

LITHIUM BATTERIES.

An alternative to Lead and Cadmium.

Overview

A **lithium-ion battery** (sometimes **Li-ion battery**) is a type of rechargeable battery in which lithium ions move from the negative electrode to the positive electrode during discharge, and reversely when charging. During discharge the negative electrode is the anode where oxidation takes place and during charge it turns into the cathode where reduction takes place. This functional meaning of the words anode and cathode is however widely ignored in the slang of battery-specialists: "anode" means negative electrode and "cathode" means positive electrode, and this somewhat abusive practice is followed in the present article. Different types of lithium-ion batteries use different chemistry and have different performance, cost, and safety characteristics. Unlike lithium primary batteries (=disposable batteries), lithium-ion cells use an intercalated lithium compound as the electrode material instead of metallic lithium.

Lithium-ion batteries are common in consumer electronics. They are one of the most popular types of battery for portable electronics, with one of the best energy-to-weight ratios, no memory effect, and a slow loss of charge when not in use. In addition to uses for consumer electronics, lithium-ion batteries are growing in popularity for defense, electric vehicles, and aerospace applications due to their high energy density.^[7] However, certain kinds of mistreatment may cause conventional lithium-ion batteries to explode.

Nowadays we are all battery consumers. They are everywhere, hiding inside a large variety of articles from toys to cars. But not all batteries are alike. Some of them are to be used until discharged and then discarded (hopefully recycled); they cannot be recharged and the experts called them primary batteries. Both conventional and alkaline batteries belong to this class. Rechargeable (a.k.a. secondary) batteries are a breed apart. We buy them to last and we want them to be ready anytime after recharge. Two main types of rechargeable batteries dominate the market right now: **Lead-acid** and **Nickel-Cadmium** batteries.

Lead batteries have been hiding in our cars for many decades. The electricity they provide is only used for starting, lighting and ignition (SLI), since they cannot store enough energy per unit weight to move the car.

In the absence of a better technology, **Nickel-Cadmium** batteries (NiCad) were adopted for feeding small appliances such as videocameras, and portable phones and computers. But any user of these batteries is aware of the need of technical improvements: they run out of charge too

quickly, even when not in use and they have a tricky "memory effect" that causes a loss of capacity. So you better watch the way you use them and charge them.

But in addition to these known problems, consumers must know that certain elements of these batteries are **highly toxic**, especially **lead and cadmium**. For the latter, recycling processes are not even well established at present. And yet, the market demand for rechargeable batteries will keep growing in the short run. Research on lighter batteries with increased energy densities for the consumer market is urgently driven by the electronics industries. After all, who would like to buy any portable equipment where the battery is the largest component?.

To the huge present worldwide market for rechargeable batteries we should add the potential future market for electric vehicles. In this field the need for improvement is even more obvious. As a matter of fact batteries are the weak link in the development of electric car prototypes which are shyly beginning to show up in the market. Their limited performance and high relative price make them hard to compete with conventional vehicles. Yet, there is a growing social demand for cleaner and environment-friendly technologies which makes the development of electric vehicles very attractive, especially for use in large cities.

Are there any ideal candidates for the development of new and improved rechargeable batteries? Indeed there are many different kinds of system under development in laboratories all over the world, each with specific advantages and problems and each better suited for particular applications.

A short list of these advanced batteries could include **Sodium/Sulfur, Zinc/Air, Metal Hydride/Nickel Oxide and Lithium batteries**. All of them have specific advantages and drawbacks but for the consumer market most experts agree that **lithium batteries**, together perhaps with **metal hydride** are the ones with a stronger potential. Metal hydride technology has been developed earlier, but lithium technology is catching up quickly with market demands.

There are many reasons to believe in the promise of **lithium** batteries. First of all, **lithium is the lightest metal there is** and this results in a high specific charge (**Figure 1**). This means that we can get the same performance with a much reduced weight (**Figure 2**).

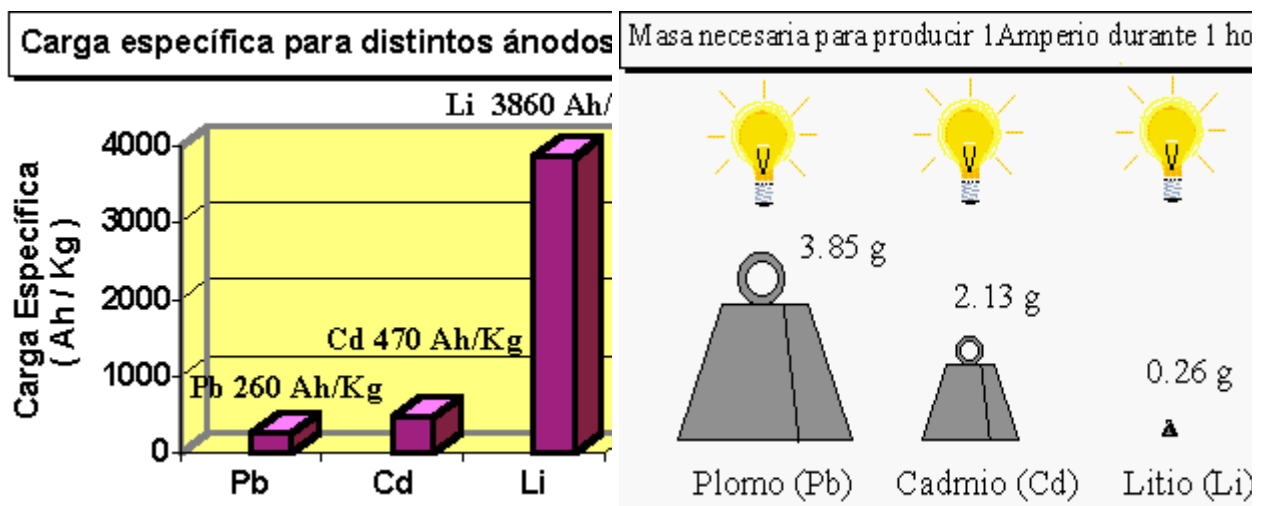


Figure 1. Specific charge for lead (Pb), cadmium (Cd) and lithium (Li) anodes.

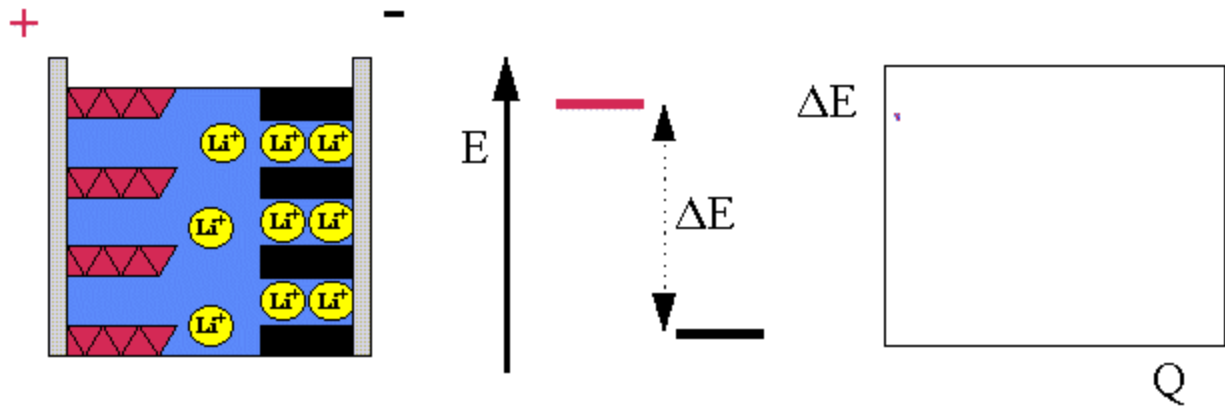
Figure 2. Mass needed to produce 1Amp for 1hour

Another advantage of **lithium** batteries is that their individual cells provide higher voltages than those of **lead** or **cadmium** and this gives you a greater energy density. And finally, to finish the list of nice features you should know that, unlike **lead** or **cadmium**, the materials in the last generation of **lithium** batteries are not a threat to the environment.

Lithium-ion batteries and the chemistry behind them.

The first laboratory prototypes of **lithium** batteries had positive electrodes (cathodes) composed of metal oxides or sulfides with the ability to intercalate and deintercalate **lithium** ions reversibly during the processes of battery discharge and charge. The negative electrode (anode) in these old **lithium** batteries was always made of metallic **lithium** which would get dissolved during discharged and plated back as metal upon recharging. But as a metal, **lithium** is very reactive, represents a potential explosion hazard and that slowed down the development of **lithium** batteries.

Fortunately that hurdle was solved in a most satisfactory way thanks to the introduction of **lithium-ion** technology. In these systems the negative electrode is not made of **lithium** metal but of other safer materials such as graphite or other carbons able to intercalate **lithium** ions. Unlike the metal, **lithium** in its ion state (Li^+) is very stable and unreactive. When intercalated in the negative electrode, its potential is much lower than when in the positive electrode (this difference of potential is in fact the source of the energy in every battery) but explosive reactivity is absolutely eliminated. The battery works with **lithium** ions shuttling from one electrode to the other through an electrolyte solution. They move spontaneously from the negative to the positive electrode during discharge giving up the energy stored. During the recharge process we spend energy in relocating those ions back in the place where they don't like to be (the negative electrode). The following animation shows this working mechanism at the atomic level.



DURING DISCHARGE: Lithium ions (yellow) spontaneously shuttle from the negative insertion electrode (black) into the electrolyte (blue) and from the electrolyte into the positive insertion electrode (red). The electrolyte allows the diffusion of ions but prevents electrons flow. At the same time electrons spontaneously flow through the only way we let them free from the negative to the positive electrode: through the load. As discharge proceeds the potential (E) of each electrode shifts resulting in a decreasing difference between them (ΔE) and thus to a decreasing voltage as we get charge (Q) out of the battery.

DURING CHARGE: Lithium ions are forced out of the positive into the electrolyte and into the negative electrode. Electrons are injected into the negative and taken from the positive electrode. In doing so we get the negative potential more negative and the positive more positive thus increasing the difference of potential which can be equated to the voltage.

NOTE: We always put more energy into charging than we get back in the discharge. That is Nature's way and one of our goals is to minimize that difference.

The introduction of **lithium-ion** technology represented a breakthrough in safety from the old **lithium** metal batteries. But it also reported additional advantages from a technical point of view.

The new mechanism provided a superior reversibility during charge/discharge cycles and therefore longer lasting battery lives.

Lithium-ion batteries are beginning to make it to the market. Sony is selling a battery with negative electrodes made of graphite and positive electrodes with the oxide LiCoO_2 as the active material. These batteries are still subject to improvement because the different elements are not completely optimized (sometimes the pull from the market is stronger than the technical thrust). Thus, the oxide can interchange reversibly only 0.5 Li ions per metal atom (Co) instead of the ideally expected figure of 1Li/1Co. Graphite anodes present an irreversible capacity larger than anticipated, etc. But all of these problems are being addressed in academic and industrial laboratories all over the world and will certainly be solved or avoided in the future. Research on **lithium** batteries also includes the manufacturing of solid state systems (with no liquid electrolyte that could possibly leak), the development of thin-film technology for the manufacturing of ultrathin batteries used in microelectronics applications and the optimization of design for achieving higher power batteries as those needed for electric vehicles .

Lithium-ion batteries used to be a promising concept that originated in academic laboratories. These days they are becoming a sound reality. They are safe, environment-friendly, can endure thousands of cycles of charge/discharge and will keep lowering their manufacturing prices as they become mass-produced. For all that they are the best alternative to cadmium (and of course to the heavier lead) in the consumer market.

Charge and discharge

During discharge, the current flowing within the battery is carried by the movement of lithium ions (Li^+) from the negative to the positive electrode, through the non-aqueous electrolyte and separator diaphragm.^[8]

During charging, an external electrical power source (the charging circuit) applies a higher voltage (but of the same polarity) than that developed by the battery chemistry, forcing the current to pass in the reverse direction. The lithium ions then migrate from the positive to the negative electrode, where they become embedded in the porous electrode material in a process known as intercalation.

Construction

The three primary functional components of a lithium-ion battery are the anode, cathode, and electrolyte. The anode of a conventional lithium-ion cell is made from carbon, the cathode is a metal oxide, and the electrolyte is a lithium salt in an organic solvent.^[9]

Commercially, the most popular material for the anode is graphite. The cathode is generally one of three materials: a layered oxide (such as lithium cobalt oxide), one based on a polyanion (such as lithium iron phosphate), or a spinel (such as lithium manganese oxide).^[10]

The electrolyte is typically a mixture of organic carbonates such as ethylene carbonate or diethyl carbonate containing complexes of lithium ions^[11]. These non-aqueous electrolytes generally use non-coordinating anion salts such as lithium hexafluorophosphate (LiPF₆), lithium hexafluoroarsenate monohydrate (LiAsF₆), lithium perchlorate (LiClO₄), lithium tetrafluoroborate (LiBF₄), and lithium triflate (LiCF₃SO₃).

Depending on the choice of material for the anode, cathode, and electrolyte, the voltage, capacity, life, and safety of a lithium-ion battery can change dramatically. Recently, novel architectures have been employed to improve the performance of these batteries.

Pure lithium is very reactive. It will vigorously react with water to form lithium hydroxide and hydrogen gas is liberated. Thus a non-aqueous electrolyte is used, and water is rigidly excluded from the battery pack by using a sealed container.

[edit] History

Lithium-ion batteries were first proposed by M.S. Whittingham (Binghamton University), at Exxon, in the 1970s.^[12] Whittingham used titanium(II) sulfide as the cathode and lithium metal as the anode.

The electrochemical properties of the lithium intercalation in graphite were first discovered in 1980 by Rachid Yazami et al. at the Grenoble Institute of Technology (INPG) and French National Centre for Scientific Research (CNRS) in France. They showed the reversible intercalation of lithium into graphite in a lithium/polymer electrolyte/graphite half cell. Their work was published in 1982 and 1983.^{[13][14]} It covered both the thermodynamics (staging) and the kinetics (diffusion) aspects of the lithium intercalation into graphite together with reversibility.

Primary lithium batteries in which the anode is made from metallic lithium pose safety issues. As a result, lithium-ion batteries were developed in which the anode, like the cathode, is made of a material containing lithium ions. In 1981, Bell Labs developed a workable graphite anode^[15] to provide an alternative to the lithium battery. Following groundbreaking cathode research by a team led by John Goodenough,^[16] the first commercial lithium-ion battery was released by Sony in 1991. The cells used layered oxide chemistry, specifically lithium cobalt oxide. These batteries revolutionized consumer electronics.

In 1983, Michael Thackeray, John Goodenough, and coworkers identified manganese spinel as a cathode material.^[17] Spinel showed great promise, since it is a low-cost material, has good electronic and lithium ion conductivity, and possesses a three-dimensional structure which gives it good structural stability. Although pure manganese spinel fades with cycling, this can be overcome with additional chemical modification of the material.^[18] Manganese spinel is currently used in commercial cells.^[19]

In 1989, Arumugam Manthiram and John Goodenough of the University of Texas at Austin showed that cathodes containing polyanions, e.g. sulfates, produce higher voltages than oxides due to the inductive effect of the polyanion.^[20]

In 1996, Akshaya Padhi, John Goodenough and coworkers identified the lithium iron phosphate (LiFePO_4) and other phospho-olivines (lithium metal phosphates with olivine structure) as cathode materials for lithium-ion batteries.^[21] LiFePO_4 is superior over other cathode materials in terms of cost, safety, stability and performance, and is most suitable for large batteries for electric automobiles and other energy storage applications such as load saving, where safety is of utmost importance. It is currently being used for most lithium-ion batteries powering portable devices such as laptop computers and power tools.^[citation needed]

In 2002, Yet-Ming Chiang and his group at MIT published a paper in which they showed a dramatic improvement in the performance of lithium batteries by boosting the material's conductivity by doping it with aluminum, niobium and zirconium, though at the time, the exact mechanism causing the increase became the subject of a heated debate.^[22]

In 2004, Chiang again increased performance by utilizing iron-phosphate particles of less than 100 nanometers (nm) in diameter. This decreased the particle density by almost a hundredfold, increased the surface area of the electrode and improved the battery's capacity and performance. Commercialization of the iron-phosphate technology led to a competitive market and a patent infringement battle between Chiang and Goodenough.^[22]

Electrochemistry

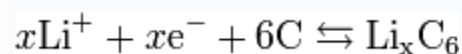
The three participants in the electrochemical reactions in a lithium-ion battery are the anode, cathode, and electrolyte.

Both the anode and cathode are materials into which, and from which, lithium can migrate. The process of lithium moving into the anode or cathode is referred to as *insertion* (or *intercalation*), and the reverse process, in which lithium moves out of the anode or cathode is referred to as *extraction* (or *deintercalation*). When a lithium-based cell is discharging, the lithium is extracted from the anode and inserted into the cathode. When the cell is charging, the reverse process occurs: lithium is extracted from the cathode and inserted into the anode.

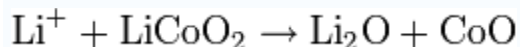
Useful work can only be extracted if electrons flow through a (closed) external circuit. The following equations are written in units of moles, making it possible to use the coefficient x . The cathode half-reaction (with charging being forwards) is:^[23]



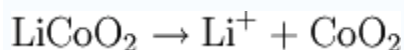
The anode half reaction is:



The overall reaction has its limits. Overdischarge will supersaturate lithium cobalt oxide, leading to the production of lithium oxide,^[24] possibly by the following irreversible reaction:



Overcharge up to 5.2 V leads to the synthesis of cobalt(IV) oxide, as evidenced by x-ray diffraction^[25]



In a lithium-ion battery the lithium ions are transported to and from the cathode or anode, with the transition metal, cobalt (Co), in Li_xCoO_2 being oxidized from Co^{3+} to Co^{4+} during charging, and reduced from Co^{4+} to Co^{3+} during discharge.

Cathodes

Cathode Material	Average Voltage	Gravimetric Capacity	Gravimetric Energy
LiCoO_2	3.7 V	140 mA·h/g	0.518 kW·h/kg
LiMn_2O_4	4.0 V	100 mA·h/g	0.400 kW·h/kg
LiNiO_2	3.5 V	180 mA·h/g	? kW·h/kg
LiFePO_4	3.3 V	150 mA·h/g	0.495 kW·h/kg
$\text{Li}_2\text{FePO}_4\text{F}$	3.6 V	115 mA·h/g	0.414 kW·h/kg
$\text{LiCo}_{1/3}\text{Ni}_{1/3}\text{Mn}_{1/3}\text{O}_2$	3.6 V	160 mA·h/g	0.576 kW·h/kg
$\text{Li}(\text{Li}_y\text{Ni}_x\text{Mn}_y\text{Co}_z)\text{O}_2$	4.2 V	220 mA·h/g	0.920 kW·h/kg

[edit] Anodes

Anode Material	Average Voltage	Gravimetric Capacity	Gravimetric Energy
Graphite (LiC ₆)	0.1-0.2 V	372 mA·h/g	0.0372-0.0744 kW·h/kg
Hard Carbon (LiC ₆)	? V	? mA·h/g	? kW·h/kg
Titanate (Li ₄ Ti ₅ O ₁₂)	1-2 V	160 mA·h/g	0.16-0.32 kW·h/kg
Si (Li _{4.4} Si) ^[26]	0.5-1 V	4212 mA·h/g	2.106-4.212 kW·h/kg
Ge (Li _{4.4} Ge) ^[27]	0.7-1.2 V	1624 mA·h/g	1.137-1.949 kW·h/kg

[edit] Electrolytes

The cell voltages given in the Electrochemistry section are larger than the potential at which aqueous solutions would electrolyze. Therefore, nonaqueous solutions are used.

Liquid electrolytes in lithium-ion batteries consist of lithium salts, such as LiPF₆, LiBF₄ or LiClO₄ in an organic solvent, such as ethylene carbonate. A liquid electrolyte conducts lithium ions, acting as a carrier between the cathode and the anode when a battery passes an electric current through an external circuit. Typical conductivities of liquid electrolyte at room temperature (20 °C) are in the range of 10 mS/cm (1 S/m), increasing by approximately 30–40% at 40 °C and decreasing by a slightly smaller amount at 0 °C.^[28]

Unfortunately, organic solvents are easily decomposed on anodes during charging. However, when appropriate organic solvents are used as the electrolyte, the solvent is decomposed on initial charging and forms a solid layer called the solid electrolyte interphase (SEI),^[29] which is electrically insulating yet sufficiently conductive to lithium ions. The interphase prevents decomposition of the electrolyte after the second charge. For example, ethylene carbonate is decomposed at a relatively high voltage, 0.7 V vs. lithium, and forms a dense and stable interface.^[citation needed]

Advantages and disadvantages

Advantages

- Lithium-ion batteries come in a wide variety of shapes and sizes so as to efficiently fit the devices they power.
- Lithium-ion batteries are often much lighter than other energy-equivalent secondary batteries.^[30] A key advantage of using lithium-ion chemistry is the high open circuit voltage that can be obtained in comparison to aqueous batteries (such as lead acid, nickel-metal hydride and nickel-cadmium).^[31] This is desirable because it increases the amount of power that can be transferred at a lower rate of current.
- Lithium-ion batteries do not suffer from the memory effect. They also have a self-discharge rate of approximately 5-10% per month, compared to over 30% per month in common nickel metal hydride batteries, approximately 1.25% per month for Low Self-Discharge NiMH batteries and 10% per month in nickel-cadmium batteries.^[32] According to one manufacturer, lithium-ion cells (and, accordingly, "dumb" lithium-ion batteries) do not have any self-discharge in the usual meaning of this word.^[23] What looks like a self-discharge in these batteries is a permanent loss of capacity (see Disadvantages of Traditional Li-ion Technology section). On the other hand, "smart" lithium-ion batteries do self-discharge, mainly due to the small constant drain of the built-in voltage monitoring circuit.

Disadvantages of traditional Li-ion technology

Shelf life

- A disadvantage of lithium-ion cells is their poor **cycle life**: upon every charge or recharge, deposits form inside the electrolyte that inhibit lithium ion transport. Over time, the capacity of the cell diminishes. The increase in internal resistance affects the cell's ability to deliver current. This problem is more pronounced in high-current applications. The increasing capacity hit means that a full charge in an older battery will not last as long as one in a new battery (although the charging time required decreases proportionally, as well).
- Also, high charge levels and elevated temperatures (whether resulting from charging or being ambient) hasten permanent capacity loss for lithium-ion batteries.^{[33][34]} The heat generated during a charge cycle is caused by the traditional carbon anode, which has been replaced with lithium titanate. Lithium titanate has been experimentally shown to drastically reduce the degenerative effects associated with charging, including expansion and other factors.^[35] See "Technology improvements" below.
- At a 100% charge level, a typical Li-ion laptop battery that is full most of the time at 25 °C or 77 °F will irreversibly lose approximately 20% capacity per year. However, a battery in a poorly ventilated laptop may be subject to prolonged exposure to higher temperatures, which will shorten its life. Different storage temperatures produce different loss results: 6% loss at 0 °C (32 °F), 20% at 25 °C (77 °F), and 35% at 40 °C (104 °F). When stored at 40%–60% charge level, the capacity loss is reduced to 2%, 4%, 15% at 0, 25 and 40 degrees Celsius respectively.^[36][citation needed]

Internal resistance

The internal resistance of lithium-ion batteries is high compared to other rechargeable chemistries such as nickel-metal hydride and nickel-cadmium. Internal resistance increases with both cycling and chronological age.^{[34][37]} Rising internal resistance causes the voltage at the terminals to drop under load, which reduces the maximum current that can be drawn. Eventually the internal resistance reaches a point at which the battery can no longer operate the equipment for an adequate period.

High drain applications such as power tools may require the battery to supply a current that would drain the battery in 4 minutes if sustained (e.g. 22.5 A for a battery with a capacity of 1.5 A·h). Lower-power devices such as MP3 players may draw low enough currents to run for 10 hours on a charge (e.g. 150 mA for a battery with a capacity of 1500 mA·h). With similar battery technology, the MP3 player's battery will last longer since it can tolerate a higher internal resistance. To power larger devices, such as electric cars, connecting many small batteries in a parallel circuit is more efficient than connecting a single large battery.^[38]

Safety requirements

Li-ion batteries are not as durable as nickel metal hydride or nickel-cadmium designs,^[citation needed] and can be extremely dangerous if mistreated. They may suffer thermal runaway and cell rupture if overheated or if charged to an excessively high voltage.^[39] In extreme cases, these effects may be described as "explosive." Furthermore, they may be irreversibly damaged if discharged below a certain voltage. To reduce these risks, lithium-ion batteries generally contain a small circuit that shuts down the battery when it is discharged below about 3 V or charged above about 4.2 V.^{[23][40]} In normal use, the battery is therefore prevented from being deeply discharged. When stored for long periods, however, the small current drawn by the protection circuitry may drain the battery below the protection circuit's lower limit, in which case normal chargers are unable to recharge the battery. More sophisticated battery analyzers can recharge deeply discharged cells by slow-charging them to reactivate the safety circuit and allow the battery to accept charge again.^[41]

Other safety features are also required for commercial lithium-ion batteries:^[23]

- shut-down separator (for overtemperature),
- tear-away tab (for internal pressure),
- vent (pressure relief), and
- thermal interrupt (overcurrent/overcharging).

These devices occupy useful space inside the cells, reduce their reliability^[citation needed]; ,and permanently and irreversibly disable the cell when activated. They are required because the anode produces heat during use, while the cathode may produce oxygen. Safety devices and improved electrode designs greatly reduce or eliminate the risk of fire or explosion.

These safety features increase the cost of lithium-ion batteries compared to nickel metal hydride cells, which only require a hydrogen/oxygen recombination device (preventing damage due to mild overcharging) and a back-up pressure valve.^[40]

Many types of lithium-ion cell cannot be charged safely below 0 °C.^[citation needed]

Product recalls

About 1% of lithium-ion batteries are recalled.^[42]

Specifications and design



A lithium-ion battery from a mobile phone.

- Specific energy density: 150 to 220 W·h/kg (540 to 720 kJ/kg)
- Volumetric energy density: 250 to 530 W·h/l (900 to 1900 J/cm³)
- Specific power density: 300 to 1500 W/kg (@ 20 seconds^[43] and 285 W·h/l)

Because lithium-ion batteries can have a variety of cathode and anode materials, the energy density and voltage vary accordingly.

Lithium-ion batteries with a lithium iron phosphate cathode and graphite anode have a nominal open-circuit voltage of 3.2 V and a typical charging voltage of 3.6 V. Lithium nickel manganese cobalt (NMC) oxide cathode with graphite anodes have a 3.7 V nominal voltage with a 4.2 V max charge. The charging procedure is performed at constant voltage with current-limiting circuitry (i.e., charging with constant current until a voltage of 4.2 V is reached in the cell and continuing with a constant voltage applied until the current drops close to zero). Typically, the charge is terminated at 3% of the initial charge current. In the past, lithium-ion batteries could not be fast-charged and needed at least two hours to fully charge. Current-generation cells can be fully charged in 45 minutes or less. Some lithium-ion varieties can reach 90% in as little as 10 minutes.^[44]

Charging procedure

Stage 1: Apply charging current limit until the voltage limit per cell is reached.^[45]

Stage 2: Apply maximum voltage per cell limit until the current declines below 3% of rated charge current.^[45]

Stage 3: Periodically apply a top-off charge about once per 500 hours.^[45]

The charge time is about three to five hours, depending upon the charger used. Generally, cell phone batteries can be charged at $1C$ and laptop-types at $0.8C$, where C is the current that would discharge the battery in one hour. Charging is usually stopped when the current goes below $0.03C$ but it can be left indefinitely depending on desired charging time. Some fast chargers skip stage 2 and claim the battery is ready at 70% charge.^[45] Laptop battery chargers sometimes gamble, and try to charge up to 4.35 V then disconnects the battery. This helps to compensate for the battery's internal resistance and charges up to 100% in short time.

Top-off charging is recommended to be initiated when voltage goes below 4.05 V/cell.^[45]

Lithium-ion^[which?] cells are charged with 4.2 ± 0.05 V/cell, except for military long-life cells where 3.92 V is used to extend battery life. Most protection circuits cut off if either 4.3 V or 90 °C is reached. If the voltage drops below 2.50 V per cell, the battery protection circuit may also render it unchargeable with regular charging equipment. Most battery protection circuits stop at 2.7–3.0 V per cell.^[45]

For safety reasons it is recommended to stay within the manufacturer's stated voltage and current ratings during both charge and discharge cycles.

Technology improvements



This article **relies extensively on quotes that were previously collated by an advocacy or lobbying group**. Please improve this article or discuss the issue on the talk page.



This article **is written like an advertisement**. Please help rewrite this article from a neutral point of view. For **blatant** advertising that would require a fundamental rewrite to become encyclopedic, use `{{db-spam}}` to mark for speedy deletion. *(September 2009)*



It has been suggested that *Nanoball batteries* be merged into this article or section. (Discuss)

Overview

Improvements focus on several areas, and often involve advances in nanotechnology and microstructures.

- Increasing cycle life and performance (decreases internal resistance and increases output power) by changing the composition of the material used in the anode and cathode, along with increasing the effective surface area of the electrodes (related developments have helped ultracapacitors) and changing materials used in the electrolyte and/or combinations thereof (e.g., Li-VOx-based cells with polymer electrolyte).
- Improving capacity by improving the structure to incorporate more active materials.
- Improving the safety of lithium-ion batteries.

Manganese spinel cathodes

LG (Lucky Goldstar Chemical), which is the third-largest producer of lithium-ion batteries, uses the lithium manganese spinel for its cathode. It is working with its subsidiary CPI to commercialize lithium-ion batteries containing manganese spinel for HEV applications.^[46] Several other companies are also working with manganese spinel, including NEC and Samsung.^[47]

Lithium iron phosphate cathode with traditional anode

Main article: Lithium iron phosphate battery

The University of Texas first licensed its patent for lithium iron phosphate cathodes to the Canadian utility Hydro-Québec.^[48] Phostech Lithium inc. was later spun-off from Hydro-Québec for the sole development of lithium iron phosphate.^[49]

Valence Technology, located in Austin, Texas, is also working on lithium iron magnesium phosphate cells. Since March 2005, the Segway Personal Transporter has been shipping with

extended-range lithium-ion batteries^[50] made by Valence Technology using iron magnesium phosphate cathode materials. Segway, Inc. chose to build their large-format battery with this cathode material because of its improved safety over metal-oxide materials. To date Valence has shipped 100,000 batteries to Segway.

In November 2005, A123Systems announced^[51] the development of lithium iron phosphate cells based on research licensed from MIT.^{[52][53]} While the battery has slightly lower energy density than other competing lithium-ion technologies, a 2 A·h cell can provide a peak of 70 amperes without damage and operate at temperatures above 60 °C (140 °F). Their first cell has been in production since 2006 and is being used in consumer products including DeWalt power tools, aviation products, automotive hybrid systems and PHEV conversions.

LiFePO₄ cells are currently available commercially.^[citation needed]

High power cathode using lithium nickel manganese cobalt (NMC)

In 2008, Imara Corporation^[54] began promoting the first *materials-agnostic* technology applied on an NMC material. This technology has the effect of lowering impedance and extending cycle life. These high power-capable cells have a higher energy density, relative to other high power cells in the market.^[55] Imara ceased operations in December 2009 due to a lack of funding.^[56]

Sony and Sanyo use NMC and NCA blended with LMO (spinel) for high-powered applications. NMC has a significant safety advantage over cobalt oxide and 50% greater energy density than FePO₄, but suffers from a poor cycle life.

Nissan Motor has nearly completed development of a lithium-ion battery using a lithium nickel manganese cobalt oxide cathode (NMC). The new system will reportedly offer almost double the capacity of Nissan/AESC's current manganese spinel cell.^[57]

Traditional cathode with lithium titanate anode

Main article: Lithium-titanate battery

In 2009, Altairnano announced the creation of a nano-sized titanate electrode material for lithium-ion batteries. It claims the prototype battery has three times the power output of existing batteries and can be fully charged in six minutes. The company also says the battery cells have now achieved a life of over 9,000 charge cycles while still retaining up to 85% charge capacity. Durability and battery life have also increased, estimated to be around 20 years, or four times longer than regular lithium-ion batteries. The batteries can operate from −50 °C to over 75 °C and will not explode or experience thermal runaway, even under severe conditions, because they do not contain graphite-coated-metal anode electrode material.^[58] The batteries are currently being tested in a new production car made by Phoenix Motorcars. They are also being tested, on a one megawatt grid scale, in the PJM Interconnection Regional Transmission Organization control area^[59], as well as by several branches of the United States Department of Defense.^[60] In addition, the batteries are being demonstrated by Proterra in their all-electric EcoRide BE35 vehicle, a lightweight 35-foot bus.^[61]

Combined anode and cathode developments

EnerDel, which started as a joint venture by Ener1 and Delphi, is working to commercialize cells containing a titanate anode and manganese spinel cathode.^[62] Although the cells show excellent thermal properties and cyclability, their low voltage may hamper commercial success.^[63] In August, 2008, EnerDel became a wholly owned subsidiary of Ener1.^[64]

[edit] Research claims

In April 2006, a group of scientists at MIT announced a process which uses a genetically modified virus to form nano-sized wires. These can be used to build ultrathin lithium-ion batteries with three times the normal energy density.^{[65][66]}

As of June 2006, researchers in France have created nanostructured battery electrodes with several times the energy capacity, by weight and volume, of conventional electrodes.^[67]

In the September 2007 issue of *Nature*, researchers from the University of Waterloo, Canada, reported a new cathode chemistry, in which the hydroxyl group in the iron phosphate cathode was replaced by fluorine.^[68] The advantages seem to be two-fold. First, there is less volume change in the cathode over a charge cycle which may improve battery life. Secondly, the chemistry allows the substitution of the lithium in the battery with either sodium or a sodium/lithium mixture (hence their reference to it as an alkali-ion battery).

In November 2007, Subaru unveiled their concept G4e electric vehicle with a lithium vanadium oxide-based lithium-ion battery, promising double the energy density of a conventional lithium-ion battery (lithium cobalt oxide and graphite).^[69] In the lab, lithium vanadium oxide anodes, paired with lithium cobalt oxide cathodes, have achieved 745Wh/l, nearly three times the volumetric energy density of conventional lithium-ion batteries.^[70]

In December 2007, researchers at Stanford University reported creating a lithium-ion nanowire battery with ten times the energy density (amount of energy available by weight) through using silicon nanowires deposited on stainless steel as the anode. The battery takes advantage of the fact that silicon can hold large amounts of lithium, and helps alleviate the longstanding problem of cracking by the small size of the wires.^[71] To gain a tenfold improvement in energy density, the cathode would need to be improved as well; however, even just improving the anode could provide "several" times the energy density, according to the team. The team leader, Yi Cui, expects to be able to commercialize the technology in about five years.^[72] Having a large capacitive anode will not increase the capacity of the battery as predicted by the author when the cathode material is far less capacitive than the anode. However, current lithium-ion capacity is mainly limited by the low theoretical capacity (372 mA·h/g) of the graphite in use as the anode material, so improvement could be significant and would then be limited by the cathode material instead.

There are trials with metal hydrides as anode material for lithium-ion batteries. A practical electrode capacity as high as 1480 mA·h/g has been reported.^[73]

In April 2009 a report in *New Scientist* claimed that Angela Belcher's team at MIT had succeeded in producing the first full virus-based 3-volt lithium-ion battery.^[74]

In November 2009, engineers at the University of Dayton Research Institute developed the world's first solid-state, rechargeable lithium air battery which was designed to address the fire and explosion risk of other lithium rechargeable batteries and make way for development of large-size lithium rechargeables for a number of industry applications, including hybrid and electric cars.^[75]

Recent studies performed at Binghamton University by M. S. Whittingham et al. determined that vanadium ions can be incorporated into the iron-containing olivine structure of LiFePO_4 ; a small amount of vanadium (around 5%) enhancing the rate capability of the LiFePO_4 olivine cathode material. The resulting compound material had higher electronic and ionic conductivities, and they were of comparable magnitude. The doping reaction kinetics were optimal under reducing atmosphere during the synthesis of the $\text{LiFe}_{0.95}\text{V}_{0.05}\text{PO}_4$ material.^[76]

Guidelines for prolonging lithium-ion battery life

- Lithium-ion batteries should never be depleted below their minimum voltage (2.4 to 2.8 V/cell, depending on chemistry). If a lithium-ion battery is stored with too low a charge, there is a risk that the charge will drop below the low-voltage threshold, resulting in an unrecoverable dead battery.^[77] Usually this does not instantly damage the battery itself but a charger or device which uses that battery will refuse to charge a dead battery. The battery appears to be dead or not existent because the protection circuit disables further discharging and there is zero voltage on the battery terminals.^[77]
- Lithium-ion batteries should be kept cool. They may be stored in a refrigerator.^[77]
- Lithium-ion batteries degrade much faster if stored in high-temperature areas.^[77]

Prolonging life in multiple cells through battery management

Li-Ion batteries require a Battery Management System to prevent operation outside each cell's Safe Operating Area (over-charge, under-charge, operation outside the safe temperature range) and balance cells to eliminate SOC mismatches, significantly improving battery efficiency and increase the overall pack capacity^[78]. As the number of cells and load currents increase, the potential for mismatch also increases^[79]. There are two kinds of mismatch in the pack: state-of-charge (SOC) and capacity/energy (C/E) mismatch. Though the SOC mismatch is more common, each problem limits the pack capacity (mA·h) to the capacity of the weakest cell.

Safety

Lithium-ion batteries can rupture, ignite, or explode when exposed to high-temperature environments, e.g. in an area that is prone to prolonged direct sunlight.^[80] Short-circuiting a lithium-ion battery can cause it to ignite or explode, and any attempt to open or modify the casing or circuitry can be dangerous.

Lithium-ion batteries normally contain safety devices to protect the cells from disturbance. However, contaminants inside the cells can defeat these safety devices. For example, approximately 10 million Sony batteries used in Dell, Sony, Apple, Lenovo/IBM, Panasonic, Toshiba, Hitachi, Fujitsu and Sharp laptops were recalled in 2006. The batteries were found to be susceptible to internal contamination by metal particles. Under some circumstances, these particles can pierce the separator, causing the cell to short. The cell will begin to rapidly convert all of its energy into heat. This creates an exothermic oxidizing reaction, raising the temperature to a few hundred degrees Celsius in a fraction of a second.^[81] A chain reaction occurs when neighboring cells heat up, and in some cases, causes the battery to ignite.

The mid-2006 Sony laptop battery recall was not the first of its kind; however, it was the largest to date. During the past decade, there have been numerous recalls of lithium-ion batteries in cellular phones and laptops owing to overheating problems. In October 2004, Kyocera Wireless recalled approximately 1 million batteries used in cellular phones due to counterfeit batteries produced in Kyocera's name.^[82] In December 2006, Dell recalled approximately 22,000 batteries from the U.S. market.^[83] In March 2007, Lenovo recalled approximately 205,000 9-cell lithium-ion batteries due to an explosion risk. In August 2007, Nokia recalled over 46 million lithium-ion batteries, warning that some of them might overheat and possibly explode.^[84] One such incident occurred in the Philippines involving an Nokia N91, which uses the BL-5C battery.^[85]

Replacing the lithium cobalt oxide cathode material in lithium-ion batteries with lithiated metal phosphate leads to longer cycle and shelf life, improves safety, but lowers capacity. Currently, these 'safer' lithium-ion batteries are mainly used in electric cars and other large-capacity battery applications, where safety issues are critical.^[86]

Another option is to use a manganese oxide or iron phosphate cathode.^[87] A new class of high power cathode materials, lithium nickel manganese cobalt (NMC) oxide has recently been introduced that have a significantly higher temperature tolerance compared to lithium cobalt oxide (see above).^[unreliable source?]

In the event of a lithium-ion battery explosion, the device may emit a dense white smoke. The fumes may cause severe irritation to the respiratory tract, eyes and skin. All precautions must be taken to limit exposure to these fumes.^[88]

[edit] Restrictions on transportation

As of January 2008, the United States Department of Transportation issued a new rule that permits passengers on board commercial aircraft to carry lithium batteries in their checked baggage if the batteries are installed in a device. Types of batteries affected by this rule are those containing lithium, including Li-ion, lithium polymer, and lithium cobalt oxide chemistries. Lithium-ion batteries containing more than 25 grams equivalent lithium content (ELC) are exempt from the rule and are forbidden in air travel.^[89] This restriction greatly reduces the chances of the batteries short-circuiting and causing a fire.

Additionally, a limited number of replacement batteries may be carried on as luggage. Such batteries must be sealed in their original protective packaging or in individual containers or plastic bags.^{[89][90]}

On 2009 fall, at least some postal administrations restricted air shipping (including EMS) of lithium batteries, lithium-ion batteries and products containing these (e.g. laptops, cell phones etc). Among these countries are Hong Kong,^[91] and Japan.^[92]

Battery Testing

Testing is designed to tell us things we want to know about individual cells and batteries.

Some typical questions are:

- Is it fully charged ?
- How much charge is left in the battery ?
- Does it meet the manufacturer's specification ?
- Has there been any deterioration in performance since it was new ?
- How long will it last ?
- Do the safety devices all work ?
- Does it generate interference or electrical noise ?
- Is it affected by interference or electrical noise ?

The answers are not always straightforward.

Indirect Measurements

Although all of the cell parameters the design engineer may wish to measure can be quantified by direct measurement, this is not always convenient or possible . For example the amount of charge left in the battery, the State of Charge (SOC) can be determined by fully discharging the battery and measuring the energy output. This takes time, it wastes energy, each test cycle shortens the battery life and it may not be practical if the battery is in use. It would also be pointless for a primary cell. For more detailed information of how this is done see the State of Charge page.

Similarly, the remaining life of a secondary cell can be determined by continuously cycling it until it fails, but there's no point in knowing the cell life expectation if you have to destroy it to find out. This is known as the State of Health (SOH) of the battery.

What is needed are simple tests or measurements which can be used as an approximation to, or indirect measure of, the desired parameter. For more information see the State of Health page

Test Conditions

In all of the following tests, and testing in general, the test conditions must be specified so that repeatable results can be obtained, and meaningful comparisons can be made. This includes factors such as method, temperature, DOD, load and duty cycle. For instance the cell capacity and cycle life, two key performance indicators could vary by 50% or more depending on the temperature and the discharge rate at which the tests were carried out. See also cell Performance Characteristics.

Battery specifications should always include the test conditions to avoid ambiguity.

Qualification Testing

Qualification testing is designed to determine whether a cell or battery is fit for the purpose for which it was intended before it is approved for use in the product. This is particularly important if the cell is to be used in a "mission critical" application. These are comprehensive tests carried out initially on a small number of cells including testing some of them to destruction if necessary. As a second stage, qualification also includes testing finished battery packs before the product is approved for release to the customer. The tests are usually carried out to verify that the cells meet the manufacturer's specification but they could also be used to test the cells to arbitrary limits set by the applications engineer to determine how long the cells survive under adverse conditions or unusual loads, to determine failure modes or safety factors.

The battery packs should also be tested with the charger recommended for the application to ensure compatibility. In particular the potential user patterns must be evaluated to ensure that the batteries do not become inadvertently overcharged. See also the section on Chargers.

Shake and Bake

Mechanical Testing

Typical tests are included in the safety standards below. They include simple tests for dimensional accuracy to dynamic testing to verify that the product can survive any static and dynamic mechanical stresses to which it may be subject.

Environmental Testing

Typical tests are included in the safety standards below. They are designed to exercise the product through all the environmental conditions likely to be encountered by the product during its lifetime.

Abuse Testing

The purpose of abuse testing is to verify that the battery is not a danger to the user or to itself either by accidental or deliberate abuse under any conceivable conditions of use. Designing foolproof batteries is ever more difficult because as we know, fools are so ingenious.

Abuse testing (always interesting to witness) is usually specified as part of the Safety Testing (below). Recent accidents with Lithium cells have highlighted the potential dangers and stricter battery design rules and a wider range of tests are being applied as well as stricter Transport Regulations for shipping the products.

Safety Standards

Consumer products normally have to comply with national or international Safety Standards required by the safety organisations of the countries in which the products are sold. Examples are UL, ANSI, CSA and IEC standards.

Typical contents

Safety Tests

Casing

- Strength, rigidity and flammability
- Mould stress (Temperature)
- Venting
- Insulation
- Electrolyte not under pressure
- No leakage
- No explosion or fire risk

Protection from or tolerance to

- Short circuit
- Overcharge (time)
- Overcharge (voltage)
- Over-discharge
- Voltage reversal
- High temperature
- Low temperature
- Misuse
- Abuse

Power output - Load test

Failsafe electronics

Marking

Instructions for use

Safety instructions

Mechanical tests

- Crush tests
- Nail penetration tests
- Shock test
- Vibration test
- Impact test
- Drop test

Environmental tests

- Heating
- Temperature cycling
- Altitude
- Humidity
- Exposure to fire

The published safety standards specify the method of testing and the limits with which the product must comply.

DEF Standards

Cells used in military applications usually have to meet more stringent requirements than those used in consumer products.

Cycle testing

This is perhaps the most important of the qualification tests. Cells are subjected to repeated charge - discharge cycles to verify that the cells meet or exceed the manufacturer's claimed cycle life. Cycle life is usually defined as the number of charge - discharge cycles a battery can perform before its nominal capacity falls below 80% of its initial rated capacity. These tests are needed to verify that the battery performance is in line with the end product reliability and lifetime expectations and will not result in excessive guarantee or warranty claims.

Temperature, charge/discharge rates and the Depth of Discharge each have a major influence on the cycle life of the cells (See the page on Cycle Life) Depending on the purpose of the tests, the temperature and the DOD should be controlled at an agreed reference level in order to have repeatable results which can be compared with a standard. Alternatively the tests can be used to simulate operating conditions in which the temperature is allowed to rise, or the DOD restricted, to determine how the cycle life will be affected.

Similarly cycle life is affected by over charging and over discharging and it is vital to set the correct voltage and current limits if the manufacturer's specification is to be verified.

Cycle testing is usually carried out banks of cells using multi channel testers which can create different charge and discharge profiles including pulsed inputs and loads. At the same time various cell performance parameters such as temperature, capacity, impedance, power output and discharge time can be monitored and recorded. Typically it takes about 5 hours for a controlled full charge discharge cycle. This means testing to 1000 cycles will take 208 days assuming working 7 days per week 24 hours per day. Thus it takes a long time to verify the effect of any ongoing improvements made to the cells. Because the ageing process is continuous and fairly linear, it is possible to predict the lifetime of a cell from a smaller number of cycles. However to prove it conclusively in order to guarantee a product lifetime would require a large number of cells and a long time. For high power batteries this could be very expensive.

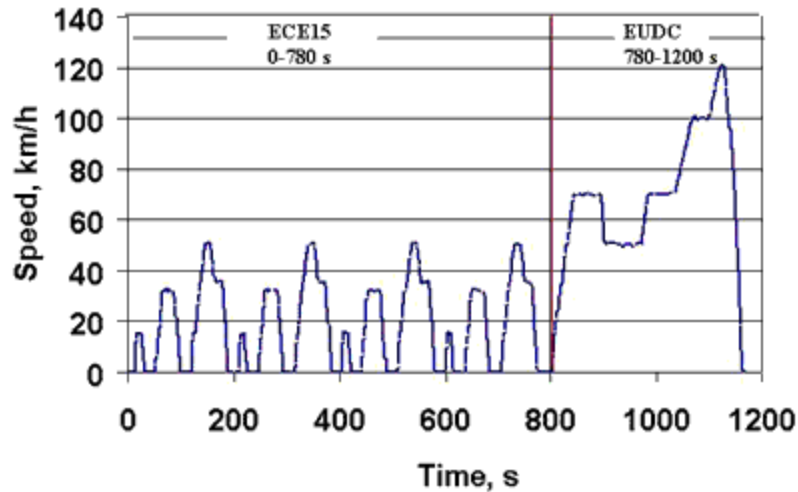
Load testing

Load testing is used to verify that the battery can deliver its specified power when needed.

The load is usually designed to be representative of the expected conditions in which the battery may be used. It may be a constant load at the C rate or pulsed loads at higher current rates or in the case of automotive batteries, the load may be designed to simulate a typical driving pattern. Low power testing is usually carried out with resistive loads. For very high power testing with variable loads other techniques may be required. A Ward-Leonard controller may be used to provide the variable load profile with the battery power being returned to the mains supply rather than being dissipated in a load.

Note that the battery may appear to have a greater capacity when it is discharged intermittently than it may have when it is discharged continuously. This is because the battery is able to recover during the idle periods between heavy intermittent current drains. Thus testing a battery capacity with a continuous high current drain will not necessarily give results which represent the capacity achievable with the actual usage profile.

Load testing is often required to be carried out with variable load levels. This may simply be pulsed loads or it could be more complex high power load profiles such as those required for electric vehicle batteries. Standard load profiles such as the Federal Urban Driving Schedule (FUDS) and the Dynamic Stress Test (DST) specified by the United States Advanced Battery Consortium (USABC), in the USA, and the United Nations Economic Commission for Europe specification (ECE-15) and the Extra Urban Driving Cycle (EUDC) in Europe have been developed to simulate driving conditions and several manufacturers have incorporated these profiles into their test equipment.



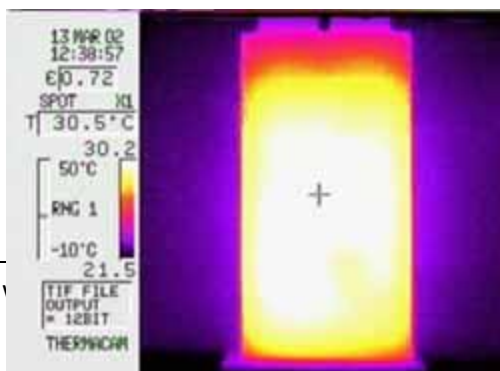
ECE-15 Simulated Driving Cycle

While these standard usage cycles have been developed to provide a basis for comparison, it should be noted that the typical user doesn't necessarily drive according to these cycles and is likely to accelerate at least twice as fast as the allowed for in the standards.

Calorimetry

Battery thermal management is critical for high-power battery packs. Obtaining accurate heat generation data from battery modules is essential for designing battery thermal management systems. A calorimeter is used to quantify the total amount of heat generated by the battery while it is cycled through its charge/discharge cycles. This is essentially an insulated box into which the battery is placed which captures and measures the heat generated the battery during cycling. The system is calibrated by comparing the heat generated by the battery with the heat generated by a known heat source.

Thermal imaging



Thermal imaging is used to check for "hot spots" which would indicate points of high thermal stress in the cell or the battery pack. It is a photographic technique which records the intensity of the infra red radiation emitted by a subject using a special camera. The image on the left is of a lithium ion pouch cell after a

prolonged discharge at 4C. In this case the temperature is evenly distributed within the cell and the cell terminals are running cool. These tests can help to identify problems such as overheating, inadequate heat sinking or air flow, undersized current conductors and interference from neighbouring cells or devices. The images can also be used to determine the best location for the temperature sensors used in protection circuits.

Electromagnetic Compatibility (EMC) testing

Electromagnetic compatibility (EMC) is the ability of electronic and electrical equipment and systems to operate without adversely affecting other electrical or electronic equipment OR being affected by other sources of interference such as power line transients, radio frequency (RF) signals, digital pulses, electrical machinery, lightning, or other influences.

Note that EMC concerns both the emission of electromagnetic interference (EMI or radio frequency interference RFI) by a product or device and the product's susceptibility to EMI emitted from other sources. The interference may be conducted through power or signal cables or the chassis of the equipment, it may be propagated through inductive or capacitive coupling or it may be radiated through the atmosphere.

Just because batteries are DC devices we can not assume that they are immune from EMC problems. At MPower we have seen the battery protection circuitry in a two way radio disabled by RF interference from the handset's transmitter. Similar problems are possible in automotive applications where the power cabling is notoriously noisy due to interference from the ignition systems and transients from electric motors and switches. While the battery itself may not emit RF interference, the same can not be said of the charger. Many chargers use switch mode regulators which are also notorious for emitting electrical noise. Radiated EMI can be critical to such applications as heart pacemakers, medical instrumentation, communications equipment and military applications.

As with many problems prevention is better than cure and it is wise to start considering EMC at the earliest possible stage of the design to avoid costly design changes when the project is submitted for final approval. This may involve system design choices such as operating frequencies, circuit layouts and enclosure design and the avoidance of designs with high transient currents.

Various techniques are used to minimise the effects EMI. Sensitive parts of the circuit may be physically separated from sources of interference, the equipment may be enclosed in a sealed

metal box, individual parts of the circuits may be shielded with metal foil, filters can be added to cables to filter out the noise,

EMC testing involves specialised test equipment and facilities. Testing must be carried out in an environment free from other sources of EMI. This usually means an anechoic chamber or a Faraday cage. Special wide range signal sources and sensitive receivers are needed to generate and measure the interference.

Some examples of EMC requirements are give in the section on Standards

Process audits

Conducting a process audit of the cell manufacturer's production facilities is further way of gaining confidence in the cells under consideration however this option is usually available only to major purchasers of high volume or high cost cells. Unless you are one of these you will have to rely on your friendly pack maker who possibly qualifies for special treatment.

The process audit involves verifying that the cell maker has appropriate quality systems in place and that these are being fully implemented at every stage of the manufacturing process. To be effective this task needs to be conducted by a team with specialist industry knowledge. Again this is a job best left to your pack maker who should have the necessary experience and credibility with the cell makers.

Inspection and Production Testing

The purpose of inspection production testing is to verify that the cells which have been purchased and the products built with them conform to agreed specifications. These tend to be short tests carried out on 100% of the throughput or on representative samples. The composition of the materials from which the components are made should not be overlooked. We have seen examples of unscrupulous suppliers plating connectors with a gold coloured alloy rather than the gold specified and using cheap plastics which buckle in the heat rather than the high quality plastics required.

Typical tests include both mechanical and electrical tests. The components are checked for dimensional accuracy and sample subassemblies are subject to weld strength testing of the interconnections. Electrical parameters measured include the internal impedance and the output voltage of the cell or battery pack with or without a load. The battery is also submitted to short duration charging and discharging pulses of about 2 milliseconds to check that the unit accepts and can deliver charge.

Battery packs are normally subjected to more comprehensive testing to ensure that the electronics are functioning correctly. The protection circuit is checked by applying a short circuit across the battery terminals for 1 or 2 seconds and checking that the current path is cut within the prescribed period and that the battery recovers afterwards. The output of the fuel gauge is checked and if the battery has built in memory, the data such as cell chemistry code, date and serial number are read out and recorded to permit traceability.

Charge conditioning or Formation

This is normally carried out by the cell manufacturer but in some circumstances it could be the responsibility of the battery pack assembler. In any case the cells must be tested to ensure that they are ready to deliver current.

Performance Monitoring

Performance monitoring is used to verify whether the cell is continuing to perform as required once it is in use in the application for which it was specified. These are individual tests specified by the user.

There are no simple direct measurements, such as placing a voltmeter across the terminals, to determine the condition of the battery. The voltmeter reading may tell us something about the state of charge (with an enormous margin of error), but it cannot tell us how well the battery will deliver current when demanded.

Internal Resistance

It is necessary to know the internal resistance of the cell in order to calculate the Joule heat generation or I^2R power loss in the cell, however a simple measurement with an ohmmeter is not possible because the current generated by the cell itself interferes with the measurement.

To determine the internal resistance, first it is necessary to measure the open circuit voltage of the cell. Then a load should be connected across the cell causing a current to flow. This will reduce the cell voltage due to the IR voltage drop across the cell which corresponds to the cell's internal resistance. The cell voltage should then be measured again when the current is flowing. The resistance is calculated by ohms law from the voltage difference between the two measurements and the current which is flowing through the cell.

Open Circuit Voltage OCV

Measuring a battery's open circuit voltage is not a reliable measure of its ability to deliver current. As a battery ages, its internal resistance builds up. This will reduce the battery's ability to accept and to hold charge, but the open circuit voltage will still appear normal despite the reduced capacity of the battery. Comparing the actual internal resistance with the resistance of a new battery will provide an indication of any deterioration in battery performance.

State Of Charge (SOC)

For many applications the user needs to know how much energy is left in a battery. The SOC is also a fundamental parameter which must be monitored and controlled in Battery Management Systems. The methods of estimating the SOC are explained in the section on State Of Charge.

State Of Health (SOH)

The State of Health is a measure of a battery's ability to deliver the specified current when called upon to do so. It is an important factor for monitoring battery performance once it has entered into use. This is treated briefly in the section below and more fully in the section on State Of Health.

Impedance and Conductance Testing

The discussion about the battery equivalent circuit in the section on Performance Characteristics shows that we can expect the battery impedance to increase with age.

Battery manufacturers have their own definitions and conventions for Impedance and Conductance based on the test method used. Though not strictly correct they serve their purpose.

The test method involves applying a small AC voltage "E" of known frequency and amplitude across the cell and measuring the in phase AC current "I" that flows in response to it.

The Impedance "Z " is calculated by Ohm's Law to be $Z=E/I$

The Conductance "C" is similarly calculated as $C=I/E$ (the reciprocal of the impedance)

Note that the impedance increases as the battery deteriorates while the conductance decreases. Thus C correlates directly with the battery's ability to produce current whereas Z gives an inverse correlation. The conductance of the cell therefore provides an indirect approximation to the State of Health of the cell. This measurement can be refined by taking other factors into account. These are outlined in the page about State of Health.

In addition to impedance and conductance these tests will obviously detect cell defects such as shorts, and open circuits.

These test methods can be used with different cell chemistries however different calibration factors must be built into the test equipment to take into account differences in the aging profiles of the different chemistries.

Impedance and conductance testing are reliable, safe, accurate, fast and they don't affect the battery performance. They can be carried out while the battery is in use or they can be used to continuously monitor the battery performance, avoiding the need for load testing or discharge testing.

DC measurements

Note that DC measurements do not recognise capacitance changes and therefore measurements of the internal resistance of the cell do not correlate so well with the SOH of the cell.

Using a conventional ohmmeter for measuring the resistance of the cables, contacts and inter-cell links is not satisfactory because the resistance is very low and the resistance of the instrument leads and the contacts causes significant errors. More accuracy can be achieved by using a Kelvin Bridge which separates the voltage measuring leads from the current source leads and thus avoids the error caused by the volt drop along the current source leads. See also charger voltage sensing.

Battery Analysers

Battery analysers are designed to provide an quick indication of the State of Health (SOH) of the battery. Some analysers also have the dual function of reconditioning the battery.

There are no industry standards for this equipment, mainly because there is no standard definition of State of Health. Each equipment manufacturer has their own favourite way defining and measuring it, from a simple conductance measurement to a weighted average of several measured parameters and the test equipment is designed to provide the corresponding answer. This should not be a problem if the same equipment is used consistently, however it does cause problems if equipment from different manufacturers is used to carry out the tests.

Failure Analysis

Cell failure analysis is best carried out by the cell manufacturers. Only they will have the detailed specifications of the cell mechanical and chemical components and it normally requires access to expensive analytical equipment such as electron microscopes and mass spectrometers which they should be expected to have. More information see [Why Batteries Fail](#) and [Lithium Battery Failures](#)