Battery University
SINCE 2003

Possible Solutions for the Battery Problem on the Boeing 787

After fewer than 100,000 flight hours, two main batteries in the Boeing 787 Dreamliner failed. This contradicts Boeing's estimate as part of certification that a smoke event involving the new Li-ion battery should only occur once in 10 million flight hours. More than a smoke event occurred, and one battery disintegrated in a thermal runaway with fire and the spewing of electrolyte that caused damage to the electronics bay (Figure 1). The Federal Aviation Administration (FAA) grounded the entire fleet of B-787 as a result.

Figure 1: Damage in aft electronics bay caused by a burning battery in a Boeing 787

The incident happened after arriving at the gates in Boston from a flight from Narita, Japan. The fire was difficult to extinguish; smoke and flames didn't break with the dry chemical of a fire extinguisher and airport firefighters used liquid Halotron.

Image courtesy of the National Transportation Safety Board, Investigative update of battery fire on Japan Airlines B-787, 7 January 2013.

Boeing chose lithium-ion to store more capacity at the same weight. The main battery is composed of eight GS Yuasa LVP10 cells and provides roughly twice the energy density compared to the traditional flooded nickel-cadmium (NiCd) that other aircraft use. The Dreamliner needs the extra capacity to run additional electrical systems, including hydraulic functions that have been electrified. Another reason for selecting Li-ion is low maintenance. Li-ion requires fewer scheduled services than NiCd, which needs regular full discharges to remove memory, adjustment of electrolyte and cleaning corrosion buildup.

The Boeing 787 is the first commercial aircraft to use Li-ion as its main battery, and there are risks associated with this. Hybrid vehicles only switched to Li-ion around 2010 with more stable chemistries. When the Li-ion battery was selected in 2005, the choices were limited and what we know today, the picked *Lithium Cobalt Oxide (LiCoC2)* may not be the best technology for onboard aviation. It is the same chemistry that triggered a major recall of computer and mobile phone batteries in 2006 when one-in-200,000 cells caused a breakdown.

CT scans done on the failed main battery of the B-787 reveal a similar breakdown that prompted the 2006 recall: a damaged electrode in one of the eight Li-ion cells apparently caused an electrical short that triggered a thermal runaway with fire. Lithium Cobalt Oxide (Li-cobalt) is known to be less stable than other lithium-based systems. For consumer product wanting optimal runtime, Li-cobalt works well, but large formats have additional challenges. Figure 2 illustrates the damaged main aircraft battery.

Figure 2: JAL Event Battery

The jarred remains of the failed B-787 main battery featuring 8 GS Yuasa LVP10 lithium-ion cells. The safety circuit at the connector end of the battery is unable to stop a thermal runaway once in progress.

Courtesy of the National Transportation Safety Board, Investigative update of battery fire on Japan Airlines B-787, 7 January 2013.

If the U.S. investigators fail to find the root cause of the battery fires, the technology could be deemed insufficiently mature for onboard aviation. Possible solutions are the use of other lithium-based batteries or moving back to NiCd. Table 1 lists the characteristics of four common lithium-ion systems.

Specifications	**Li-cobalt** $LiCoO_2$ (LCO)	**Li-manganese** $LiMn_2O_4$ (LMO)	**Li-phosphate** $LiFePO_4$ (LFP)	**NMC**[1] $LiNiMnCoO_2$
Voltage per cell	3.60 / 3.70V	3.80V	3.30V	3.60 / 3.70V
Charge limit	4.20V	4.20V	3.60V	4.20V
Cycle life[2]	500–1,000	500–1,000	1,000–2,000	1,000–2,000
Operating temp.	Average	Average	Good	Good
Specific Energy	150–190Wh/kg	100–135Wh/kg	90–120Wh/kg	140-180Wh/kg
Specific Power	1C	10C, 40C pulse	35C continuous	10C
Safety	Less safe	Moderately safe	Safest Li-ion	Moderately safe

Thermal runaway[3]	150°C (302°F)	250°C (482°F)	270°C (518°F)	210°C (410°F)
Cost	Cobalt cost high	Moderate	High	Moderate
In use since	1994	1996	1999	2003
Researchers, manufacturers	Sanyo, GS Yuasa, LG Chem Hitachi, Samsung, Toshiba	Hitachi, Samsung, Sanyo, GS Yuasa, LG Chem, Toshiba	A123, GS Yuasa, BYD, ATL, Lishen, JCI/Saft	Sony, Sanyo, LG Chem, GS Yuasa, Hitachi, Samsung
Notes	High specific energy but limited power; laptops, mobile phones	High power, good specific energy; power tools, EVs medical devices	High power, mod. energy, rugged and safe, flat discharge curve	High specific energy, high power; in tools, e-bikes, EVs

Table 1: Characteristics of the four most commonly used lithium-ion batteries
Specific energy refers to capacity (energy storage); specific power denotes load capability.

[1] NMC stands for nickel-manganese-cobalt. NMC, NCM, CMN, CNM, MNC and MCN are similar.
[2] Application and environment govern cycle life; the numbers do not always apply correctly.
[3] A fully charged battery raises the thermal runaway temperature, a partial charge lowers it.

The performance of the different Li-ion systems can best be illustrated with spider webs. The graphics demonstrate *specific energy* (capacity); *specific power,* (current delivery); *safety*; *performance* (at hot and cold temperatures); *life span* (cycle life); and *cost.* The values are estimated and may vary.

Lithium Cobalt Oxide($LiCoO_2$)

Li-cobalt is characterized by a high specific energy but moderate safety, life span and specific power. Li-cobalt should not be charged and discharged at currents exceeding the Ah rating. Forcing a fast charge or applying a load above 1C could cause overheating. The manufacturer recommends a charge C-rate of 0.8C, and most battery protection circuits for this chemistry limit the charge and discharge currents to about 1C (1A for a battery rated at 1Ah). The battery consists of a cobalt oxide cathode and a graphite carbon anode. Li-cobalt is one of the first lithium-ion batteries and is the preferred chemistry for laptops, mobile phones and digital cameras. Figure 2 summarizes the performance of Li-cobalt.

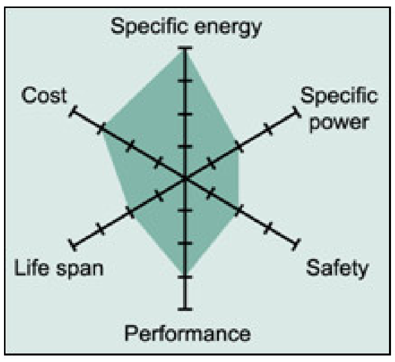

Figure 2: **Snapshot of an average Li-cobalt battery**

One of the first Li-ion chemistries; offers high specific energy (capacity) but provides moderate performance in specific power, safety and life span. The relative high internal resistance causes the battery to heat up during high load and rapid charge.

Courtesy of Cadex

Lithium Manganese Oxide($LiMn_2O_4$)

Lithium manganese oxide as cathode material forms a three-dimensional spinel structure that improves ion flow on the electrodes. This results in a low internal resistance for good current handling and solid thermal stability. The negatives are low life span and a specific energy that is about one-third less than Li-cobalt. Figure 3 shows the spider web of a typical Li-manganese battery.

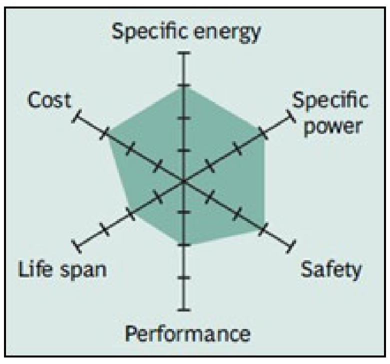

Figure 3: Snapshot of a typical Li-manganese battery

Moderate in overall performance; newer designs offer improvements in specific power, safety and life span.

Courtesy of BCG research

Lithium Iron Phosphate ($LiFePO_4$)

In 1996, the University of Texas (and other contributors) discovered phosphate as cathode material for rechargeable lithium batteries. Li-phosphate offers good electrochemical performance with low resistance. This is made possible with nano-scale phosphate cathode material. The key benefits are excellent thermal stability, tolerant to abuse, high current rating and long cycle life. On the negative, the lower voltage of 3.30V/cell reduces the specific energy. Although the flat voltage discharge provides enduring power handling, it complicates state-of-charge measurement. Li-phosphate is not interchangeable with other lithium-based systems; the lower cell voltage requires a different charger setting. Figure 4 summarizes the attributes of Li-phosphate. Typical uses are power tools, electric powertrain and increasingly also large energy storage systems (ESS).

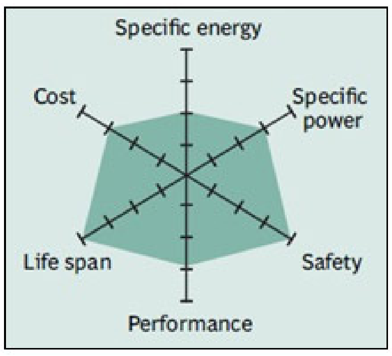

Figure 4: Snapshot of a typical Li-phosphate battery

Li-phosphate is one of the most robust Li-ion systems in terms of safety and life span, but offers moderate specific energy (capacity). The low internal resistance keeps the battery cool during high load and fast charge conditions.

Courtesy of BCG research

Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$)

The NMC uses nickel, manganese and cobalt as cathode material. Nickel is known for its high specific energy but low stability, and manganese forms a spinel structure for low internal resistance but offers limited specific energy. Combining the metals results in a winning formula delivering a specific energy that is equal to Li-cobalt with improved safety and enhanced life span. Figure 5 summarizes these results. NMC batteries are relatively new and are widely used in power tools, power tools and e-bikes.

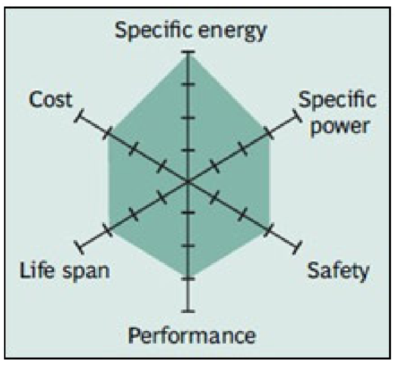

Figure 5: Snapshot of NMC

NMC offers good overall performance with high specific energy, low internal resistance and a moderate price. This is the preferred battery for electric powertrains and industrial applications.

Courtesy of BCG research

The spider webs list only the most basic attributes of a battery and omits other important features, such as toxicity, internal resistance, charge times, charge acceptance at cold temperatures, capacity loss during storage, self-discharge and safety if abused and when getting old.

Safety considerations for lithium-ion batteries in aviation

Aviation has some of the most stringent demands and this causes challenges when introducing new battery chemistries for onboard functions. Let's look at these conditions in more detail.

A single safety breach with bad press can turn the public against the incumbent airplane. Two battery incidents on a new airplane hint to a design flaw and Boeing must realize that Li-ion serving as the main battery may not be as well understood as NiCd and lead acid systems.

Explaining the 2006 recall involving 6 million lithium-ion packs, Sony said that on rare occasions microscopic metal particles may come into contact with other parts in a Li-ion cell, leading to a short circuit. Battery manufacturers try to minimize the presence of such particles but admit that eliminating all metallic dust is nearly impossible. Cells with ultra-thin separators of only 20–25µm are more susceptible to impurities than older designs with lower Ah ratings.

According to a major Lithium-ion battery manufacturer, field failures occur randomly in roughly one of every 4 to 5 million battery cells coming off the production line. Current technologies are nearing their theoretical limit on specific energy using conventional metal oxides and battery manufacturers are improving methods to enhance safety and increase the life span. But the problem persists in that on rare occasions an electrical short can develop inside the cell. This is suspected on the B-787 batteries.

A mild short only causes elevated self-discharge and the heat buildup is minimal. However, if enough microscopic metallic particles converge on one spot, a sizable current flow can develop with time between the electrodes and the area heats up, causing further damage. An uneven separator can also trigger cell failure. Poor conductivity caused by a dry spot increases resistance, which can generate local heat spots that can weaken the integrity of the separator. When an electrical short occurs, the temperature quickly reaches 500°C (932°F), leading to a thermal runaway. The failed battery on the Boeing 787 is reported to have reached 260°C (500°F), a temperature that induces a thermal runaway.

During a thermal runaway, the elevated heat of the failing cell may propagate to neighboring cells, causing them to become thermally unstable also. This appears to have happened on the Boeing 787 battery. A chain reaction can occur when each cell disintegrates on its own timetable. A Li-ion battery can disintegrate in a few seconds or over several hours as each cell is being consumed on its own accord. To increase safety, batteries should include dividers to protect the failing cell from spreading to the neighboring one. (The Tesla Roadster using Li-cobalt encases each cell in its own metal compartment.)

A flaming Li-ion battery is difficult to extinguish. Dowsing with water may not be effective and special chemicals are required. If possible, remove the burning battery from flammable materials, place it into the open and use water to cool the surrounding area. This is not possible with a burning aircraft battery and the FAA may require that a Li-ion be allowed to burn out in the aircraft without causing damage. Containing a thermal event would require a fire and explosion-safe battery enclosure and battery manufacturers are working on such models.

The question asked is: "When should a battery be replaced to meet the mandated safety?" NiCd batteries in avionics are retired when the capacity drops below a given threshold. Low capacity may also be used to determine the end-of-life of an aging Li-ion, but it is possible that safety concerns require an earlier replacement. Laboratory stress tests may not reveal this accurately, but field use will.

As the investigation of the battery fire continues, conspiracies arise of improper wiring, and this is very unlikely. If it were true, the protection circuit would safeguard the battery from possible excess voltage and loading conditions.

Incorrect charging is another suspect. There is suspect that the Li-ion battery was kept on trickle charge once fully charged. Li-ion cannot absorb overcharge and the charge current must be cut off when fully charged. A continuous trickle charge (maintenance charge) could cause plating of metallic lithium that can lead an electrical short. To reduce stress, Li-ion should dwell slightly below the 100% state-of-charge after a full charge. A recharge can be applied when the charge drops to say 80 to 90%.

When a fault develops in the battery core, as is probable with the two failed B-787 packs, peripheral safety circuits have limited effect; they only protect the battery from outside interference. Once in thermal runaway condition, neither the charger, nor the protection circuit can stop the event; only containment can in the form of a protective battery enclosure.

Life span reflects *cycle count* and *longevity* governed by environment conditions and usage pattern. This includes temperature, depth of discharge and load currents. A shallow discharge is preferred over full cycles, and a slow three-hour charge is better than a rapid charge, but most importantly the battery should be kept cool. Aging manifests itself mainly through capacity loss; capacity is the leading health indicator of most batteries.

Heat is the enemy of the battery; keeping a Li-ion in a fully charged state adds further stress. The worst condition is retaining a fully charged Li-ion at high temperature. Table 2 estimates the recoverable capacity of lead acid, nickel-based and Li-ion batteries after one year of storage at different temperatures.

Temperature	**Lead acid** at full charge	**Nickel-based** at any charge	**Lithium-ion** (Li-cobalt)	
			40% charge	100% charge
0°C	97%	99%	98%	94%
25°C	90%	97%	96%	80%
40°C	62%	95%	85%	65%
60°C	38% (after 6 months)	70%	75%	60% (after 3 months)

Table 2: Estimated recoverable capacity when storing a battery for one year.
Elevated temperature hastens permanent capacity loss. Li-ion is also sensitive to charge levels.

Performance manifests itself in the delivery of power during blistering summer heat and in freezing temperatures. Li-ion does not perform as well as NiCd at low temperature. While NiCd can accept a slow charge when cold, Li-ion should not be charged below freezing. Fast-charging is only permissible from 5 to 45°C (41 to 113°F). Although Li-ion appears to be charging, a plating of metallic lithium can occur on the anode during cold temperature charging. Batteries affected by cold charging are more vulnerable to failure if exposed to vibration or other stressful conditions. (Some Li-ion cells are made to charge down to –10°C (14°F) but at a reduced rate.)

Specific energy demonstrates how much energy a battery can store. Li-ion can hold more energy by weight and size than nickel and lead-based systems, however, Li-ion batteries for aviation (and other industrial applications) are optimized for safety and longevity, not capacity. This reflects in a lower specific energy than enjoyed on consumer products. In addition, the B-787 charges the LVP10 to only 4.025V/cell instead of the traditional 4.20V. This prolongs battery life but reduces the capacity from the specified 100% to about 75%. Li-ion batteries in satellites and electric powertrains use similar practices by avoiding full charges and limiting deep discharges.

Li-ion does not need deep discharge cycles to reverse memory as NiCd does; however, an occasional deep discharge is advisable as a learn cycle to calibrate the battery management system (BMS). BMS is known to lose accuracy over time.

Specific power demonstrates the ability to deliver current for an electrical load. According to Table 1 earlier, Li-cobalt, the battery chosen for the B-787, only handles 1C, while Li-manganese and NMC can deliver discharge currents at 10C and Li-phosphate at 35C; 10 and 35 times higher than their rated Ah. With low internal resistance, these systems run cooler than Li-cobalt.

The **Cost** to manufacture Li-ion batteries is higher than NiCd; the most economical battery is lead acid. Material costs are not the sole reason for the higher cost; complex assembly procedures boost the price. The battery market has predicted lower Li-ion prices but this has not yet materialized. The protection circuit required for all Li-ion to assure safety and longevity adds to the cost further.

Conclusion

Boeing selected lithium-ion because the battery meets the performance and design objectives of the 787 in providing added electrical function at reduced weight. "Nothing we learned during the design of the 787, or since then, has led us to change our fundamental assessment of the technology," a company spokesman said. But with the 787 grounded worldwide, Boeing is struggling to understand why its multiple safety systems failed to stop the damage to the battery.

Given that the battery serves only as start-and-backup system, which can be neglected when other power sources become available on a running aircraft, an aircraft manufacturer may place more importance on the propulsion system than the battery, but an uncontrollable battery fire is a concern. Here, Li-ion has a disadvantage over the traditional NiCd. All batteries are subject to failure and there is also a reported incident where the battery circuit breaker of a Boeing 777 had to be pulled because of an overheating NiCd battery. In the early 1970s, the National Transportation Safety Board reported several battery incidents per year involving the then new nickel-cadmium, but none let to casualties. A redesign eventually made NiCd safe and it became a standard for airliners.

When Thales, the maker of the electrical system, decided on Li-cobalt for the B-787 battery in 2005, they chose an available system that offered high capacity. Meanwhile more stable chemistries have been developed, and it would have been advisable had Boeing considered one of these technologies before releasing the plane. While Li-manganese, Li-phosphate and NMC can endure internal heat of 200°C (392°F) and higher, Li-cobalt becomes unstable at 150°C (302°F).

Nor did the 2006 fire at Securaplane, the maker of the onboard chargers for the B-787, deter the use of the chosen battery system. A Li-ion exploded during testing and burned the administrative building to the ground. Securaplane, a unit of Britain's Meggitt Plc., said that they will "contribute to the investigation process" by the U.S. National Transportation Safety Board and the FAA, but determined that the battery fire involved prototypes that were not installed in Boeing 787 aircraft. Adding to this concern, a lithium-ion battery also destroyed a Cessna Citation jet on the ground in 2011. Cessna is now very cautious.

There is the option to go back to NiCd, and the wide-body, long-range Airbus 350 in development by European aircraft manufacturer Airbus may do that. It will require a different charging system and a modified BMS. In addition, the lower specific energy of NiCd will double the battery numbers and weight, but the Airbus 350 is said to be less dependent on electric power than the Dreamliner.

Lithium-ion batteries have not yet matured and it is advisable that aircraft manufacturers design planes that allow updating to more advanced technologies as better batteries become available. Now a retro-fit on the Boeing 787 is said to take two years. More flexible designs would allow moving with the time.

Aircraft are pressurized to an altitude of 6,000 feet (1830 meters) and thinner air may affect Li-ion batteries differently than at sea levels. In addition, large-format Li-ion batteries have added mechanical strain compared to smaller packs. Battery diagnostics has not advanced as rapidly as other technologies and hidden anomalies can often go undetected until a disassembly develops. Cadex Electronics has made critical progress in these areas but more development will be needed.

Battery testing is complex and no single measurement can capture all irregularities. As a doctor is trained to use a wide selection of medical instruments to diagnose an illness, so also does a battery need different technologies to detect anomalies that can develop. While a fading battery on a mobile phone simply becomes a nuisance to the user, a malfunctioning aviation battery can have serious consequences.

References:

National Transportation Safety Board presentation "Investigative Update of Battery fire Japan Airlines B-787 – Jan 7, 2013 by Deborah A.P. Hersman, Chairman

Batteries in a Portable World, 3rd edition, by Isidor Buchmann

Comments

On March 8, 2013 at 1:11pm

Carl wrote:

BATTERIES ARE DANGEROUS!

This is an excellent example as to the reason why these archaic energy storage devices should be replaced. If banks of SUPERCAPACITORS were used along with high current dc/dc converters, this would have been avoided!

On March 8, 2013 at 1:13pm

Chet Haibel wrote:

Excellent article, thank you. I would say to go to the Lithium Phosphate AND design flame-containing enclosures for each cell that can arrest spread of runaway condition.

On March 8, 2013 at 2:33pm

charlie scuilla wrote:

Who posted this? There are mistakes in the about.

On March 8, 2013 at 2:34pm

charlie scuilla wrote:

There are mistakes in the above statement.

On March 8, 2013 at 2:51pm

Stephen Skinner (past Boeing employee) wrote:

Why does the media, including this site, not research & discuss more than just the energy source -BATTERIES- and the -LOAD- our demand side. The batteries should be in a system more complex than just this. There should be a very critical need for a battery management components: a controller board & resistors that that help manage the enemy, out of optimum operating temperatures! Also media to remove or add out of range temperatures, by controlled air movement or liquids or even phase change materials. Todays state of batteries need alot of help to over come there lethal fragility.

On March 8, 2013 at 3:06pm

malcolm doble wrote:

Good article; NiCd or other such as LiFePO4 seem too be a much better choice.

Drop a few seats or skip the piano and use heavier batteries.

On March 8, 2013 at 3:19pm

Arthur wrote:

Why not consider NiMH batteries. They have slightly lower energy density, but much safer. The Panasonic EV95 batteries had great reliability in the Toyota RAV4-EV from 2002-3.

On March 8, 2013 at 5:29pm

Soto Ndiaye wrote:

A very good article!
Industries (aviation, automotive, telecommunication, nuclear power plants ...) involved in energy storage and batteries in particular have to invest more in research about these new generation batteries. Their technologies are relatively more complex than lead-acid batteries. Incidents related thereto may also be complex and far-reaching.

On March 8, 2013 at 6:23pm

Charlie Scuilla wrote:

The article written above is a collection of news articles and a referenced media hearing - The cells are not the LVP10. There are other mistakes in the article. Go to the NTSB website for information. This is not a chemistry issue. All chemical batteries can have thermal runaways or a hazardous under short circuit conditions. Supercaps are not the solution either. They can catch on fire too.

On March 8, 2013 at 6:43pm

TJ Moran wrote:

Excellent, unbiased, objective article. Battery University is an unparalleled resource.

On March 8, 2013 at 11:40pm

Pankaj wrote:

A good Article, It has some mistakes, major part is based on media reports.

On March 8, 2013 at 11:40pm

C N Navalekar wrote:

cell by cell monitoring (V&I) could detect internal failure . Also thermal fuse would disconnect the defective (shorted) cell and damage can be well controlled.

On March 9, 2013 at 1:20am

Noud Vermeulen wrote:

Thank you for the informative article. Meanwhile the NTSB did not find the root-cause. See http://www.ntsb.gov/investigations/2013/boeing_787/JAL_B-787_1-24-13.pdf
They are conducting a very thorough investigation.
Findings until now:
- Signs of thermal runaway
- Signs of electric short circuiting
- Electrical arc between battery cell and battery case; not believed to be initiating event.
So, still too early to draw conclusions.
Interestingly, the cells consist of 5 parallel 15Ah pouch cells in an ALU container.

Keep up doing the good work!

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