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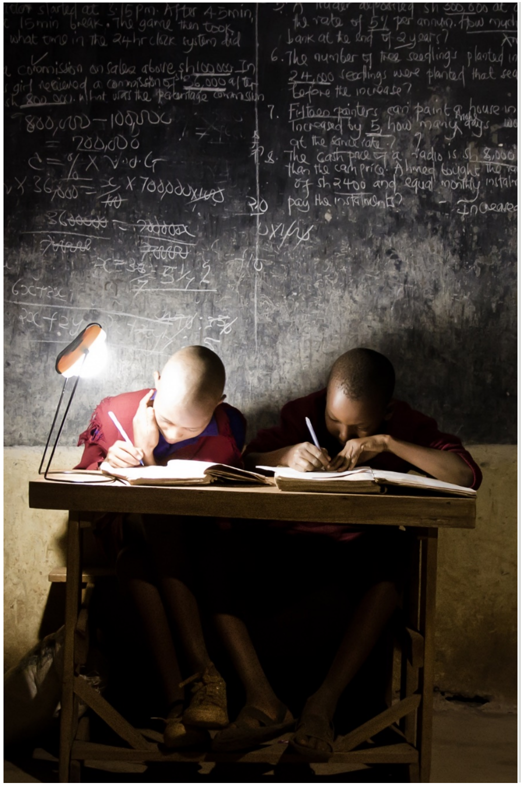
TECHNICAL NOTES



Lithium-ion Batteries Part I: General overview and 2019 update

This Technical Note is a 2019 update on the current state of lithium-ion (Li-ion) battery technology. It describes the basic functional elements of Li-ion battery cells, compares several existing and emerging lithium-ion battery technologies, and provides a brief overview of safety, testing, and transportation issues involved in designing products with lithium-ion batteries. Parts II and III of this series provide additional depth regarding Li-ion safety, testing, and transportation as these relate to off-grid products.

Introduction

Lithium-ion (Li-ion) batteries have become the predominant energy storage means for off-grid solar products due to their high efficiency, low cost, high capacity, lack of memory effect, and long cycle life. Li-ion is an evolving technology, first marketed in the early 1990s, and research and development work is ongoing to improve safety, increase performance, and extend lifetime. This Technical Note is a 2019 update that describes the types of Li-ion batteries currently on the market, new technologies that promise substantial performance enhancements, and briefly outlines proper control methods, safety considerations, testing, and shipping protocols. It is the first in a three-part series. Parts II and III discuss safety, testing, and shipping in more detail and can be found on the Lighting Global website.

Li-ion batteries feature many characteristics that are well-suited for use in off-grid applications. They have a long cycle life and do not suffer from the high self-discharge rate and memory effect of nickel-cadmium (NiCd) and nickel metal hydride (NiMH) batteries. Charging efficiency is excellent, up to 99% for some Li-ion chemistries. Unlike sealed lead acid (SLA) and NiCd, Li-ion batteries do not contain toxic heavy metals.

Li-ion systems must be correctly designed to achieve good performance and avoid serious safety hazards that can result from battery cell abuse and improper operation. Overcharging, overheating, short-circuiting, or damaging a charged Li-ion battery can result in fire or explosion. Proper design and testing can avoid these hazards and ensure safety, high performance, and long lasting operation of off-grid products.

Lithium-ion battery fundamentals

All battery cells have positive and negative terminals, and these are connected to internal electrodes (physical chemical structures) that store and release electrochemical energy that is used to drive an external electrical load. Li-ion batteries use a process known as intercalation, in which lithium ions[*] are incorporated into the structure of the electrode materials. Inside the cell, lithium ions move from the positive to the negative electrode during charging and from the negative to the positive electrode as the battery is discharged. Electrons move through an external circuit in the same direction as the lithium ions, driven by an external charger (when charging) or by the stored potential chemical energy (available to drive a load) when the battery is discharging.

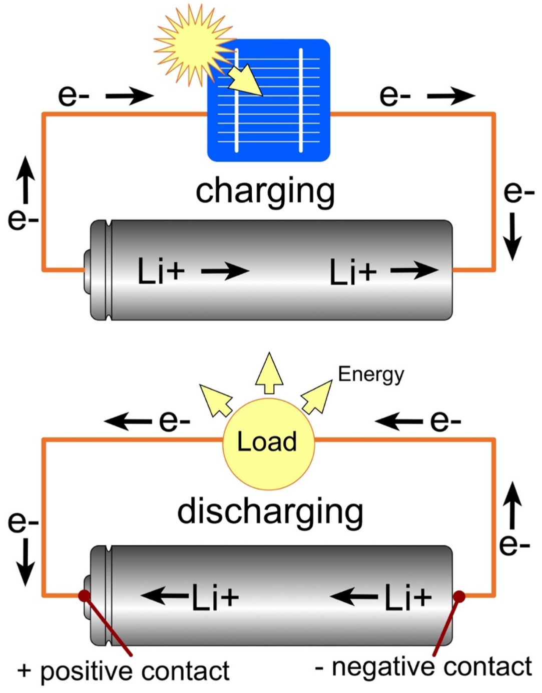


FIGURE 1. LITHIUM ION AND ELECTRON FLOW IN A LI-ION CYLINDRICAL CELL WITH EXTERNAL CIRCUIT

Types of Li-Ion Batteries

The term “lithium-ion battery” refers to a large and diverse family of different battery chemistries, form factors, sizes, and cell constructions. At a basic level, all li-ion battery cells have three functional layers: the positive electrode (cathode), the negative electrode (anode), and the separator. The separator is typically a polymeric membrane saturated with a liquid electrolyte that enables lithium ion transport but prevents direct contact between the electrodes. These thin layers are either rolled or stacked to increase the effective surface area available for energy storage, and then packaged in an outer cell housing (Figure A1).

Positive electrode (cathode) materials[1]

Li-ion batteries are often classified according to the composition of their positive electrodes. Table 1 lists the major types of positive electrode (cathode) materials commercially available on the market.

TABLE 1: COMMON POSITIVE ELECTRODE MATERIALS.[2]

Material	Abbr.	Description
Lithium cobalt oxide $LiCoO_2$	LCO	Original commercial type; expensive raw materials.
Nickel cobalt aluminum $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	NCA	Highest energy density per unit mass.
Nickel manganese cobalt $LiNi_{1-x-y}Mn_xCo_yO_2$	NMC NCM	Safer and less expensive than LCO. Good cycle life. Promising technology.
Lithium manganese oxide $LiMn_2O_4$	LMO	Safer and less expensive than LCO, but poor cycle life.
Lithium iron phosphate $LiFePO_4$	LFP	Very safe, high power, but lower energy density. Best high-temperature stability.

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[*] A lithium ion is a lithium atom that has been stripped of an electron, leaving behind a positively charged particle.

[1] Buchman, I. BU-205: Types of Lithium-ion. Battery University [Internet]. 2019 April 24 [cited 2019 June 4]. Available from: https://batteryuniversity.com/learn/article/types_of_lithium_ion

[2] Dahn J, Ehrlich G. Lithium-Ion Batteries. In: Linden’s Handbook of Batteries. 4th ed. New York: McGraw-Hill; 2011. Chapter 26.

Table A1 gives additional performance characteristics of Li-ion, lead-acid, NiMH, and NiCd batteries.

Lithium cobalt oxide (LCO)

Lithium cobalt oxide was the first widely commercialized cathode material and is still in common use in consumer products. LCO has high energy density but is not well suited for use in off-grid products because of lower cycle life and poorer safety. Nonetheless, LCO batteries are ubiquitous and still frequently used for these applications.

Lithium manganese oxide (LMO)

Pure LMO batteries have good thermal stability and safety but lower cycle life; they have declined in commercial use and have been replaced by blending the manganese oxide with nickel and cobalt (NMC).

Nickel cobalt aluminum (NCA)

Like LCO, NCA batteries have lower thermal stability than competing technologies. Their cost and cycle life also make them less attractive for off-grid products.

Lithium nickel manganese cobalt oxide (NMC, NCM)

Different blends of nickel, manganese, and cobalt are a successful and promising approach for Li-ion batteries. The ratio of these three elements is sometimes listed in the electrode name – an equal mix would have the chemical formula $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ and be listed as NMC 1-1-1 or simply NMC 111. NMC blends offer combinations of good cycle life, safety, and high energy density. The ratios of elements can be tailored to emphasize qualities that target specific applications including off-grid products.

Lithium Iron Phosphate ($LiFePO_4$)

$LiFePO_4$ batteries exhibit qualities that make them ideally suited for off-grid products where cost, safety, stability, and cycle life are primary requirements.[3] They have lower energy density than competing Li-ion chemistries and a lower output voltage of 3.2V, but this is acceptable for most off-grid applications. Many successful off-grid products use $LiFePO_4$ batteries.

Negative electrode (anode) materials

Carbon based anodes

Graphite formulations are used for the negative electrode in the majority of Li-ion commercial cells. They can be natural graphite, artificial graphite, or amorphous carbon.[4] Lithium ions become intercalated in the carbon sheet structures when the cell is charged and released during discharge. When the cell is first charged, a solid electrolyte interphase (SEI) layer forms on the graphite surface. The SEI layer stabilizes the anode by preventing reactions between the graphite and the electrolyte. SEI layer integrity plays an important role in cell performance.

Lithium titanate (LTO)

Lithium titanate (LTO) anode materials can be used with LMO or NMC cathodes to make a Li-ion cell. LTO cells offers very high cycle life, excellent thermal stability, excellent safety, and good low temperature operation. However, they have much lower energy density than other Li-ion technologies and a low cell voltage of 2.4V.

Cell construction

Li-ion cells are available in rigid cylindrical and prismatic (rectangular) constructions. Cylindrical cells are a well-established technology and are used for many other battery types, and prismatic cells have a long history of being used in mobile phones and other consumer electronic devices. These cells typically have built-in safety mechanisms that are designed to shut off current flow out of the battery (if the temperature of the cell escalates to a dangerous level) as well as release internal pressure from gas buildup in the case of an internal short circuit or other cell abuse event.

“Pouch” cells are a newer technology, similar in shape to prismatic cells, that use a thin, flexible laminate instead of a rigid housing. They offer cost, size, and weight savings, but may not offer the same safety and durability qualities of prismatic cells.

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[3] Ding, Yu, Pei Pan, Lihui Chen, Zhengbing Fu, Jun Du, Liangui Guo, and Feng Wang. LiFePO4 composites decorated with nitrogen-doped carbon as superior cathode materials for lithium-ion batteries. Ionics 23.12 (2017): 3295-3302.

[4] Garche J, Brandt K, In: Li-Battery Safety. Elsevier; 2018 Chapter 3.3

Cylindrical cells

Li-ion cylindrical cells are made by rolling long strips of cathode foil, separator, and anode foil together and inserting into a rigid stainless steel or aluminum cell housing or "can" (Figure 2). The can is filled with liquid electrolyte, safety disks are inserted into the top, and the electrodes are welded to the outer battery terminals (in this case, the top and bottom of the cell). The cell is hermetically sealed by crimping the top disk assembly closed.

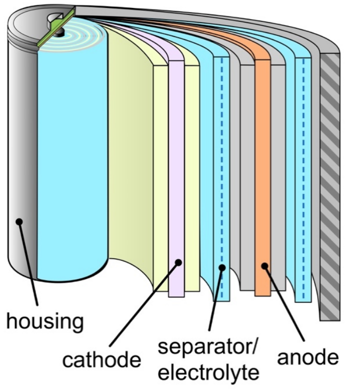

FIGURE 2. SIMPLIFIED CYLINDRICAL CELL DIAGRAM

Prismatic cells

Prismatic cells are similar in construction to cylindrical cells but use a flat rectangular housing to lower the overall thickness of the cell. The electrode/separator assembly can be rolled, as with cylindrical cells, or it can be a rectangular stack of individual electrodes (similar to a deck of cards). The battery terminals can be placed as contact pads on the top or side of the housing. The prismatic cell thin form factor is well suited to use in consumer electronics, particularly when ease of battery replacement is desirable.

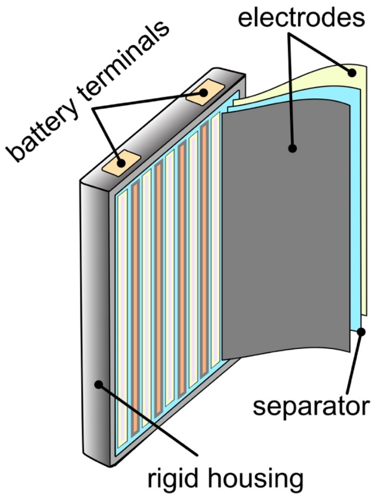

FIGURE 3. PRISMATIC CELL

Pouch cells (sometimes called "lithium polymer")

Like prismatic cells, pouch cells have a thin rectangular form factor. They are composed of rectangular stacks of individual electrode/separator layers, but instead of a rigid metal case they use a laminated flexible polymer/aluminum "bag". The electrodes have tabs along one side; these are welded together with battery terminal tabs that stick out of the top of the bag. The assembly is saturated with a liquid electrolyte and the bag is heat-sealed. By eliminating the rigid housing, pouch cells save on cost, weight, and thickness. The flexible pouch is, however, prone to swelling and this can pose problems with lifetime, capacity loss, and safety.

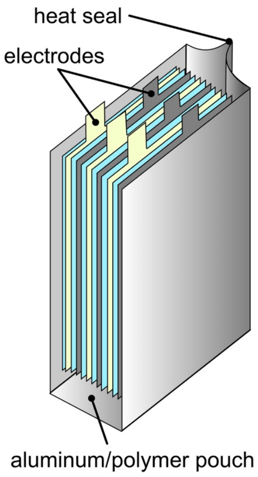

FIGURE 4. POUCH CELL

Lithium polymer (LiPo) vs. lithium polymer electrolyte vs. solid-state Li-ion batteries

Pouch cells are often labelled as “lithium polymer” (LiPo, Li-Po) cells. This designation is incomplete, however, and is analogous to a $LiFeO_4$ battery being labelled simply “Li-ion.” The electrodes, separator, and liquid electrolyte in pouch cells are often identical to those used in cylindrical and prismatic cells.

In contrast, lithium solid polymer electrolyte or gel polymer electrolyte batteries replace the liquid electrolyte with a solid polymer or gel electrolyte.[5] These systems are frequently discussed in technical and research literature, and the “polymer” or “solid polymer” designation in this case is referring to the separator/ electrolyte system. This technology can be used with cylindrical, prismatic, OR pouch cell housings. The solid polymer electrolyte batteries mentioned above are also referred to as “solid-state” Li-ion batteries.

No accurate, standardized, industry-wide naming convention exists (as of 2019) for LiPo, lithium polymer, and solid state Li-ion batteries. This can be confusing to consumers of off-grid products, and manufacturers are encouraged to label their battery systems with chemistry-specific designations including the cathode chemistry and electrolyte type (liquid, gel, solid).

Absent a battery chemistry listing from a manufacturer, specification sheet, or Material Safety Data Sheet (MSDS), the following trends have been observed:

- LiPo and lithium polymer often refers to pouch cells with liquid electrolytes.
- Solid-state Li-ion refers to any cell that uses a solid polymer or “dry” separator/electrolyte system without any liquid component.
- The terms gel polymer electrolyte and solid polymer electrolyte exist primarily in technical literature and should not be confused with lithium polymer or LiPo pouch cells.

Next generation Li-ion battery technologies

Advanced separator and electrolyte systems

The solid-state and polymer electrolyte technologies mentioned above represent a major next-generation approach for Li-ion batteries. These systems use either a gelled electrolyte (a lithium salt suspended in a polymer gel) or a solid polymer electrolyte (e.g. an inorganic lithium salt dissolved in a polyethylene oxide (PEO) framework). Polymer electrolytes contain no or reduced organic solvents and therefore mitigate or completely eliminate the hazard posed from this flammable component and substantially increase the safety of the cell. High cost and low ionic conductivity of polymer electrolytes remain substantial barriers to commercialization.

Separators with improved thermal properties are currently available for use with liquid electrolytes. Shutdown separators, for example, feature both PE and PP layers and are designed so that the pores in the film melt closed, and shut down current flow, when the cell overheats. Ceramics can also be incorporated into the separator to increase temperature resistance.[6]

New cathode materials

Several new cathode materials are under development. “5-volt” materials like $LiNi_{0.5}Mn_{1.5}O_4$ support higher voltages and thus higher energy densities than existing materials, which usually have a maximum charging voltage of 4.2 V (see Table A2). Alternative phosphate materials such as $LiMnPO_4$ may offer the advantages of $LiFePO_4$ while supporting voltages and thus energy densities comparable to or higher than those of other Li-ion chemistries.[7] Some of these new materials will require new electrolytes and other cell components able to withstand the higher voltages, and thus far technical barriers remain. Higher battery voltages would be very attractive to many Li-ion applications.

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[5] Garche J, Brandt K, In: Li-ion Battery Safety. Elsevier; 2018 Chapter 7B

[6] Garche J, Brandt K, In: Li-ion Battery Safety. Elsevier; 2018 Chapter 3.5

[7] Zaghib K, Trudeau M, Guerfi A, Trottier J, Mauger A, Veillette R, Julien CM. New advanced cathode material: $LiMnPO_4$ encapsulated with $LiFePO_4$. Journal of Power Sources. 2012 April 15;204:177-181.

Cathode blends

Blends of various cathode materials are being researched to improve performance and reduce cost.

Lithium NMC 111 is being joined by other cathode mixtures to increase certain performance aspects and lower cost by reducing the amount of cobalt. NMC 811, NMC 532, and NMC 442, among others, are being developed and tested for commercial use (particularly automotive applications).[8]

Cathode blends can also include $LiFePO_4$ and NMC.[9] In order to be commercially successful, research results will need to produce a cell with a combination of the best qualities of the component materials at an acceptable cost.

New anode materials

Anodes based on silicon provide higher energy density than graphite but can be difficult to manufacture.[1] Research to bring "3-D" nanostructured silicon anode materials to the market is ongoing; nanotechnology could also result in improvements to cathode materials.[10]

The molecular structure of silicon enables a large increase in Li+ ion storage and could greatly increase the capacity, energy density, and specific energy capability of the anode (up to a factor of 10 by some estimates). The challenge lies in developing a material with low volume change during charge/discharge.[11]

Charging and Discharging Li-ion Batteries

Proper charge control and protection circuitry is critical for Li-ion batteries. Overcharging a Li-ion battery can lead to a fire or explosion, and overdischarging can permanently damage the battery.

Li-ion batteries are usually charged in two steps (Figure 2). The first step is a constant-current charge at 0.5-1*C* until the battery reaches its maximum voltage, usually 4.1-4.2 V/cell. After the ending voltage is reached, the battery is charged at constant voltage until the current drops below a threshold, between 0.02*C* and 0.1*C*[12,13] , or for a fixed amount of time, around 2 hours. If the battery is severely depleted, a slow charge (0.1*C*) is necessary to bring the voltage up to 2.5-3 V/cell before the 0.5-1*C* charge can begin; however, attempting to charge a severely depleted battery may be unsafe, and the battery may have permanent capacity loss.[14,15]

Li-ion batteries are not harmed by a partial charge; in fact, charging to a lower voltage will extend the cycle life of the battery, but with a significant capacity penalty. Charging a 4.2-volt battery to 4.1 V results in a 10% or larger reduction in capacity.[12] Accurate voltage regulation is critical for safely charging Li-ion batteries; the tolerance for overcharging can be 50 mV or less.[15] Charging cells in series requires circuitry to balance the voltage between cells so that no individual cell exceeds its maximum voltage.

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[8] Cui, Suihan, Yi Wei, Tongchao Liu, Wenjun Deng, Zongxiang Hu, Yantao Su, Hao Li, Maofan Li, Hua Guo, Yandong Duan, Weidong Wang, Mumin Rao, Jiaxin Zheng, Xinwei Wang, and Feng Pan. Optimized Temperature Effect of Li-Ion Diffusion with Layer Distance in Li(Ni x Mn y Co z)O 2 Cathode Materials for High Performance Li-Ion Battery. Advanced Energy Materials 6.4 (2016): n/a-n/a.

[9] Besnard, Nicolas, Aurélien Etiemble, Thierry Douillard, Olivier Dubrunfaut, Pierre Tran-Van, Laurent Gautier, Sylvain Franger, Jean-Claude Badot, Eric Maire, and Bernard Lestriez. Multiscale Morphological and Electrical Characterization of Charge Transport Limitations to the Power Performance of Positive Electrode Blends for Lithium-Ion Batteries. Advanced Energy Materials 7.8 (2017): n/a-n/a.

[10] Patel P. Nanostructured Silicon Key to Better Batteries. IEEE Spectrum [Internet]. 2011 August [cited 2019 June 2]. Available from: http://spectrum.ieee.org/consumer-electronics/portable-devices/nanostructured-silicon-key-to-better-batteries

[11] Feng, Kun, Matthew Li, Wenwen Liu, Ali Ghorbani Kashkooli, Xingcheng Xiao, Mei Cai, and Zhongwei Chen. "Silicon-Based Anodes for Lithium-Ion Batteries: From Fundamentals to Practical Applications." Small 14.8 (2018): n/a-n/a.

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[13] Texas Instruments. Li-Ion Battery Charger solution using the MSP430. 2018 May [cited 2019 June 11]. Available from: http://www.ti.com/lit/an/slaa287a/slaa287a.pdf

[14] Maleki H, Howard JN. Effects of overdischarge on performance and thermal stability of a Li-ion cell. Journal of Power Sources. 2006 October 6; 160(2):1395-1402.

[15] Buchman, I. BU-409: Charging Lithium-ion. Battery University [Internet]. 2018 April 24 [cited 2019 June 4]. Available from: http://batteryuniversity.com/learn/article/charging_lithium_ion_batteries

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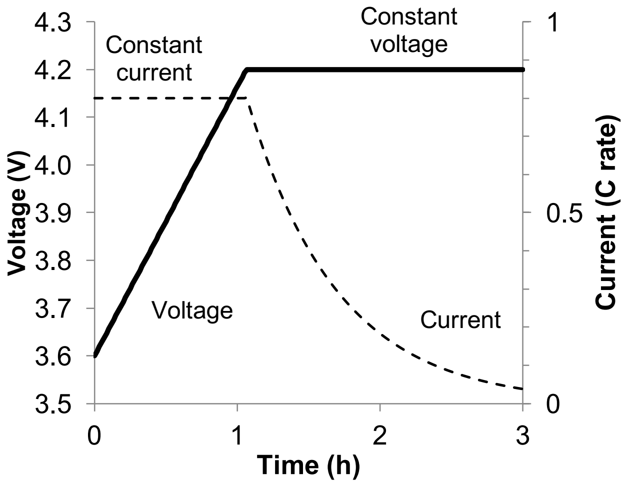

FIGURE 2: APPROXIMATE CURRENT AND VOLTAGE DURING TYPICAL LI-ION CHARGE CYCLE. EXACT VALUES DEPEND ON CHARGING CONDITIONS AND BATTERY TYPE.

Most Li-ion batteries should not be charged at ambient temperatures below 0°C or above 45-50°C.[16] Charging at high temperature will decrease cycle life and may present a safety hazard; phosphate-based batteries may have somewhat better high-temperature performance than other Li-ion chemistries. Charging at low temperatures may lead to the growth of lithium metal dendrites,[17] which can result in an internal short circuit, destroying the battery and potentially causing a fire. Ensuring that the temperature remains within the acceptable range is especially important for products that may be charged outdoors in direct sunlight.

Unlike NiCd and NiMH cells, lithium ion batteries do not have a memory effect and do not benefit from full discharge cycles. Fully discharging a Li-ion battery will reduce its life, and discharging the battery below 2.5-3 V/cell can cause permanent damage [18] or short-circuiting.[19]

Voltage and temperature limits vary from battery to battery. The voltage and temperature ranges in this technical note are general guidelines; the battery manufacturer’s datasheets should be consulted for the limits that apply to specific battery models.

Shelf life and battery storage

Li-ion batteries have a very low self-discharge rate.[20] Most “self-discharge” is actually standby current from connected electronics built into the battery cell, battery pack, or the finished product. Standby current varies according to the design of those electronics. Manufacturers should measure the current consumption of connected electronics and store their batteries in a partially discharged state, with enough current reserve to keep the battery from overdischarging.

In most cases, this means batteries should be stored at or near room temperature (25°C) at 20-40% state of charge.[21] Storage while fully charged or in elevated temperatures should be avoided as this will put stress on the cell, reduce battery life, and increase the amount of energy available for thermal runaway should an accident occur.

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[16] Maleki, Hossein, Hsin Wang, Wally Porter, and Jerry Hallmark. "Li-Ion polymer cells thermal property changes as a function of cycle-life." Journal of Power Sources 263 (2014): 223-230.

[17] Waldmann, Thomas, Björn-Ingo Hogg, and Margret Wohlfahrt-Mehrens. Li plating as unwanted side reaction in commercial Li-ion cells – A review. Journal of Power Sources 384 (2018): 107-124.

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[19] Lee Y-S, Cheng M-W. Intelligent control battery equalization for series connected lithium-ion battery strings. IEEE Transactions on Industrial Electronics. 2005 October;52(5):1297- 1307.

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[21] Garche J, Brandt K, Li-Battery Safety. Elsevier B.V.; 2018 Chapter 11A2

Disposal

The metals in lithium-ion batteries, including cobalt, nickel, manganese, iron, and aluminum, are not as toxic as the lead or cadmium in SLA or NiCd batteries; many governments allow their disposal in landfills. While Li-ion batteries can be recycled to recover metals, recycling is expensive, and the recycling infrastructure is not as widespread as that for lead-acid batteries. Charged lithium-ion batteries pose a fire or explosion hazard if crushed, punctured, or incinerated; batteries should be fully discharged before disposal.

Li-ion safety overview[22]

While all batteries can present safety hazards if used improperly, Li-ion batteries are especially sensitive to proper handling and treatment. Li-ion batteries can vent electrolyte, catch fire, or explode if overcharged, overheated, or short-circuited. Unlike the water-based electrolytes in SLA, NiCd, and NiMH batteries, Li-ion electrolytes use flammable organic solvents. Li-ion battery fires can be extinguished with water or standard dry chemical fire extinguishers.[23]

Detailed safety and hazards information can be found in Part II of this Li-ion battery series. Briefly, Li-ion battery management should always adhere to the following:

- Li-ion cells should always be charged according to the battery manufacturer’s specifications. Under no circumstances should cells be subject to overcharge, overdischarge, or short circuit.
- Cells should not be subject to high temperature charging (>45 °C) or low temperature charging (<0 °C).
- Cells should never be subject to mechanical abuse or stress.
- Cells should only be stored in a partially discharged state, typically between 20-40%.
- Cells used in battery packs should be individually monitored and controlled by a battery management system (BMS) to prevent electrical abuse.
- Battery packs should be designed to allow passive cooling of individual cells, and cell spacing should be designed to prevent thermal runaway from spreading cell-to-cell.

Battery testing and transportation[24]

The United Nations (UN), Underwriters Laboratories (UL), and the International Electrotechnical Commission (IEC) have published standards for safety testing of Li-ion batteries. Testing according to the UN Manual of Tests and Criteria, Part III, Subsection 38.3 (UN 38.3) is required for most shipments of Li-ion batteries. UN38.3, UL 1642, and IEC 62133 (among others) define a series of tests, including but not limited to overcharge, short circuit (both internal and external), crush, impact, altitude, and heating tests. To pass, batteries must not catch fire or explode, and in some cases must not leak or overheat.

In addition to these standards, the Institute of Electrical and Electronics Engineers (IEEE) has published standards for batteries in portable computers (IEEE 1625) and cellular telephones (IEEE 1725); these standards specify additional design and manufacturing requirements, many of which are intended to prevent internal short-circuiting.

Air transport restrictions

International regulations established by the International Air Transport Association (IATA) and the International Civil Aviation Organization (ICAO) restrict the shipment by air of lithium-ion batteries. In general, small batteries contained within equipment are subject to fewer restrictions than large batteries or batteries packaged separately from equipment, as long as the batteries pass the safety tests defined in UN 38.3.).

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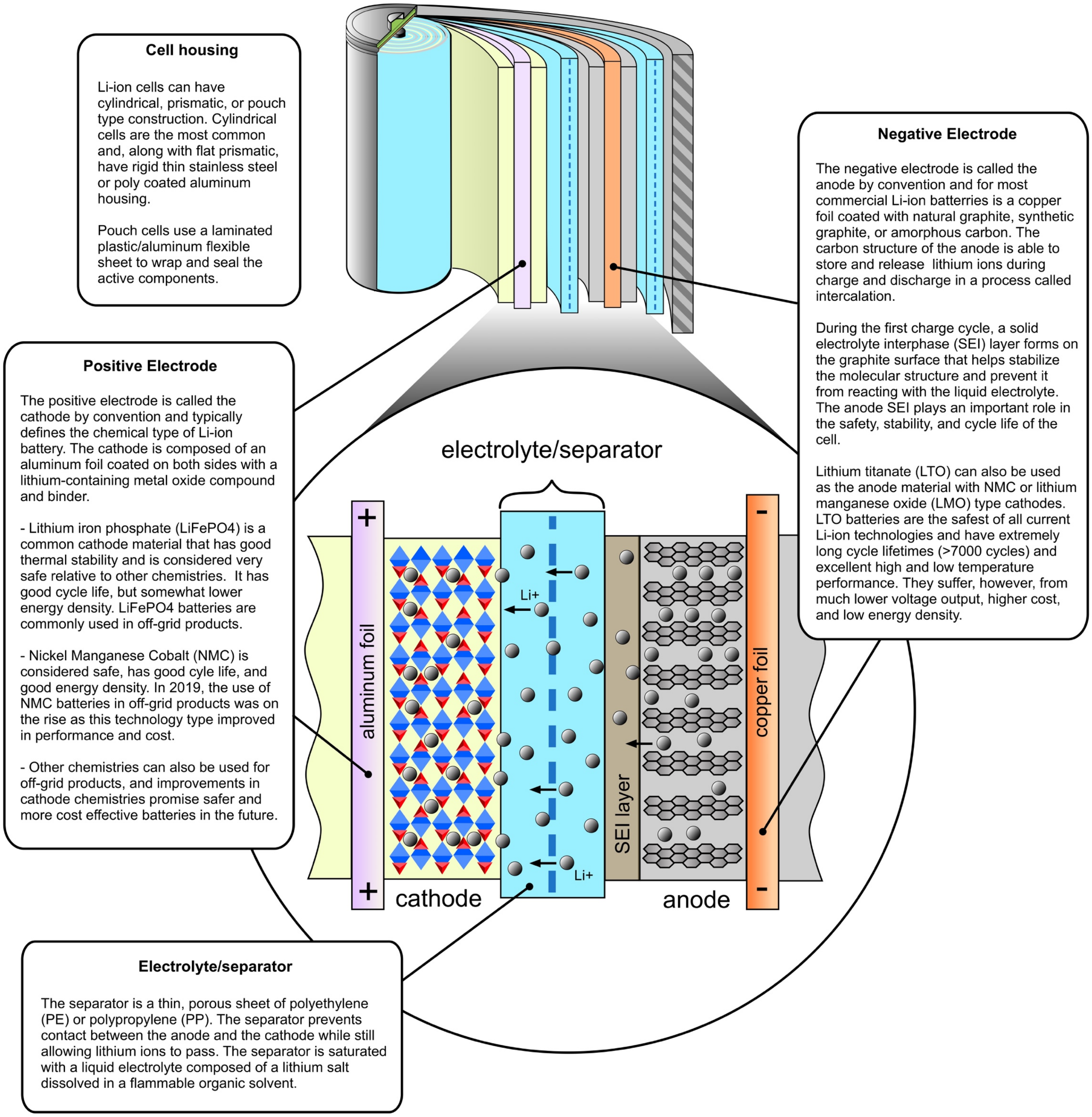
[22] see also Lighting Global, Li-ion Batteries Part II: Safety, Technical Notes Issue 31, June 2019

[23] Woods Hole Oceanographic Institution. Lithium Battery Safety. February 2010 [cited 2019 June 11]. Available from: https://aeasseincludes.assp.org/professionalsafety/pastissues/055/02/F2Reif_0210Z.pdf

[24] see also Lighting Global, Li-ion Batteries Part III: Safety Standards and Regulations, Technical Notes Issue 32, June 2019

Appendix: Battery construction and comparison of performance characteristics



Cell housing

Li-ion cells can have cylindrical, prismatic, or pouch type construction. Cylindrical cells are the most common and, along with flat prismatic, have rigid thin stainless steel or poly coated aluminum housing.

Pouch cells use a laminated plastic/aluminum flexible sheet to wrap and seal the active components.

Negative Electrode

The negative electrode is called the anode by convention and for most commercial Li-ion batteries is a copper foil coated with natural graphite, synthetic graphite, or amorphous carbon. The carbon structure of the anode is able to store and release lithium ions during charge and discharge in a process called intercalation.

During the first charge cycle, a solid electrolyte interphase (SEI) layer forms on the graphite surface that helps stabilize the molecular structure and prevent it from reacting with the liquid electrolyte. The anode SEI plays an important role in the safety, stability, and cycle life of the cell.

Lithium titanate (LTO) can also be used as the anode material with NMC or lithium manganese oxide (LMO) type cathodes. LTO batteries are the safest of all current Li-ion technologies and have extremely long cycle lifetimes (>7000 cycles) and excellent high and low temperature performance. They suffer, however, from much lower voltage output, higher cost, and low energy density.

Positive Electrode

The positive electrode is called the cathode by convention and typically defines the chemical type of Li-ion battery. The cathode is composed of an aluminum foil coated on both sides with a lithium-containing metal oxide compound and binder.

- Lithium iron phosphate (LiFePO4) is a common cathode material that has good thermal stability and is considered very safe relative to other chemistries. It has good cycle life, but somewhat lower energy density. LiFePO4 batteries are commonly used in off-grid products.

- Nickel Manganese Cobalt (NMC) is considered safe, has good cyle life, and good energy density. In 2019, the use of NMC batteries in off-grid products was on the rise as this technology type improved in performance and cost.

- Other chemistries can also be used for off-grid products, and improvements in cathode chemistries promise safer and more cost effective batteries in the future.

Electrolyte/separator

The separator is a thin, porous sheet of polyethylene (PE) or polypropylene (PP). The separator prevents contact between the anode and the cathode while still allowing lithium ions to pass. The separator is saturated with a liquid electrolyte composed of a lithium salt dissolved in a flammable organic solvent.

FIGURE A1. A SIMPLIFIED DIAGRAM OF AN 18650 LITHIUM IRON PHOSPHATE CYLINDRICAL CELL BATTERY DEPICTING THE PRIMARY FUNCTIONAL ELEMENTS: POSITIVE ELECTRODE (CATHODE), NEGATIVE ELECTRODE (ANODE) AND ELECTROLYTE/SEPARATOR.

TABLE A1: COMPARISON OF LI-ION (GRAPHITE ANODE) TO OTHER RECHARGEABLE BATTERY CHEMISTRIES

Characteristic	$LiCoO_2$ (LCO)	$LiFePO_4$ (LFP)	SLA	NiCd	NiMH
Nominal voltage per cell	3.7	2.5-3.6[1]	2.0[25]	1.2[25]	1.2[25]
Specific energy (Wh/kg)	175-200[2,25]	60-110[2]	30-40	35-80[25,26]	55-110[25,27]
Energy density (Wh/L)	400-640[2]	125-250[1]	50-90[25,26]	100-150[25,26]	160[26]-420[28]
Cycle life (to 80% original capacity at 100% DOD)	500+[1]	1000+[2]	200-300 (up to 400 at 80% DOD)[29]	300-1000[25]	500-1000[25]
Calendar life (years)	>5[2]	>5[1]	2-8[25]	5-7[25]	5-10[25]
Ambient temperature during charge (°C)	0-45[2]	0-45[2]	-40-50[25]	0-40[25]	0-40[25]
Ambient temperature during discharge (°C)	-20-60[2]	-30-60[2]	-40-60[25]	-20-70[25]	-20-65[25]
Self-discharge capacity loss per month	2-10%[25]	2-10%	4-8%[25]	15-20%[25]	15-30% (conv.) 2% (advanced)[30]
Memory effect	No[2]	No[2]	No[25]	Yes[25]	Yes, less than NiCd[25]
Toxic metals	None	None	Lead	Cadmium	None
Battery management system required	Yes	Yes	No	No	No

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TABLE A2: COMPARISON OF LI-ION (GRAPHITE ANODE) TO OTHER RECHARGEABLE BATTERY CHEMISTRIES

Positive electrode	LCO and NCA	NMC	LMO		$LiFePO_4$
Negative electrode	Graphite	Graphite	Graphite	Lithium titanate	Graphite
Optimized for	Energy	Energy or Power	Power	Cycle life	Power
Operating voltage range	2.5-4.2 (rarely 4.35)	2.5-4.2 (rarely 4.35)	2.5-4.2	1.5-2.8	2.0-3.65
Nominal voltage	3.6-3.7	3.6-3.7[21]	3.7-3.8[21]	2.3	3.2
Specific energy (Wh/kg)	175-240 cyl 130-200 polymer	100-240	100-150	70	60-110
Energy density (Wh/L)	400-640 cyl 250-450 polymer	250-640	250-350	120	125-250
Discharge rate (continuous)	2-3*C*	2-3*C* (power cells >30*C*)	>30*C*	10*C*	10-125*C*
Cycle life (100% DOD to 80% capacity)	500+	500+	500+	4000+	1000+
Ambient temperature during charge (°C)	0-45	0-45	0-45	-20-45	0-45
Ambient temperature during discharge (°C)	-20-60	-20-60	-30-60	-30-60	-30-60