enter the contract, which requires development of a quality manual. The definition of the quality requirement was issued by Thales.

AS9100 is a widely adopted and standardized quality management system specific to the aerospace industry and, when adopted, requires establishment of a quality system for production of aviation products. AS9100 has requirements that do not exist in ISO 9001 and were required to be incorporated in GS Yuasa Quality System before the contract was awarded. The special manufacturing processes above AS9100 requirements were defined in the contract received from Thales as defined in the Boeing SCD.

Work orders and special assembly processes were defined by engineering drawings. These were flowed down from documents that included AS9100 and other special requirements specific to the aircraft. GS Yuasa conducted FAI to meet/satisfy quality requirement(s).

Boeing had not performed a quality audit of GS Yuasa prior to the incident. Subsequently, Boeing conducted an audit of Thales in France with GS Yuasa as a supplier consultant. During that discussion, Boeing wanted to know about GS Yuasa's manufacturing capability as part of a production readiness assessment— GS Yuasa does quality audits of its internal departments twice a year. In addition, GS Yuasa audits 12-13 of its external suppliers/vendors each year. The selection criteria were based on inspection results of products received the previous year, which were defined in the quality system.

GS Yuasa audited Kanto Aircraft Instruments in January 16, 2006 and December 19, 2008. From the 2006 audit, there were six findings; from the 2008 audit, there were five findings. According to GS Yuasa, all discrepancies had been addressed.

7.6 Kanto Aircraft Instruments

As part of the Thales flow down requirement to its suppliers (through GS Yuasa), KAI was to ensure delivered products and internal processes were based on AS9100 standards. KAI developed its quality assurance plan to meet the standards.

According to KAI, audits of its suppliers are scheduled at a minimum interval of 5 years. Between January 2012 and December 2013, KAI reported that it conducted two physical audits: one for the circuit board material supplier and one for the supplier of the BMU resistors. Both audits found no issues.

[12] Quality Management System Certification for the Aerospace Industry. "AS" Standards – Americas; "EN" Standards – Europe; "JIS Q" Standards – Japan/Asia. International Standards -9100 was the quality system for Aerospace Manufacturers. JIS Q 9100 was Japan Industrial Standard (JIS) of quality management system for the aerospace and defense industry which was equivalent to AS9100 in USA and EN9100 in Europe.

8.0 Service History

According to Thales and GS Yuasa, GS Yuasa was allowed to direct ship production batteries to Boeing's logistics vendor New Breed, Inc. In turn, Boeing production battery returns were also direct shipped to GS Yuasa. According to GS Yuasa, the batteries returned by Boeing were returned primarily for two major reasons: over discharging and improper battery connection. Others had been returned because of shorting of the battery terminals and mechanical impact damage. Boeing and GS Yuasa records show that of approximately 300 batteries shipped to Boeing, approximately 130 have been returned as of the end of 2012 for all reasons noted above. According to Boeing, there has been a learning curve associated with installation and charging of the battery (once installed in the production line) as well as utilizing the battery during production testing of newly installed electrical equipment. Boeing implemented several mitigation processes and procedures the intent of which was to prevent inadvertent discharge of installed batteries. In addition, Boeing also established procedures to test and charge batteries which had been subject to discharge but not to the point of being 'latched out' (thus preventing recharging).These mitigation actions have significantly reduced the number of removed batteries for inadvertent discharge during the airplane manufacturing process.

GS Yuasa ships battery spares to operators/airlines through Thales. However, with the approval from Thales, Japanese operators ANA and JAL were able to directly return the batteries to GS Yuasa due to their proximity to manufacturer. Conversely, operators/airlines sent their batteries to GS Yuasa via Thales. According to GS Yuasa and Thales, batteries returned by the operators were for three major reasons: overdischarging, malfunctioning of Battery Management Unit and cell imbalance.

Even though GS Yuasa stated that they had the capability to repair their batteries, they had not sought to obtain a qualification as a repair station and were therefore not authorized to make repairs (e.g. replacement of cells). GS Yuasa, however, created a Component Maintenance Manual (CMM) for the 787 Battery at the request of Thales and Boeing. GS Yuasa had also created a field tester to inspect batteries in the field as a part of the CMM.

9.0 Boeing Airplane Manufacturing Process

At the time of the event, Boeing manufactured 787's on one of four assembly lines. The Everett facility housed the main and surge assembly lines as well as a line established at the Everett Modification Center. The surge line and the Everett Modification Center lines were temporary in nature and were to be consolidated with the main Everett line once production reached full rate. The fourth assembly line is located in Charleston, South Carolina.

Main and APU Batteries are directly shipped from GS Yuasa to New Breed Logistics, Inc. (Boeing's logistics supplier) for the 787. The New Breed facility provides interior and systems 787 components to the Everett factory floor in a "just in time" manner to aid in the efficiency of the manufacturing process. A similar facility exists in South Carolina for that 787 production line.

When New Breed receives the batteries, they accomplish an external inspection of the packaging of the batteries and verify the part and serial numbers. This information was then entered into the computer database, and the batteries are then stored in the warehouse until Boeing requests them. The warehouse was temperature controlled but was an otherwise ambient condition facility. Batteries are stored on pallets located on the facility floor. New Breed does not perform any type of testing on the state of charge of the batteries upon receipt. Batteries that arrive with packaging damage or inconsistent part / serial numbers are placed into a separate area called 'Grief' where Boeing was contacted for final disposition.

According to New Breed, the Boeing Production Line requests 787 components electronically through a shared computer system. New Breed then delivers the parts by truck and trailer directly to Boeing within 24 hours.

Final assembly of the 787 begins with receipt of the wings and barrel sections as manufactured in various locations around the world. These components are stored until scheduled to enter the final assembly plant (both Everett and Charleston). The Everett line consists of five separate assembly work areas called 'positions'. Major assembly starts at Position '0' and proceeds to position '4'where the completed airplane is rolled out for painting, ground and flight testing, and delivery to the customer. The basic fuselage is completed at position 2 along with the wiring, power generating, and control components. Both the Main and APU batteries are installed at position 2; both batteries are hand carried and installed in their respective positions. Once all components are installed and wiring continuity checks are carried out, factory power is applied to the airplane. It is at this stage that both batteries are charged to 100% of their capacity by their respective battery charger. At the time of final assembly of line 84, Boeing did not have the capability to charge or test batteries outside of the airplane.

Boeing started production of airplane Line 84 on June 7, 2012, at its Charleston, South Carolina facility where Section 46 (aft mid-fuselage barrel) was built. Section 46 was then shipped to Boeing's Everett facility. Final assembly of Line 84 commenced with the barrel sections arriving at final assembly position 0 on 28 September 2012.

The incident APU Battery (P/N: B3856-901; S/N 394) was manufactured by GS Yuasa and received final inspection on 9 September 2012. It was shipped to New Breed on 27 September 2012, and was installed on the airplane on October 15, 2012. According to Boeing build records, the APU Battery was first fully charged by the airplane system on October 19, 2012. The battery electrical connector was removed and reinstalled on December 6, 2012, to facilitate a routine inspection of a nearby power panel (i.e. – remove live battery power from the panel for the inspection). The removal/install paperwork orders indicate that no work or testing was done on the battery other than removal of the connectors.

Line 84's original main battery (P/N: B3856-901; S/N 398) was installed on 17 October 2012. It was then removed from the airplane on October 23, 2012, because of a low voltage condition. A second main battery (P/N: B3856-901; S/N 412) was then installed on the same day as the removal of the original battery. Battery S/N 412 was manufactured by GS Yuasa in September 2012.

Boeing's GS Yuasa Audit review of the build books for both the delivered Main and APU batteries showed the batteries were brand new, and there were no repair histories for either of the batteries.

Boeing delivered Line 84 airplane (JA829J) to Japan Airlines on December 20, 2012. The airplane had accumulated 169 flight hours and 22 flight cycles at the time of the incident.

10.0 FAA's Role in the Manufacturing Production Process

According to the FAA's Code of Federal Regulations, 14 CFR Part 21.137, each holder of a production certificate must establish and describe in writing a quality system that ensures that each product and article conforms to its approved design and was in a condition for safe operation. To comply with the regulations Boeing created the Boeing Commercial Airplanes (BCA) Quality Manual. The manual details the internal processes and procedures to comply with the 14 requirements outlined in the regulations.

According to the Boeing Quality manual, Boeing uses their internal Supplier Management Organization to oversee all aspects of the production supply chain (i.e. definition of requirements, selection, negotiation/award of contracts, supplier performance, product conformance, etc.). Furthermore, as part of the Boeing supplier selection process, Boeing requires suppliers to have an approved Quality Management System (QMS) (i.e. AS9100C) by either Boeing 2nd party audit or Boeing recognition of an accredited aerospace QMS certificate, issued by an aerospace accredited Certification Body (CB).

Certificate Management (CM) oversight responsibilities for a Production Approval Holder (PAH) will be accomplished by the Manufacturing Inspection District Office (MIDO). The MIDO has responsibility of the geographical area in which the PAH is located. The Certificate Management Office (CMO) is a specific office usually assigned to large PAH's. The CMO has CM oversight responsibility of the PAH and its manufacturing sites wherever they are located. The FAA remains responsible for CM when a product, article, or its supplied parts are produced in a location other than the United States.

The Certificate Management Office (CMO) has no decision or stake in the selection of PAH suppliers other than the requirements defined in the quality system. A supplier control audit is conducted as part of the Certificate Management of the Boeing Company. The audit evaluates the Boeing Quality Manual process and procedures in controlling the articles, materials, supplies, and services provided to the Boeing Company. Additionally, the supplier control audits determine the supplier's compliance to purchase orders and quality requirements.

Current FAA policy is to use an automated supplier selection process using Risk-Based Resource Targeting (RBRT) and the Category Parts List (CPL). The RBRT assessment tool is used to assign risk to a PAH according to the likelihood that it will produce nonconforming products, articles, or parts, and consequential results associated with introducing those products, articles, or parts into its system.

The CPL contains a list of assemblies and part(s) that have been assigned a category rating of 1 or 2. To receive a category rating of 1, an assembly or part must be one whose failure could prevent continued safe flight and landing, and resulting consequences could reduce safety margins, degrade performance, or cause loss of capability to conduct certain flight operations. To receive a category rating of 2, an assembly or part must be one whose failure would not prevent continued safe flight and landing, but whose resulting consequences may reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions or subsequent failures.

The Principal Inspector (PI) determines whether a PAH or associate facility is controlling its suppliers by reviewing the results of the PI audit at the PAH or associate facility, when applicable, and the results of the supplier control audits at the selected PAH/associate facility suppliers. A supplier control audit is conducted as part of the CM of the PAH or associate facility that evaluates the system established to control the articles, materials, supplies, and services provided by outside sources. This audit is conducted by the MIDO/CMO assigned CM responsibility for the PAH or associate facility. High Risk Facilities such as the Boeing Company, having a screened supplier listing greater than 100, the minimum requirement for the CMO to conduct Supplier Control Audits (SCA) is 9 suppliers annually. The Boeing CMO has conducted 47 SCAs for Fiscal Year 2013.

The 787 battery was not considered a critical part because it was regarded by the FAA Aircraft Certification Office as a redundant system and was not listed on the CPL as a critical component so the manufacturer of the battery has not been selected by the FAA system as a supplier to be evaluated.

After the incident, the FAA conducted an audit at GS Yuasa, Kyoto, Japan (Battery Manufacturer) and Kanto Aircraft Instruments, Kanagawa, Japan (Battery Management Unit manufacturer) from January 21-29, 2013. The audit was performed to ensure compliance to regulations and the companies' quality system. Prior to the January audit, the FAA had not conducted an audit of Thales sub-tier suppliers: GS YUASA or KAI.

The results of the FAA audit for GS Yuasa revealed:

1) Non-compliance with component/assembly part marking as well as no traceability to assembly drawings and instructions.
2) Non-compliance to assembly and installation instructions of battery components
3) Non-compliance to returned battery storage procedures.
4) Non-compliance to Boeing and GS Yuasa Quality Manuals with regards to root cause and analysis of returned batteries.

The results of the FAA audit for KAI revealed:

1) Non-compliance to recording in process discrepancies. Productions defects discovered during product inspection and or final acceptance function test are corrected, repaired, and retested without documentation.

2) Non-compliance to automatic process for the applications of solder to the BMU PC board.
3) Non-compliance to BMU Bill of Material. Bill of Materials does not give allowance to use alternate part numbers in the BMU.

According to the FAA, the corrective actions by Boeing/Thales/GS Yuasa/Kanto have been completed and have been submitted to the FAA for corrective action verification. Corrective action verification has been fully verified by the FAA that includes On-site verification. The FAA has found the corrective actions were acceptable and the Letter of Investigation was in the process of being closed.

Submitted by:

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