Soaring Ambitions and Hard Realities: The Boeing 787 Dreamliner and Flight Safety

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On the morning of January 16, 2013, the passengers of All Nippon Airlines (ANA) flight number 692 noticed an acrid and unpleasant odor in the cabin of the brand new Boeing 787 Dreamliner that they were flying in. Something definitely seemed amiss. Shortly after takeoff, the public address system came alive with the voice of a flight attendant. The announcement she made was sobering: the pilot was about to make an emergency landing. The plane was soon on the tarmac at Takamatsu airport near Osaka with the emergency doors open and smoke already starting to fill the cabin. The 129 passengers and eight crew members were forced to slide down the emergency chutes to safety (Negishi & Kelly, 2013).

After this incident, ANA and its competitor Japan Airlines, which together owned 24 of the 50 Dreamliners in world-wide operation at the time, decided to ground all of their 787's. Japan's transportation minister did not mince his words:" I see this as a serious incident which could have led to a serious accident", he declared (Tabuchi & Mouawad, 2013).

This was not the first time, nor was it to be the last, that the heralded 787 Dreamliner made the news. However, this was not the kind of news that its builder, The Boeing Company, expected. The critical press followed a series of mishaps and incidents that had marred the debut of what constituted, in many ways, a real feat of engineering. A week earlier, a cleaning crew reported smoke in the cabin of a Dreamliner operated by Japan Airlines and parked at a gate in Boston's Logan airport.   Then just two days later, on January 9, a wiring problem was detected on a United Airlines 787.

Both smoke related incidents were traced to the lithium-ion battery technology used for the main as well as the auxiliary power unit (APU) batteries in the Boeing 787. Initial investigations indicated that an internal short-circuit resulted in an uncontrolled increase in pressure and temperature in a battery cell in the Boston incident. The failure of one cell then resulted in the

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This case has been written on the basis of published sources only. Consequently, the interpretation and perspectives presented in this case are neither necessarily those of the companies mentioned in the case nor of their employees.

failure of adjacent cells, a process known as a thermal runaway. The release of smoke and the production of a flame were contained within the battery case (Hart, 2014) (Figure 1).

<u>Figure 1</u>

JAL Event Battery- January 7, 2013 Logan Airport. Charred remains of failed B-787 main battery featuring 8 GS Yuasa LVP 10 Lithium-ion cells. Safety circuit at the connector end of the battery was unable to stop a thermal runaway once in progress.

Source- Possible solutions for the battery problem on the Boeing 787-Battery University Downloaded July 30, 2014 from http://batteryuniversity.com/learn/article/possible_solutions_for_the_battery_problem_on_the_Boeing_787 - “Public domain image”

Aircraft Incident Report, Auxiliary Power Unit Battery Fire, Japan Airlines Boeing 7878, JA8291, Boston, Massachusetts, January 7, 2013, National Transportation Safety Board

A few hours after the ANA 692 incident, the Federal Aviation Administration (FAA) took the unusual step of ordering the grounding of all US operated 787’s until the safety issues associated with the new type of battery could be solved by Boeing. Japan’s transportation authorities and other foreign regulators followed suit. It would take 123 days and a redesigned battery system for the FAA to lift the ban on operating the airplane. In the new battery set-up, the power cells were spaced further apart from each other to minimize the risk of fire.

In the unlikely event that a fire might occur in the future, Boeing had designed a steel box enclosure that was added in order to prevent it from spreading. In addition, a new ventilation system ensured that fumes from a fire would be directed outside the plane (Lebeau, 2013). Although the FAA had signaled its approval of Boeing's safety measures, the mystery of what caused the malfunction of the battery system remained. Boeing's chief engineer, Michael Sinnett recognized that "we may never get to a single root cause" (Tabuchi, 2013).

A New Way of Building Planes

The Boeing Company, originally called Pacific Aero Products Co., was founded in 1916 and from the earliest seaplane produced by the company through the latter part of the 1990s, every Boeing airplane was built the same way. Boeing engineers and draftsmen designed and created the detailed specifications for parts and assemblies which were then built by their suppliers. In this way, Boeing knew exactly what needed to be done by their suppliers. When a problem cropped up, which it inevitably did in the launching of a new aircraft model, Boeing engineers and managers could troubleshoot the issue. Then, together with their suppliers they could make the necessary corrections.

In the late 1990s, Boeing created a strategic vision in which it changed its role in airplane production from a manufacturer (Newhouse, 2007) to a planner and assembler of high tech airplanes. The result of this new strategy was that Boeing significantly changed the way its supply chain functioned. Boeing described this change as one in which it went from a global partnership model to a global team of risk-sharing partners. In this new supply chain configuration, Boeing's principal suppliers, its tier-1 suppliers, assumed total responsibility for designing and building plane assemblies (Exhibit 2). In turn, the tier-1 suppliers built assemblies with parts designed and manufactured by their own suppliers.

The exemplar that Boeing used to pattern its new supply chain configuration after was not a competitor in the aircraft building business but was instead, Toyota Motor Corporation. Boeing followed an approach that is quite common in competitive industries; copying the processes of an even more successful firm in order to increase its standing with external stakeholders such as financial institutions or governmental regulatory agencies. (DiMaggio & Powell, 1983).

Boeing Reconfigures its Supply Chain

In addition to the major changes to the airplane itself, Boeing also undertook to revamp the way its supply chain functioned. In previous airplane models, Boeing worked with its supplier partners in a "build to print method" whereby Boeing's engineers developed the design and detailed drawings for every part of the plane. Boeing then contracted them to build the parts to specification. The 787 approach was changed to a "build to performance" approach in which Boeing provided performance metrics (Kotha & Nolan, 2005) that needed to be met and the suppliers would design, draw and manufacture the parts.

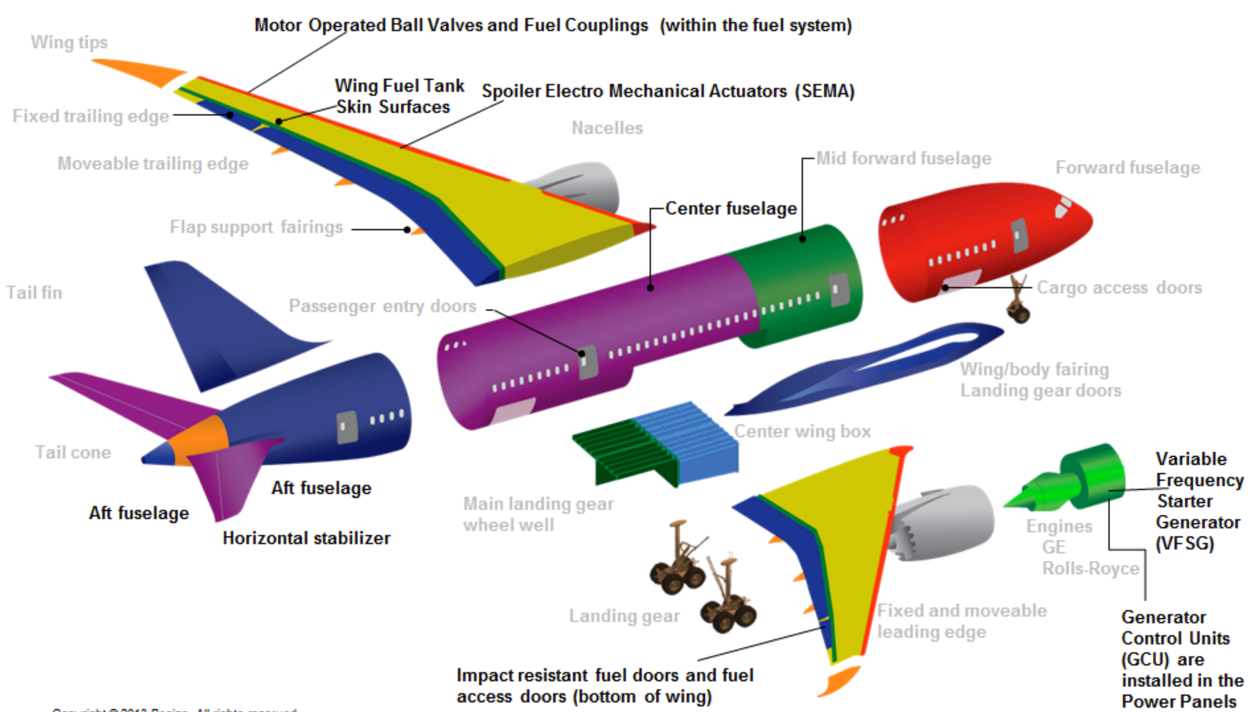
A total of approximately 2.5 million different parts were used in manufacturing a 787 plane. This large number was organized in such a way as to give principal integration and assembly responsibility to approximately 50 world class industrial companies that made up Boeing's tier-1 suppliers. This group included such companies as GE, Rolls Royce, Mitsubishi, Fuji and Boeing subsidiaries in Charleston, Wichita and Winnipeg, Canada (Figure 2, Table 1).

Figure 2

BOEING 787–8 DESIGN, CERTIFICATION, AND MANUFACTURING SYSTEMS REVIEW

BOEING 787–8 CRITICAL SYSTEMS REVIEW TEAM

B787 Components/Systems Selected for Deep-Dive Review



Source- Federal Aviation Administration Report- Boeing 787- 8 Design, Certification and Manufacturing Systems Review. March 19, 2014. Boeing 787-8 Critical Systems Review Team Downloaded April 8, 2014- "Public domain image"

Table 1- Boeing Suppliers

Aircraft part	Supplier and location
Aft fuselage, Tail fin	Boeing Puget Sound
Horizontal stabilizer, Center fuselage	Alenia, Italy
Wing tips	KAA, Korea
Forward fuselage	Spirit, US; Kawasaki, Japan
Center wing box	Fuji, Japan
Wing	Mitsubishi, Japan
Landing gear	Messier-Dowty, France
Lithium-ion batteries	Yuasa, Japan

Thales of France, for example, a tier-1 supplier, was the principal supplier of flight displays, in-flight entertainment systems and the on-board electrical power system. Thales in turn worked with GS Yuasa of Japan which manufactured the lithium-ion batteries and Securaplane of Arizona which built the battery charging system. The various assemblies were tested and certified by the tier-1 suppliers. However, in some cases, the assemblies may not have functioned in the same manner when they were tested by themselves as they did when they were placed in their final working environment in the aircraft itself (Hart, 2014).

Tier 1 Suppliers and Risk Sharing Partners

Boeing previously had design and testing expertise in-house. The company employed more than 2,000 employees including many engineers whose sole job was to design and build the electronic controls for its aircraft (Gates, May 25, 2013). The unit, Boeing Commercial Electronics (BCE) was dispersed and eventually sold off when the 787 project was in its initial stages. For all aircraft preceding the 787, the BCE integrated the components from the various suppliers to make sure that they worked properly. A long-time industry analyst, Richard Aboulafia from Teal Aviation Group said of the 787 “without complete oversight of the subsystems, they might be finding systems glitches for years” (Gates, May 25, 2013).

Boeing however, appeared to feel comfortable with its approach. Senior Vice President and 787 chief project engineer Michael Sinnett told a National Transportation Safety Board (NTSB) investigative hearing into the battery failures in January of 2013 that the company maintained tight oversight and overall control over its systems partners (Gates, May 25, 2013). Sinnett went on to say that although the relationship between Boeing and its airframe suppliers was new, Boeing’s relationship with its systems providers was “more traditional” (Gates, May 25, 2013). Boeing had insisted that its tier1 suppliers take the role of true risk-sharing partners and fund and direct the R&D work required to develop the new technology and systems.

The Toyota Production System (TPS) and the 787 Dreamliner: Institutional Isomorphism

Boeing's stated aim, when it began development of the 787 was to copy Toyota Automobile's relationship with its suppliers (Cizmeci, 2005). Toyota relied heavily upon its suppliers to design and manufacture parts and assemblies for its new car models. The TPS system developed organically over many years but was never formally established by Toyota as a "new way" of doing things (Spear & Bowen, 1999). In the early days of Toyota's growth as an auto assembler it lacked sufficient capital to develop new car models. An approach developed in which their main suppliers agreed to assume responsibility for some parts development. The result was an enhancement of Toyota's car line offerings and increased growth and mutual success.

As head of the auto group, Toyota often provided its own engineers to its suppliers on a short-term basis to assist them with the development and early production of various parts and assemblies. As a result, it knew exactly what was being produced and could assist when necessary in troubleshooting and correcting defects (Liker & Choi, 2004). The formal and informal dominance of Toyota as the head of its network may have been unusual from an American perspective but it was not from a Japanese cultural point of view (Hofstede, 1980). This dominance was related to the cultural norms of Japan in that Toyota acted as the "clan leader" of its keiretsu or organizational network. This position required junior members, in this case auto parts suppliers, to accept lower profit levels than Toyota but obligated Toyota to assist and "look out for" these companies. Cross ownership common in the keiretsu structure further strengthened and legitimized these relationships.

The nature of Toyota's buyer-supplier relationship was one of cooperation (Liker & Choi, 2004). Toyota never wrote a contract in which its suppliers were not assured of making a profit (Ahmadjian & Lincoln, 2000). The TPS system was an expression of Toyota's commitment to ensure constant improvement in both the quality of the parts themselves as well as the processes that produced them. The suppliers, in turn, improved their capabilities and increased their profits through constant process improvement and cost reductions. Indeed, Toyota encouraged most suppliers to increase their business with other companies, particularly in other industries, provided they did not supply any direct competitors of Toyota (Liker & Choi, 2004).

The fact that, Boeing, a large US aircraft company copied the approach of a Japanese auto company was unusual but not without precedent. Many large and well-known companies had copied successful firms in other industries. Institutional isomorphism was a well-established theory and it had been studied extensively (DiMaggio & Powell, 1983). An example is Google's adoption of the internal entrepreneurial approach of 3M Corp. with respect to the empowerment of its engineers. Boeing's approach was unique because of the scope of its implementation across all elements of the production process including its core operational functions.

Boeing's arm's length relationship with its suppliers differed greatly from the close relationship enjoyed by Toyota and its suppliers due to radically different cultural contexts. As a result, Boeing could not fully recognize or evaluate the nature of the TPS relationships when it decided to adopt the global risk sharing arrangement. The new supplier relationship was initiated simultaneously with the introduction of a radically different aircraft structure. The coincidence of both changes at the same time was too great to be handled in the normal course of business.

A New Model for a Changing Market

The new airplane model, the 787 Dreamliner was a radical departure from previous Boeing models. It would be the first commercial aircraft built with composite materials including graphite which would reduce its weight and enhance its fuel efficiency. Boeing, in the early 2000s, believed that the air-travel market was fragmenting with increasing numbers of travelers desirous of point-to-point travel (Economist, 2005). Up to this point, most long distance travel was routed through hub airports and then distributed through smaller planes to secondary airports. Boeing believed that the greater comfort of flying direct would be preferred by most travelers (Economist, 2005).

As a consequence, forecasters at Boeing believed that airlines would need 25,000 new planes over the following 20 years (Beck, 2004) with no more than 400 very large aircraft among these (Economist, 2005). An added positive incentive for developing a new model was that airline fleets world-wide might consider retiring their fuel inefficient Boeing 767s and Airbus 300s if they were provided with a new model. Rapidly increasing oil prices in this time frame also contributed to this need. The new plane would need to be both fuel efficient and provide a high level of passenger comfort if it were to be a market winner.

Increasing air travel to Asia, particularly China and India was also considered to be of great importance. Boeing predicted that Chinese carriers would purchase more than 2,200 planes in the 20 years after 2005 (Kotha & Nolan, 2005). Airbus Industrie, Boeing's main commercial rival from Europe predicted that Chinese carriers would order at least 1,800 planes. Both Boeing and Airbus predicted that passenger traffic in China would increase more than 8% annually. Over the intervening years these predictions have borne out and the Asia-Pacific region accounted for a third of the increase in global traffic increase in 2015 (IATA, 2016). Part of this increase in Asian travel is linked to the increase in Asian discount airlines which began in 2001 but increased substantially in 2011 and 2012 (Wassener, 2012)The current surge in airlines' orders for new aircraft has produced an unprecented backlog at both Boeing and Airbus, as suppliers strain to keep up with demand (Wall & Cameron, 2017).

In order to satisfy these diverse demands, Boeing envisioned a plane that could fly long-haul routes, from Asia to Europe or the US, but in an intermediate size (200 to 300 seats). In addition, this plane was positioned to compete favorably with Airbus's mid-size model, the A330. The anticipated range of the 787 was more than 8,300 nautical miles as compared to Airbus 330's 6,500. This difference in range meant that airlines flying the 787 would be able to open up a large number of new city to city routes, a potentially important market.

Airbus's response to the burgeoning Asian market demand was to develop a mega-plane, the Airbus 380 with a capacity of 550 passengers. Unlike the A380, the 787 enabled airlines to do more direct city to city travel. The A380 needed to connect through regional hubs, which forced passengers to change airplanes adding to discomfort on long-haul flights. The combination of the 787's better fuel economy, greater in-cabin comfort and smaller size meant that it was ideally positioned to serve the growing commercial traffic between Asian centers and US regional cities.

The use of lighter composite materials in the fuselage and wings was sparked by Boeing's need to reduce fuel consumption by 20%. Some added benefits of composite, as opposed to aluminum fuselages, included the ability of the operator to reduce cabin pressure while increasing humidity levels thereby reducing passengers' fatigue on long-haul trips. Boeing also decided to change the way on-board systems were powered in a bid to further reduce weight and enhance efficiency of the plane.

Delays With the New Model

Boeing delivered its first 787 to ANA in September 2011, three years behind schedule and more than $20 billion in greater development costs than originally forecast (ICRA Online, 2015). Four years earlier, Boeing acknowledged "challenges with out-of-sequence production work, including part shortages, and remaining software and system integration activities" (Lefty Coaster, 2011). It later announced that the company had to deal with continued "challenges to assemble the first airplanes" (Lefty Coaster, 2011). The following year, there were additional supply chain issues and manufacturing problems that pushed back the first flight to December 2009. The following year an onboard electrical fire in a control panel and computer safety problems resulted in denial of certification by the FAA until the issues were addressed.

Having 800 orders from 50 customers, Boeing needed to act expeditiously to bring the plane to market. At the same time, it needed to protect its reputation by meeting the safety and quality standards expected by its customers and the flying public. Indeed, the cost over-runs and delays could adversely affect not just the company's profitability but also its credibility. Boeing did compensate its customers for the repeated delays in delivery as is typical in the industry. The problems continued after the delivery of the first fifty 787's to seven foreign airlines and one US-based airline.

As Jeff Smisek, the chief executive of United Airlines, said of the grounded Dreamliners, "it was a fairly expensive piece of sculpture to have on the ground". Nevertheless, many experts like Scott Hamilton, the managing director of an aviation consulting firm, believed that Boeing would "work its way through this" (Drew, 2013), thanks to its technical ability and financial muscle.

The 787's New Battery

Boeing opted for what they termed a no-bleed electrical systems architecture which greatly reduced the necessity of a pneumatic system and converted the power source of most functions previously powered by bleed air from the engines to electric power (Sinnett, 2007). That is, in all previous airplanes, some of the high-speed air from the engines was diverted to provide power for a number of plane systems including cabin pressurization, flight control actuators and landing gear actuators. By eliminating this power diversion, the no-bleed system improved fuel consumption, reduced maintenance costs and improved reliability due to the use of modern power electronics and fewer components in the engine installation (Sinnett, 2007). The power for these systems was to be supplied by a lithium-ion battery set-up which was judged to be more precise and efficient than the pneumatic system.

Lithium-ion batteries had many advantages over other batteries in terms of how rapidly they could be re-charged, the length of time that they could hold their charge and their relatively light weight. There had, however, been issues with fires occurring in uses other than in aviation. For example, the Chevrolet Volt hybrid car experienced numerous fires after several lithium-ion battery packs spontaneously burst into flames following tests (Babbage, 2013). Another example is illustrated by the massive recall of Samsung Galaxy note 7 phones (Weise, 2016) after a number of incidents involving exploding or burning smartphones. While “batteries were found to be the cause” according to the company, the “root cause” of the failure was not determined (Martin & Jeong, 2017). Samsung has taken measures to refurbish the phone’s power systems. Similarly, Boeing believed that they had taken the necessary precautions to eliminate the possibility a thermal runaway in the 787 based on a radical design change.

Lithium-Ion Batteries and Thermal Runaway

Boeing changed its on-board systems power supply approach in the 787 model. Boeing faced a key decision in selecting the type of battery they could use. The trade-offs were between an established design that could provide safe and reliable power and a newer one that promised superior power but lacked a long track record. A battery option that provided more power per pound of weight was desirable because it saved fuel and cut costs. However, as the power potential increased, so did the potential for a fire.

At the time (2005), the commercially available batteries that Boeing or its suppliers could choose included lithium-ion, nickel cadmium and lead-acid (automobile). The lithium-ion battery provided twice the energy density compared to nickel cadmium. Since the 787 needed extra power capacity this made the lithium-ion battery an immediate front runner (Battery University, 2013). An additional advantage of the lithium-ion battery was that it was lower maintenance, requiring fewer scheduled services (Battery University, 2013). The 787 was the first commercial aircraft to use the lithium-ion battery as its main on-board power source. However, the battery had been used in other products including computers and mobile phones. In 2006, breakdowns in the battery caused a major recall by Sony of 6 million laptop units.

A thermal runaway refers to the catching fire of successive battery cells. The failed battery on the Boeing 787 involved in the Boston airport fire was reported to have reached approximately 500° F, a high enough temperature to induce a thermal runaway. The 787 battery had a total of 8 cells. If one cell caught fire and the temperature were high enough, it could cause other cells to burn as well. This could happen in a rapid (minutes) or a slow (hours) burn fashion. Lithium-ion fires are difficult to extinguish because the material of the battery itself feeds the flame. Dowsing with water is not sufficient to put out the flame and special chemicals are necessary. Containing a thermal event may require a separate battery enclosure.

The NTSB (Hart, 2014) reported that nickel cadmium batteries posed some problems when they were introduced into aircraft usage in the 1970s. After a redesign, the nickel cadmium battery was judged safe and became the standard for the industry. Thales, Boeing's Tier 1 supplier of the electrical systems, chose an available battery in 2005 that offered high capacity, manufactured by GS Yuasa of Japan. A subsequent fire in 2006 at Securaplane in Arizona, the on-board battery charger supplier to Thales, did not deter the choice of the battery system. In that incident, a lithium-ion battery exploded during testing and burned down the company's administrative building. Securaplane indicated that this was a battery prototype and was not installed in the 787s in question.

Search for the Cause and What to do Next

In the 787's first year of service, at least four aircraft owned by different operators suffered problems of varying severity stemming from their lithium-ion batteries. Technical challenges are typical with new plane model launches and Boeing was confident that it could solve the battery issues at hand. No accidents in which passengers or personnel had been injured, or worse, had happened. Nevertheless, two major battery thermal runaway events had taken place within the first 50 odd thousand flight hours of operation. Boeing, however, had predicted that this would not occur within the first 10 million flight hours. Clearly something was going on that was not foreseen by either Boeing or the airlines.

The batteries were part of a larger electrical system with components manufactured and assembled by at least three unrelated and geographically distant companies. Boeing did not act in a functional coordinator role nor did it have a real understanding of how the pieces fit together (Tang and Zimmerman, 2009). Mike Bair, an early head of the 787 program revealed more details in a meeting of business leaders in Washington state in 2007. In a departure from past practice, Boeing, he said, gave less detailed specifications to their subcontractors. The latter had in turn subcontracted engineering to their own suppliers (Hiltzik, 2011). This approach added to the level of uncertainty and made it even more difficult for Boeing to supervise design and manufacture. Boeing's commercial aviation chief, Jim Albaugh, told a group of business students at Seattle University that Boeing "gave work to people that had never really done this kind of technology before and then we didn't provide the oversight that was necessary" (Hiltzik, 2011). He added that the company now recognized that "we need to know how to do every major system on the airplane better than our suppliers do" (Hiltzik, 2011).

Mike Sinnett, head engineer of the 787 plane said that the company didn't know the specific root cause but that issues had been traced back to a single lot of circuit boards manufactured by a sub-tier supplier (Gates, Feb. 2, 2013). Since Boeing had never made batteries it was not unusual that they would not have a very strong grasp of battery issues. In a March, 2013 interview given during the period in which the 787 had been grounded by the FAA, Sinnett said that Boeing had not pinned down the exact cause of the overheating and the company might never know what and who was responsible (Tabuchi, 2013). He indicated that they had more than 500 engineers working with outside experts on the problem and had spent more than 200,000 hours of analysis, engineering and testing work to understand what had caused the batteries to overheat and burn. Engineers had examined 80 potential problems that could lead to a battery fire that were grouped into four categories and they designed solutions for every category (Tabuchi, 2013).

Boeing settled on a solution based on fire retardation and containment rather than on elimination of the cause which proved elusive to ascertain. Their approach was to create an enclosure that would quickly starve a flame of oxygen. “We’ve been able to demonstrate that no fire is possible inside the enclosure” Sinnett said (Tabuchi, 2013). The FAA approved Boeing’s plan to test the fixes and ultimately agreed to lift the ban on April 25, 2013. The estimated cost to airlines to modify each plane was $464,678 (Gates, April 25, 2013). On Monday May 20th, 2013, a United Airlines flight from Houston to Chicago ended the long hiatus during which the Dreamliner was grounded in the United States.

On January 14, 2014, almost a year to the day after the ANA 692 incident, a Japan Airlines Boeing 787 poised to leave Tokyo’s Narita airport for Bangkok had to be withdrawn from service. It was replaced with another aircraft when white smoke was observed emanating from the plane’s overheated main battery. The battery overheating occurred during pre-flight maintenance. (Flight Global, 2014) However, in the last three years, no new incident involving the batteries in the Boeing 787 has been reported. This seems to validate Boeing’s decision to address the fire hazard by adopting measures designed to contain any potential thermal runaway.

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