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BATTERIES IN A PORTABLE WORLD

A Handbook on Rechargeable
Batteries for Non-Engineers



Fourth Edition

Batteries in a Portable World

*A Handbook on Rechargeable
Batteries for Non-Engineers*

Isidor Buchmann

published by

Cadex Electronics Inc.

Fourth Edition

In association with www.BatteryUniversity.com



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Library and Archives Canada Cataloguing in Publication

Buchmann, Isidor, 1943–

Batteries in a portable world: a handbook on rechargeable batteries for non-engineers.

Fourth edition

Includes bibliographical references and index.
ISBN 978-0-9682118-4-7

1. Storage batteries. I. Cadex Electronics Inc. II. Title.

Printed in Canada

The information in this book is provided for the benefit of all battery users. Batteries have become our steady travel companion. They help us reach a friend, allow us to work outside the confines of four walls, offer entertainment when time permits and enable personal transportation. But most importantly, batteries connect humanity and support missions that help people in need.

I dedicate this book to my five children and many grandchildren, who have a keen interest in batteries. They understand the importance of clean power to maintain freedom of mobility while protecting our environment and reducing the dependence on fossil fuel. They also want to pass our wonderful world to future generations as God's gift to us, well-sustained and unspoiled by mankind.

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With Special Thanks

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Jeff Dahn |

DAHN is recognized worldwide as a distinguished scientist in the field of advanced lithium batteries. He is one of the pioneering developers of the lithium-ion battery, has authored 610 refereed journal papers and has issued or filed 65 patented inventions. According to the Electrochemical Society Interface, Dahn is one of the most prolific authors in the *Journal of the Electrochemical Society* and has one of the most-cited papers in the journal.

Dahn obtained his B.Sc. in physics from Dalhousie University (1978) and earned his Ph.D. from the University of British Columbia in 1982. He then worked at the National Research Council (NRC) of Canada (1982–85) and at Moli Energy Limited (1985–1990) before taking up a faculty position in the Physics Department at Simon Fraser University in 1990. He joined Dalhousie University in 1996 as the NSERC/3M Canada Industrial Research Chair in Materials for Advanced Batteries and was appointed Canada Research Chair in 2003.

Dahn has received numerous national and international awards, including the Herzberg Medal, Canadian Association of Physicists; Battery Division Research Award of the Electrochemical Society (1996) and the Battery Division Technology Award (2011); NSERC University/Industry Synergy Award for collaborative efforts with 3M Canada (2003) and the Medal for Excellence in Teaching from the Canadian Association of Physicists. In 2015, Dahn entered an exclusive agreement with Tesla Motors for a five-year partnership beginning in June 2016.

Paul Craig | Director of Technology at E-One Moli Energy (Canada) Ltd.

CRAIG began his battery career in 1986 in the R&D department at Moli Energy,

where he designed equipment for manufacturing and testing of rechargeable lithium batteries. As Senior Applications Engineer, he developed fuel gauges for smart batteries and was responsible for specifying and approving batteries for military, medical and commercial use. In his position as Director of Technology he is a key interface between the battery industry and the R&D department. Craig travels the world and devotes equal time to batteries for portable applications and the electric vehicle. He provided invaluable resources for this book, especially on manganese-based chemistries and user applications.

Jörn Tinnemeyer | Senior Director Energy Storage Systems, Teco Group

TINNEMEYER has contributed to this book on the electrical, chemical and implicative side of the battery. He has won many prestigious awards, honors and international research scholarships, but his main achievements are battery rapid-test technologies to estimate state-of-health that secured five patents. Today, these innovations are in commercial use and are known as Spectro™ and QuickSort™. Tinnemeyer holds a degree from the University of Toronto in mathematics and applied physics, completed graduate work in high-energy physics at Simon Fraser University and earned a master's degree in astronautics and space engineering at Cranfield University in the UK.

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SHOA received her Ph.D. in electrical engineering from the University of British Columbia (UBC) in the field of modeling and characterization of electrochemical systems. She contributed to multi-dimensional modeling for energy storage systems including batteries, fuel cells and polymer actuators and sensors. She has won prestigious awards in the area of applied electrochemical systems, received the NSREC industrial postdoctoral fellowship and completed the postdoctoral program at Automotive Fuel Cell Cooperation (AFCC) as a research scientist. Shoa has authored a book chapter and 15 peer-reviewed articles in the areas of electro-chemical devices, served on the Graduate Advisory Board at UBC and supervised graduate students in conducting research in energy storage systems. With her research team, Shoa is studying new

products in battery management and diagnostics, including battery rapid-testing.

**David Conn | Professor Emeritus of Electrical and Computer Engineering,
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CONN received his Ph.D. degree from Queen's University (1970) in the field of Microwave Device Modelling where he introduced the concepts of State-Space-Analysis to the microwave community. This technique allows the combination of circuit and device modeling into one unified method of studying microwave systems.

He conducted research and development in academia and played a significant role in developing microwave solid state circuits while working in the digital radio department of Bell-Northern Research. His research spanned the areas from circuit applications to opto-electronic measurement systems. He was later appointed an NSERC Research Chair at McMaster University where he became Chair of the Electrical and Computer Engineering Department and an Associate Member of the Engineering Physics Department.

Acknowledgments

The author thanks Cadex Electronics for sponsoring this book. The Cadex staff has been most supportive in providing discoveries from their laboratories and sharing material that is of interest to battery users. Special attention goes to the advancements in diagnostic technologies and rapid-testing in particular.

The author also thanks Bill Campbell, John Bradshaw, David Conn and Deborah Hutton for their dedicated editing and proofreading efforts. Special thanks go to Ljuba Levstek for the line drawings in Chapter 1 and Corporate Graphics for production assistance. No one is able to complete a book single-handedly and in the end it's the teamwork that adds quality and provides completeness.

Preface to the Fourth Edition

Battery research is advancing at a rapid pace, which is a clear indication that the Super Battery has not yet been found but it might be just around the corner. While today's batteries satisfy most portable applications, improvements are needed if this power source is to become a serious contender for the electric vehicle.

The fourth edition of *Batteries in a Portable World* comes with much new material. The first edition appeared in 1997 and the handy little book sold out quickly. The larger second edition was published in 2001 and served public safety, healthcare and defense industries, as well as esteemed hobbyists and everyday battery users. The third edition was released in 2011; steady demand prompted me to write this fourth edition.

There are no black and whites in batteries, only shades of gray. The battery is a black box with a mind of its own: mystical and unexplainable. For some, the battery causes no problems whatsoever; for others it's nothing but a headache. With so much hype about batteries, people want unbiased knowledge, not just test data.

The material of this book is also on www.BatteryUniversity.com. The website went live in 2003 and quickly gained popularity. Besides being a teaching tool, it has become a social media network to exchange information about your battery experience. Users' input, in my opinion, is as important as reams of laboratory test data. The critical mass speaks louder than the promises made by device manufacturers, which cannot always be met.

Much effort is devoted to battery care, and it appears as if battery diagnostics are stuck in medieval times. Let's not blame our scientists for this; the technology is complex. Also good care alone does not always show the expected results. The often asked question, "How many cycles can I get out of

“my battery if I do this?” has no quantitative answer. The reasons for the eventual demise are multifold and have similarities with our own human frailty. We suffer health issues even if we try to keep fit and eat our vegetables.

This book is written for the professional needing a basic understanding of how a battery behaves, a student completing an essay, and a user wanting to get the most out of a battery. The information comes from my battle-tested experience working with batteries in the Cadex laboratories as well as from research organizations and everyday battery users. I appreciate these contributions; the results get filtered and receive a citation where appropriate.

There is no perfect battery and each pack is tailored for a given use. Batteries in consumer products are optimized for long runtime, small size and low cost; longevity is less important. Industrial batteries may have high load capabilities and improved reliability, but the pack gets bulkier. A third variety offers long service life and these packs are expensive.

All batteries have one thing in common: they run for a while, need recharging and require an eventual replacement as the capacity fades. Battery replacement comes often before retiring the host. The idea of an uninterrupted energy source is still a pipedream.

Introduction

The word “battery” comes from the Old French word *baterie*, meaning “action of beating,” relating to a group of cannons in battle. In the endeavor to find an energy storage device, scientists in the 1700s adopted the term “battery” to represent multiple electrochemical cells connected together.

The battery consists of two electrodes that are isolated by a separator and soaked in electrolyte to promote the movement of ions. New active materials are being tried, each offering unique attributes but none delivering an ultimate solution.

*

Improvements have been slow. Whereas Moore’s Law, doubled the number of transistors in an integrated circuit every two years, capacity gain of lithium-ion (Li-ion) has been about 8 percent per year in the last two decades.

Theoretical battery models reveal specific energy levels that are ten times higher than the commercial equivalent. They remain theoretical, and these lofty goals may never be achieved in real life.

The battery is a feeble vessel that is slow to fill, holds limited energy, runs for a time like a wind-up toy, fades and eventually becomes a nuisance. It exhibits human qualities in that it needs recuperation from the daily travails by applying a long and restful charge. It then delivers for a time and quits on its own terms. Some batteries need as much charging time as they deliver, and there is a resemblance to growing teenagers. (I raised five.)

The lithium-ion family receives the most attention and is gradually replacing the nickel-based predecessors that dominated the battery world until the 1990s. Lead acid with its many warts and blemishes holds a solid position for starter and standby batteries. No other system can meet its price and robustness for now.

Li-ion is expensive but when calculating the price-per-cycle, it wins over

lead acid when repeat cycling is required. Basing calculations on cost per kilowatt hour (kWh) no longer holds; operational costs must be considered. A battery expert said that the switch from lead acid to Li-ion will be faster than the advancement of the Internet.

We want to learn as much about batteries as possible, but this book addresses only the most commonly used battery systems. My background is in electrical, and I tackle batteries from the electrical side rather than studying chemical reactions. I avoid formulas, and I back my material with practical and hands-on field data.

* In 1965, Gordon Moore said that the number of transistors in an integrated circuit would double every two years. The prediction became true and is being carried into the 21st century. Applied to a battery, Moore's Law would shrink a starter battery in a car to the size of a coin.

Part One

Sharing Battery Knowledge

A battery behaves like a human being.
It senses the kindness provided and
delivers on the care and attention given.

Chapter 1 | Crash Course on Batteries

When Was the Battery Invented?

One of the most remarkable and novel discoveries in the last 400 years was electricity. We might ask, “Has electricity been around that long?” The answer is yes, and perhaps much longer. Its practical use has only been at our disposal since the mid to late 1800s, and in a limited way at first. Some of the earliest public works gaining attention were streets lights in Berlin in 1882, lighting up the Chicago World’s Fair in 1893 with 250,000 light bulbs, and illuminating a bridge over the river Seine during the Paris 1900 World Fair.

The use of electricity may go back further. While constructing a railway in 1936 near Baghdad, workers uncovered what appeared to be a prehistoric battery, also known as the Parthian Battery. The object dates back to the Parthian empire and is believed to be 2,000 years old. The battery consisted of a clay jar that was filled with a vinegar solution into which an iron rod surrounded by a copper cylinder was inserted. This device produced 1.1 to 2.0 volts of electricity.

Figure 1-1 illustrates the Parthian Battery.

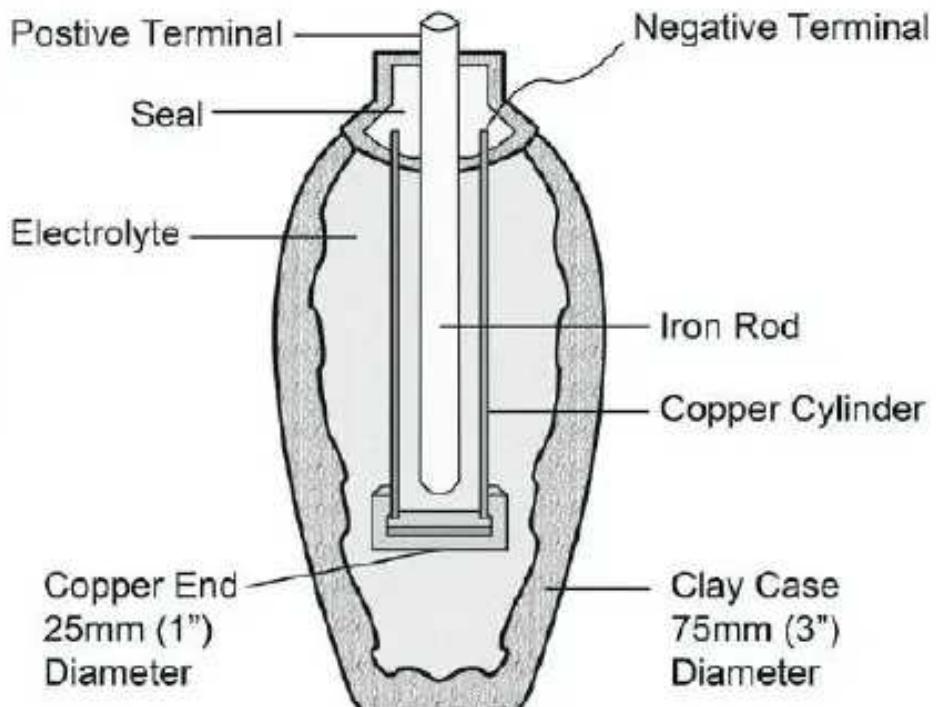
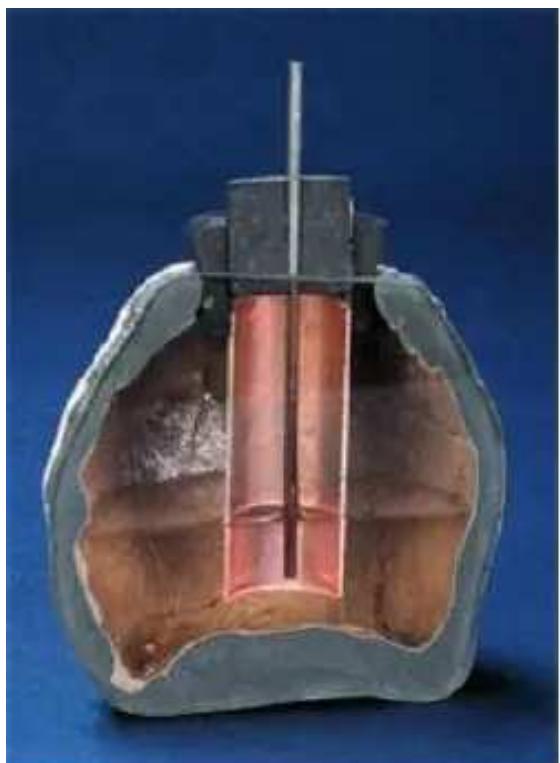


Figure 1-1: Parthian Battery.

A clay jar of a prehistoric battery holds an iron rod surrounded by a copper cylinder. When filled with vinegar or an electrolytic solution, the jar produces 1.1 to 2 volts.

Not all scientists accept the Parthian Battery as a source of energy. It is possible that the appliance was used for electroplating, adding a layer of gold or other precious metals to a surface. The Egyptians are said to have electroplated antimony onto copper over 4,300 years ago. Archeological evidence suggests that the Babylonians were the first to discover and employ a galvanic technique in the manufacturing of jewelry by using an electrolyte that was based on grape juice to gold-plate stoneware. The Parthians who ruled Baghdad (247 BC–224 AD) may have utilized batteries to electroplate silver.

One of the earliest methods to generate electricity in modern times was by creating a static charge. In 1660, Otto von Guericke constructed an electrical machine featuring a large sulfur globe that, when rubbed and turned, attracted feathers and small pieces of paper. Guericke proved that the sparks generated were electrical in nature.

In 1744, Ewald Georg von Kleist developed the Leyden jar that stored static charge in a glass jar that was lined with metallic foil on the inside and outside of the container. Many scientists, including Peter van Musschenbroek, professor at

Leiden, the Netherlands, thought that electricity resembled a fluid that could be captured in a bottle. They did not know that the two metallic foils formed a capacitor. When charged up with high voltage, the Leyden jar gave the gentlemen an unexplainable hefty shock when they touched the metallic foil.

The first practical use of static electricity was the “electric pistol” that Alessandro Volta (1745–1827) invented. He wanted to provide long-distance communications, albeit only one Boolean bit. An iron wire supported by wooden poles was to be strung from Como to Milan, Italy. At the receiving end, the wire would terminate in a jar filled with methane gas. To signal a coded event, an electrical spark would be sent through the strung wire to detonate the jar. This communications link was never built. Figure 1-2 shows a pencil rendering of Alessandro Volta.



Figure 1-2: Alessandro Volta, inventor of the electric battery.

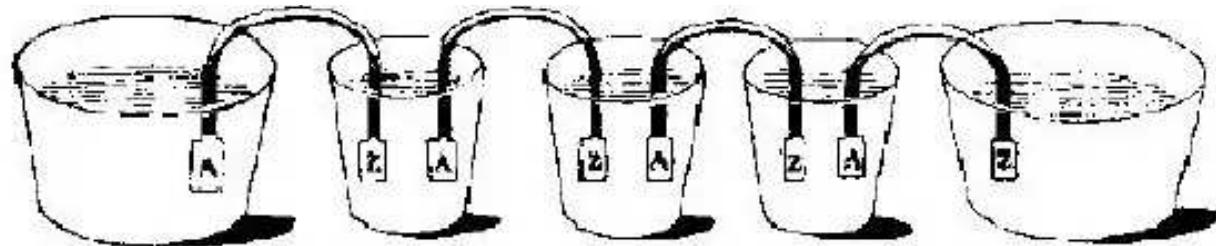
Volta's discovery of the decomposition of water by an electrical current laid the foundation of electrochemistry.

Courtesy of Cadex

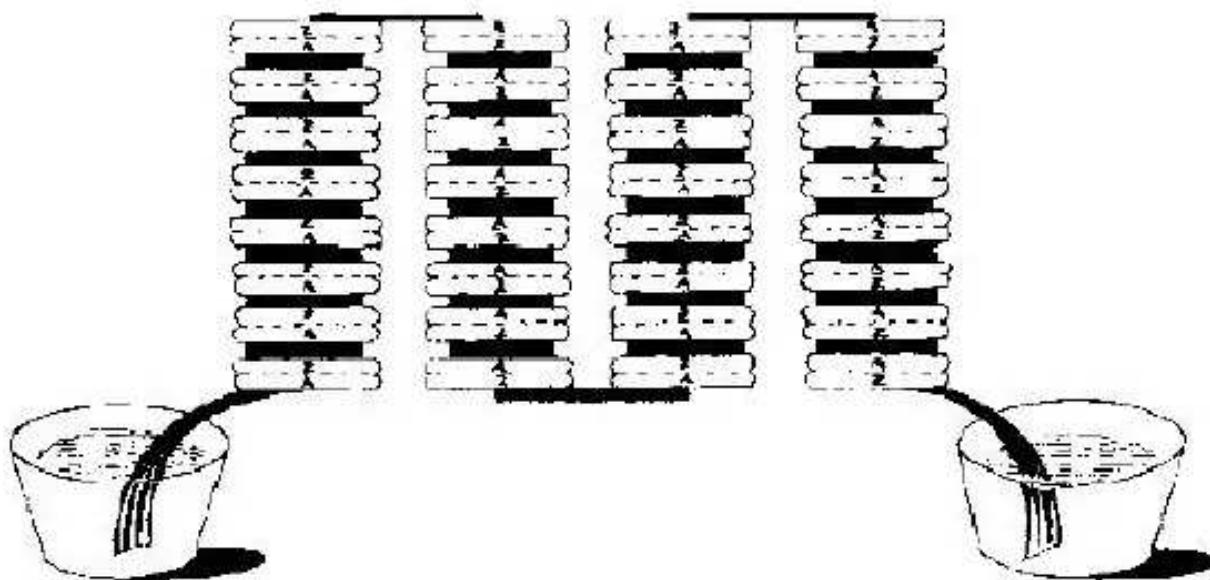
In 1791, while working at Bologna University, Luigi Galvani discovered that the muscle of a frog would contract when touched by a metallic object. This phenomenon became known as animal electricity. Prompted by these experiments, Volta initiated a series of experiments using zinc, lead, tin and iron as negative plates; and copper, silver, gold and graphite as positive plates. The interest in galvanic electricity soon became widespread.

Early Batteries

In 1800, Volta discovered that certain fluids would generate a continuous flow of electrical power when used as a conductor. This led to the invention of the first voltaic cell, more commonly known as the *battery*. Volta learned further that the voltage would increase when voltaic cells were stacked on top of each other. Figure 1-3 illustrates such a series connection.



Silver (A) and zinc (Z) metals are immersed in cups filled with electrolyte and connected in series.



Silver and zinc electrodes are connected in series, separated by paper soaked with electrolyte.

Figure 1-3: Volta's experiments with the electric battery in 1796. Metals in a battery have different electron affinities. Volta noticed that the voltage potential of dissimilar metals became stronger the farther apart the affinity numbers moved.

The first number in the metals listed below demonstrates the affinity to attract electrons; the second is the oxidation state.

$$\text{Zinc} = 1.6 / -0.76 \text{ V}$$

Lead = 1.9 / -0.13 V

Tin = 1.8 / -1.07 V

Iron = 1.8 / -0.04 V

Copper = 1.9 / 0.159 V

Silver = 1.9 / 1.98 V

Gold = 2.4 / 1.83 V

Carbon = 2.5 / 0.13 V

The metals determine the battery voltage; they were separated with moist paper soaked in salt water.

Courtesy of Cadex

In the same year, Volta released his discovery of a continuous source of electricity to the Royal Society of London. No longer were experiments limited to a brief display of sparks that lasted a fraction of a second; an endless stream of electric current now seemed possible.

France was one of the first nations to officially recognize Volta's discoveries. This was during a time when France was approaching the height of scientific advancements. New ideas were welcomed with open arms as they helped to support the country's political agenda. In a series of lectures, Volta addressed the Institute of France. Napoleon Bonaparte participated in the experiments, drawing sparks from the battery, melting a steel wire, discharging an electric pistol and decomposing water into its elements (see Figure 1-4).

In 1800, Sir Humphry Davy, inventor of the miner's safety lamp, began testing the chemical effects of electricity and found out that decomposition occurred when passing electrical current through substances. This process was later called *electrolysis*.

He made new discoveries by installing the world's largest and most powerful electric battery in the vaults of the Royal Institution of London, connecting the battery to charcoal electrodes. Witnesses reported that his so-called voltaic arc lamp produced "the most brilliant ascending arch of light ever seen."



Figure 1-4: Volta's experimentations at the Institute of France.

Volta's discoveries so impressed the world that in November 1800, the Institute of France invited him to lecture at events in which Napoleon Bonaparte participated. Napoleon helped with the experiments, drawing sparks from the battery, melting a steel wire, discharging an electric pistol and decomposing water into its elements.

Courtesy of Cadex

In 1802, William Cruickshank designed the first electric battery for mass production. He arranged square sheets of copper with equal-sized sheets of zinc placed into a long rectangular wooden box and soldered together. Grooves in the box held the metal plates in position. The sealed box was then filled with an electrolyte of brine, or watered-down acid. This resembled the flooded battery that is still with us today. Figure 1-5 illustrates his battery workshop.



Figure 1-5: Cruickshank and the first flooded battery.

William Cruickshank, an English chemist, built a battery of electric cells by joining zinc and copper plates in a wooden box filled with an electrolyte solution. The flooded design did not dry out with use and provided more energy than Volta's disc arrangement.

Courtesy of Cadex

Invention of the Rechargeable Battery

In 1836, John F. Daniell, an English chemist, developed an improved battery that produced a steadier current than earlier attempts to store electrical energy. In 1859, the French physician Gaston Planté invented the first rechargeable battery based on lead acid, a system that is still used today. Until then, all batteries were

primary, meaning they could not be recharged.

In 1899, Waldmar Jungner from Sweden invented the nickel-cadmium (NiCd) battery that used nickel as the positive electrode (cathode) and cadmium as the negative (anode). High material costs compared to lead limited its use.

Two years later, Thomas Edison replaced cadmium with iron, and this battery was called nickel-iron (NiFe). Low specific energy (capacity), poor performance at low temperature and high self-discharge limited the success of the nickel-iron battery. It was not until 1932 that Schlecht and Ackermann achieved higher load currents and improved the longevity of NiCd by inventing the sintered pole plate. In 1947, Georg Neumann succeeded in sealing the cell.

For many years, NiCd was the only rechargeable battery for portable applications. In the 1990s, environmentalists in Europe became concerned about the harm incurred when NiCd is carelessly disposed. The Battery Directive 2006/66/EC now restricts the sale of NiCd batteries in the European Union except for specialty industrial use for which no replacement is suitable. The alternative is nickel-metal-hydride (NiMH), a more environmentally friendly battery that is similar to NiCd.

Most research activities today revolve around improving lithium-based systems, first commercialized by Sony in 1991. Besides powering cellular phones, laptops, digital cameras, power tools and medical devices, Li-ion is also used for electric vehicles and satellites. The battery has a number of benefits, most notably its high specific energy, simple charging, low maintenance and being environmentally benign.

Electricity Through Magnetism

Generating electricity through magnetism came relatively late. In 1820, André-Marie Ampère (1775–1836) noticed that wires carrying an electric current were at times attracted to, and at other times repelled from, one another. In 1831, Michael Faraday (1791–1867) demonstrated how a copper disc provided a constant flow of electricity while revolving in a strong magnetic field. Faraday, assisting Humphry Davy and his research team, succeeded in generating an

endless electrical force as long as the movement between a coil and magnet continued. This led to the invention of the electric generator, as well as the electric motor by reversing the process.

Shortly thereafter, transformers were developed that converted alternating current (AC) to any desired voltage. In 1833, Faraday established the foundation of electrochemistry on which Faraday's law is based. It relates to electromagnetism found in transformers, inductors and many types of electrical motors and generators. Once the relationship with magnetism was understood, large generators were built to produce a steady flow of electricity. Motors followed that enabled mechanical movement and Thomas Edison's light bulb appeared to conquer darkness.



Figure 1-6: Nikola Tesla (1856–1943).

Serbian-American physicist, inventor and engineer best known for alternating current supply systems and rotating magnetic fields.

Early electrical plants produced direct current (DC) with distribution limitations from the plant of no more than 3km (~2 miles) in distance. In around 1886, the Niagara Falls Power Company offered \$100,000 for a method to transmit electricity over a long distance. When no one responded, the world's brightest minds met in London, England. The prize was eventually given to Nikola Tesla (1856–1943), a Serbian immigrant who created the AC transmission system.

DC systems run on low voltage and require heavy wires; AC could be transformed to higher voltages for transmission over light wires and then reduced for use. Older folks supported DC while younger geniuses gravitated towards AC. Thomas Edison was dead set against AC, giving danger by electrocution as a reason.

The disagreement continued, but AC became the accepted norm that was also supported by Europe. George Westinghouse, an American inventor and manufacturer, began developing the Tesla system to the displeasure of Thomas Edison.

In 1883, Westinghouse created a lighting system for Niagara Falls using AC current and to everyone's amazement lit up the Chicago World's Fair in 1893. Westinghouse then built three large generators to transform energy from the Niagara Falls to electricity. Three-phase AC technology developed by Tesla enabled the transmission of electric power over great distances cheaply. Electricity was thus made widely available to humanity to improve the quality of life.

Telecommunications by wire strung along railways operated mostly by primary batteries that needed frequent replacement. Telex, an early means to transmit data, was digital in that the batteries activated a series of relays. The price to send a message was based on the number of relay clicks required.

In the mid-1800s, telegraphy opened new careers for bright young men. Staff operating these devices moved into the growing middle class, far removed from mills and mines burdened with labor, dirt and danger. Steel magnate Andrew Carnegie recalled his early days as a telegraphy messenger; Alfred

Hitchcock started his career as an estimator before becoming an illustrator.

The invention of the electronic vacuum tube in the early 1900s formed the significant next step towards high technology. It enabled frequency oscillators, signal amplifications and digital switching. This led to radio broadcasting in the 1920s and the first digital computer, called ENIAC, in 1946. The invention of the transistor in 1947 paved the way for the arrival of the integrated circuit 10 years later, and the microprocessor that ushered in the Information Age. This forever changed the way we live and work.

Early Innovators

Inventions are well documented and credit goes to the dignified inventors. Benjamin Franklin (1706–1790) invented the Franklin stove, bifocal eyeglasses and the lightning rod. He was unequaled in American history as an inventor until Thomas Edison emerged.

Edison was a good businessman who may have taken credit for earlier discoveries others had made. Contrary to popular belief, Edison did not invent the light bulb; he improved on a 50-year-old idea by using a small, carbonized filament lit up in a better vacuum. In the end, it was Edison who gained financial reward by making the concept commercially viable.

The phonograph is another invention for which Edison is credited, rightly or wrongly. The cylinder phonograph introduced in 1877 recorded and played back sound. He envisioned this invention becoming a business machine, eventually eliminating the written letter, but the public wanted to play music. Making multiple copies for sale from a cylinder posed a problem as a tenor needed to sing into 10 flaring horns to produce simultaneous recording.

It was Emile Berliner who initiated the transition from cylinders to discs to

enable mass production — and the gramophone was born. Master recordings were made on zinc plates that were electroplated, and a negative image was prepared to stamp multiple discs. Berliner records were 7 inches (177mm) in diameter and played for 2 minutes per side, running at 60–70 rpm.

The gramophones of 1896 were made by Philadelphia machinist Eldridge Johnson, who added a spring motor to drive the previously hand-rotated turntable. Berliner discs produced a louder sound than the Edison cylinders and the popularity of the gramophone grew. Berliner transferred his patents to Johnson, and the Victor Talking Machine Company was formed, also known as His Master's Voice. Much to Edison's surprise and annoyance, gramophone records became a hot consumer item as folks wanted to "own" recorded music from famous artists such as tenor Caruso. (Phonograph refers to "word"; gramophone is a trademark for a record player.)

Thomas Edison may be the best remembered inventor in the USA, but he lost out to Tesla's AC over DC as the electric power source, the Berliner gramophone disc over the cylindrical recording system, and lead acid over his much promoted nickel-iron battery for the electric vehicle. Nevertheless, Edison grew wealthy and lived in a mansion while Tesla struggled financially. None of the companies that Tesla started survived, while Edison's businesses amalgamated into the mighty General Electric in 1892. Edison was also connected with other well-known people in the industry, such as George Eastman, the founder of Kodak. This may be the reason for the many high-quality photos of these two fine gentlemen.

Countries often credit their own citizens for having made important inventions, whether deserved or not. When visiting museums in Europe, the USA and Japan, one sees such bestowment. The work to develop the car, x-ray machines, telephones, broadcast radio, TV and computers might have been done in parallel, not knowing of others' advancements at that time, and the rightful inventor is often not clearly known or identified.

Similar uncertainties exist with the invention of new battery systems, and

we give respect to research teams and organizations rather than individuals. Table 1-7 summarizes battery advancements and lists inventors when available.

Year	Inventor	Activity
1600	William Gilbert (UK)	Establishment of electrochemistry study
1745	Ewald Georg von Kleist (NL)	Invention of Leyden jar. Stores static electricity
1791	Luigi Galvani (Italy)	Discovery of "animal electricity"
1800	Alessandro Volta (Italy)	Invention of the voltaic cell (zinc, copper disks)
1802	William Cruickshank (UK)	First electric battery capable of mass production
1820	André-Marie Ampère (France)	Electricity through magnetism
1833	Michael Faraday (UK)	Announcement of Faraday's law
1836	John F. Daniell (UK)	Invention of the Daniell cell
1839	William Robert Grove (UK)	Invention of the fuel cell (H_2/O_2)
1859	Gaston Planté (France)	Invention of the lead acid battery
1868	Georges Leclanché (France)	Invention of the Leclanché cell (zinc-carbon)
1899	Waldemar Jungner (Sweden)	Invention of the nickel-cadmium battery
1901	Thomas A. Edison (USA)	Invention of the nickel-iron battery
1932	Schlecht & Ackermann (Germany)	Invention of the sintered pole plate
1947	Georg Neumann (Germany)	Successfully sealing the nickel-cadmium battery
1949	Lewis Urry, Eveready Battery	Invention of the alkaline-manganese battery
1970s	Group effort	Development of valve-regulated lead acid battery
1990	Group effort	Commercialization of nickel-metal-hydride battery
1991	Sony (Japan)	Commercialization of lithium-ion battery
1994	Bellcore (USA)	Commercialization of lithium-ion polymer
1996	Moli Energy (Canada)	Introduction of Li-ion with manganese cathode
1996	University of Texas (USA)	Identification of Li-phosphate ($LiFePO_4$)
2002	University of Montreal, Quebec Hydro, MIT, others	Improvement of Li-phosphate, nanotechnology, commercialization

Table 1-7: History of modern battery development. No new major battery system has entered the commercial market since the invention of Li-phosphate in 1996.

Global Battery Markets

According to The Freedonia Group, a Cleveland-based industry research firm, the world demand for primary and secondary batteries is forecasted to grow by 7.7 percent annually, amounting to US\$120 billion in 2019. The real growth lies

in secondary (rechargeable) batteries and according to Frost & Sullivan, secondary batteries account for 76.4 percent of the global market, a number that is expected to increase to 82.6 percent in 2015. The demand is driven by mobile phones and tablets. Earlier estimations over-estimated the demand for electric vehicles and the figures have since been adjusted downwards.

In 2009, primary batteries made up 23.6 percent of the global market, and Frost & Sullivan predicted a 7.4 percent decline by 2015. Non-rechargeable batteries are used in watches, electronic keys, remote controls, toys, flashlights, beacons and military devices in combat.

Overview of Battery Types

Batteries are classified by chemistry, and the most common are lithium-, lead-, and nickel-based systems. Figure 1-8 illustrates the distribution of these chemistries. At a 37 percent revenue share, Li-ion is the battery of choice for portable devices and the electric powertrain. There are no other systems that threaten its dominance today.

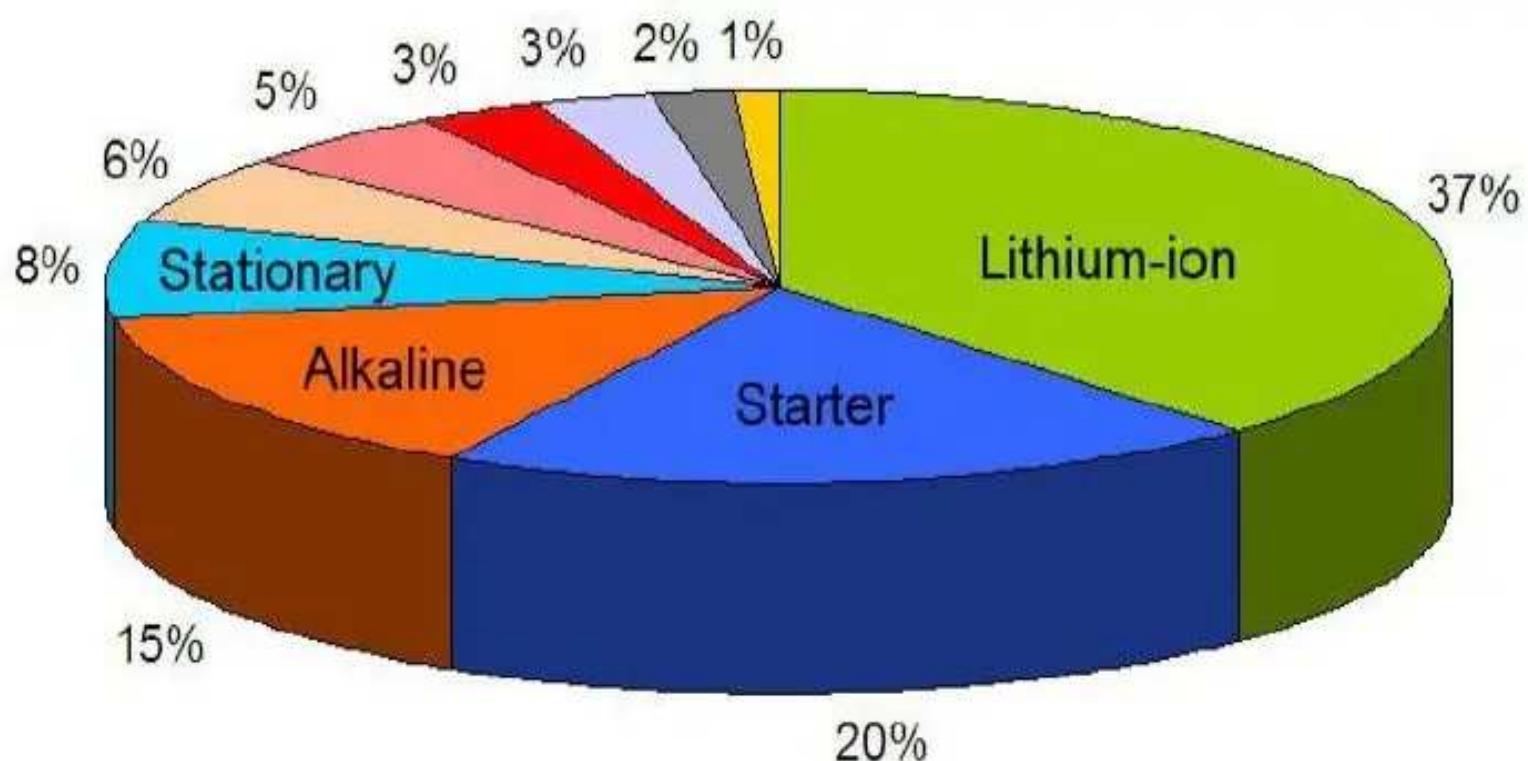


Figure 1-8: Revenue by battery chemistries.

37% Lithium-ion
20% Lead acid, starter battery

15% Alkaline, primary
8% Lead acid, stationary
6% Zinc-carbon, primary
5% Lead acid, deep-cycle
3% Nickel-metal-hydride
3% Lithium, primary
2% Nickel-cadmium
1% Other

Source: Frost & Sullivan (2009)

Lead acid stands its ground as being a robust and economical power source for bulk use. Even though Li-ion is making inroads into the lead acid market, the demand for lead acid batteries is still growing. The applications are divided into starter batteries for automotive, also known as SLI (20%), stationary batteries for power backup (8%), and deep-cycle batteries for wheeled mobility (5%) such as golf cars, wheelchairs and scissor lifts.

High specific energy and long storage have made alkaline more popular than the old zinc- carbon, which Georges Leclanché invented in 1868. Nickel-metal-hydride (NiMH) continues to hold an important role as it replaces applications previously served by nickel-cadmium (NiCd). However, at a 3 percent market share and declining, NiMH is becoming a minor player.

An emerging battery usage is the electric powertrain for personal transportation. Battery cost, longevity and environmental issues dictate how quickly the automotive sector will adopt this new propulsion system. Fossil fuel is cheap, convenient and readily available; alternative modes face stiff opposition, especially in North America. Government incentives may be needed, but such intervention distorts the true energy cost, shields underlying problems with fossil fuel and serves select lobby groups with short-term solutions. (See “Electric Powertrain” on page 305.)

New markets that further boost battery growth are the electric bicycle and storage systems for renewable energy, from which homeowners, businesses and developing nations are benefiting. Large grid storage batteries collect surplus energy during high activity and bridge the gap when the input is low or when

user demand is heavy. (See “Grid Storage Batteries” on page 304.)

Advancements in Batteries

Batteries are advancing on two fronts, reflecting in increased *specific energy* for longer runtimes and improved *specific power* for high-current load requirements. Improving one characteristic of the battery may not automatically strengthen the other and there is often a compromise. Figure 1-9 illustrates the relationship between specific energy in Wh/kg and specific power in W/kg.

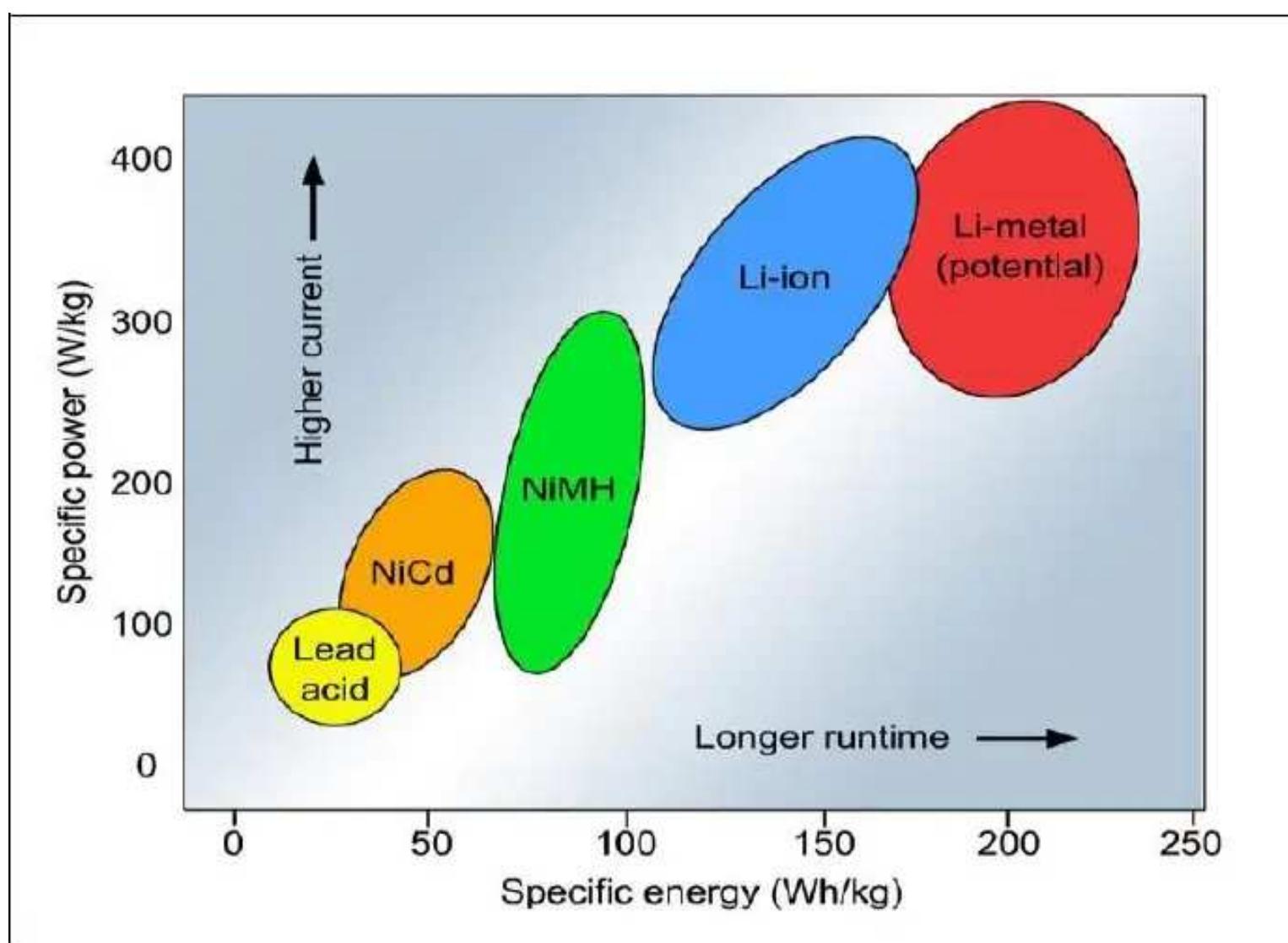


Figure 1-9: Specific energy and specific power of rechargeable batteries.

Specific energy is the capacity a battery can hold in watt-hours per kilogram (Wh/kg), and specific power is the battery’s ability to deliver power in watts per kilogram (W/kg).

The best performing battery in terms of specific energy and specific power is the secondary lithium-metal (Li-metal). An early version was introduced in the 1980s by then Moli Energy, but instability with metallic lithium on the anode

prompted a recall in 1991. Solid lithium tends to form metal filaments, or dendrites, that cause short circuits. Further attempts to solve this problem by other companies ended in discontinuing the developments.

The unique qualities of Li-metal are prompting manufacturers to revisit this powerful chemistry. Taming the dendrites and achieving the desired safety standard may be achieved by mixing metallic lithium with tin and silicon. Graphene is also being tried as part of an improved separator. Graphene is a thin layer of pure carbon with a thickness of one atom bonded together in a hexagonal honeycomb. (See “Graphite” on page 119.) Multi-layer separators that prevent the penetration of dendrites have also been tried. New experimental Li-metal batteries achieve 300Wh/kg and higher. This is of special interest for the electric vehicle.

Battery Breakthroughs: Myth or Fact?

The battery is increasingly promoted as a green energy solution to liberate society from the dependency of fossil fuel. While this is noble and right, the battery has not yet matured to assume this vital task. Pushing the boundaries of the battery reminds us of its many limitations by being an electrochemical power source that is slow to fill, holds limited energy, runs for a time like a wind-up toy, and has a short life span of only a few hundred cycles before it becomes a nuisance.

In an age where surprise developments flash before our eyes almost daily, the battery seems slow in maturing. Improvements achieved since the commercialization of lithium-ion in 1991 by Sony are pale compared to the vast advancements made in microelectronics. Compared to Moore’s Law, where the number of transistors in an integrated circuit doubles every two years, Li-ion only gained 8 percent capacity per year during the last two decades. This has slowed to 5 percent, but the good news is a cost reduction of 8 percent per year.

Progress is being made but not without roadblocks. Lithium-air, proposed in the 1970s with a theoretical specific energy resembling gasoline, has been delayed due to stability and air-purity issues as the battery “breathes” oxygen

from the air. The promising lithium-metal introduced in the 1980s still grows dendrites, leading to possible violent events if an electrical short develops. Lithium-sulfur may be close to commercialization, but scientists must still resolve the short cycle life. The redox-flow battery promises to be an alternative for large battery systems by pumping fluids from external tanks through a membrane that resembles a battery, but the system suffers from corrosion.

There is a glimmer of hope to increase the energy density of Li-ion by coating the anode with graphene, a layer that is only one atom thick. This is said to quadruple the energy. Emerging battery technologies take four years to commercialize, and there are no heavy lifters.

The Joint Centre for Energy Storage Research (JCESR) is more optimistic; they gathered the brightest minds from US national laboratories, universities and private enterprises to improve the battery. With a grant of \$120 million from the US Department of Energy, JCESR wants to develop a battery that is “five times more powerful and five times cheaper in five years.” They call this the 5-5-5 Plan, which should get a boost by throwing a ton of money at it.

Toyota is also in the race for a new battery, calling it the “Sakichi battery” after Sakichi Toyoda, the inventor of Japan’s power loom. (The surname Toyoda is spelled with a *d*.) Sakichi Toyoda is often called the father of the Japanese industrial revolution, and it is said that in 1925 he promised a yet-to-be-claimed prize of 1 million yen for a storage battery that produces more energy than gasoline. To qualify, the Sakichi battery must also be durable and quick to charge. The prize has not yet been claimed.

Consumers are generally satisfied with battery performance in portable devices, but the electric vehicle (EV) has a higher demand; cost and endurance will determine the long-term success. It’s as if the EV sets the threshold for how far the battery can go.

It makes little sense to use batteries to propel trains, ocean-going ships and large airplanes. Batteries are simply too heavy. If all engines and the fuel in an aircraft were to be replaced with batteries, the flight would last under 10 minutes

before the fuel would be exhausted. Competing against fossil fuel with a net calorific value that is 100 times higher than the battery is a challenge. (See “Net Calorific Value” on page 326.) Conversely, petroleum cannot match the battery, which is clean, quiet, small, and has an immediate start-up with the flick of a switch.

Getting to Know the Battery

Nature offers many ways to produce power. Most result through combustion, mechanical movement and photosynthesis, as in a solar cell. Electrical energy generation of the battery develops by an electrochemical reaction between two metals of different affinities. When exposed to acids, a voltage develops between the metals as part of ion transfer; closing the circuit induces a current. In 1800, inventor Alessandro Volta discovered that the voltage potential became stronger the farther apart the affinity numbers moved.

The simplest manifestation of a battery is a lemon. Driving a zinc-plated nail and a copper coin into a lemon creates a voltage, but this quasi battery does not deliver much power. Any electrical load causes the voltage to collapse and to light an incandescent flashlight bulb, 500 lemons are needed. The energy does not come from the lemon itself but from the chemical change in dissolving zinc into the acid or lemon juice. Figure 1-10 illustrates the lemon battery.

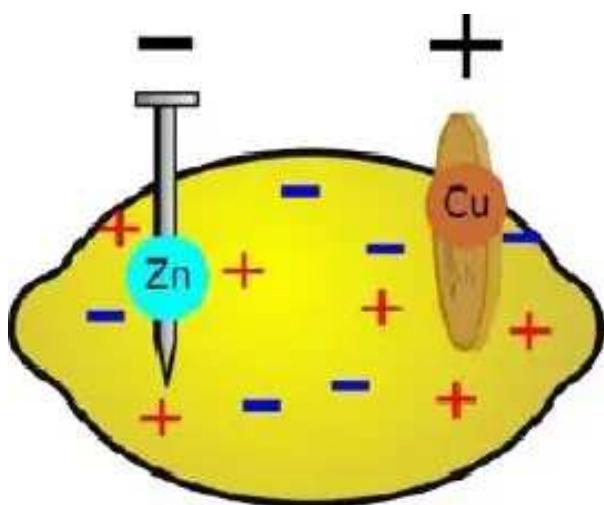


Figure 1-10: Lemon battery.

The experiment is often used for educational purposes. The electrodes are zinc in the form of a galvanized nail and copper in a coin. The lemon juice acts as electrolyte to induce a chemical reaction.

Standard potential of zinc = -0.76

Standard potential of copper = 0.34

Cell potential with conducting path = 1.10V

Elements with the greatest negative electrode potential serve as cathodes; those with the highest positive potential assist as anodes. The difference between the electrodes provides the *terminal voltage*. For a rechargeable battery to be practical, the chemical reactions between the elements must be reversible. To complicate matters further, chemical reactions between compounds cannot consume the active chemicals, and this limits the pool of suitable electrodes.

Multiplying the voltage by the current provides power. Power is measured in watts in honor of James Watt, the 18th-century developer of the steam engine. The amount of energy a battery can store is expressed in watt-hours (Wh).

All energy sources have limitations, and power must be harnessed carefully so as not to cause an overload. An analogy is a bicycle rider (Figure 1-11) who chooses the best gear ratio to transfer power into propulsion. On a flat road, a high gear provides high speed with moderate pedal torque simulating high voltage. Climbing a hill, the pedal torque increases while the speed decreases. This, in our analogy, results in a lower voltage and higher current. The pedal force the rider exerts relates to torque in newton meter (Nm); the endurance before exhaustion defines energy in watt-hours (Wh).



Figure 1-11: Analogy of a bicycle rider.

Energy is the product of power and time, measured in watt-hours (Wh); power is the flow of energy at any one time, measured in watts (W).

A battery is rated in ampere-hours (Ah). This specifies how much charge a pack can hold. Like fluid in a container, the energy can be dispensed slowly over a long period of time or rapidly in a short time. The amount of liquid a container holds is analogous to the energy in a battery; how quickly the liquid is dispensed is analogous to power.

The physical dimensions are specified by volume in liters (l) and kilograms (kg). Adding dimension and weight provides *specific energy* in Wh/kg, *power density* in W/l and *specific power* in W/kg. Most batteries are rated in Wh/kg, revealing how much energy a given weight can generate. Wh/l denotes watt-hours per liter. (See “Battery Definitions” on page 35.)

Batteries are custom-fit for a specific use, and manufacturers are well in tune with customer needs. Mobile phone and EV markets are examples of clever adaptations at opposite extremes. While batteries for consumer products emphasize small size, high specific energy and low cost, industrial batteries strive for reliable performance and long life. Safety in all applications is of utmost importance.

The Octagon Battery

A battery has some of the most stringent requirements and is on par with complex pharmaceutical products for which one change can have multiple side effects. To make a battery viable as an electric storage device, eight basic requirements must be met and a battery is fittingly called the *octagon battery* (Figure 1-12). The eight key elements to a working battery are as follows.



Figure 1-12: Octagon battery.

So-called because of the eight critical requirements needed to achieve basic function. Many new arrivals claim to meet or exceed some prerequisites but fail in others, limiting market acceptance.

Courtesy of Cadex

1. **High specific energy**
A key feature in consumer products is long runtime, and device manufacturers achieve this by building batteries with high ampere-hours (Ah). The term *lithium-ion* is synonymous with a high specific energy. This does not mean that all Li-ion batteries have high Ah ratings. While the Energy Cell in an 18650 package can have 250Ah/kg, the same chemistry in a Power Cell is 150Ah/kg or less, and a long-life Li-ion for the powertrain is as low as 60Ah/kg. Furthermore, consumer NiMH has about 90Ah/kg compared to a 45Ah/kg for long-life units in the electric powertrain, 45Ah/kg being almost par with lead acid.
2. **High specific power**
Batteries made for power tools and electric powertrains provide high load capabilities but the specific energy is low.
3. **Affordable price**
Materials, refining processes, manufacturing, quality control and cell matching add cost to battery manufacturing; volume production only assists in part to reduce costs. Single cell use in mobile phones when no cell matching is required also lowers costs.
4. **Long life**

Nowhere is longevity more important than in large, expensive battery packs. If the battery life of the electric car could be extended from the

anticipated 8–10 years to 20 years, driving an EV could be justified even if the initial investment is high. Longevity does not depend on battery design alone but also on how the battery is used. Adverse temperature, fast charge times and harsh discharge conditions stress the battery.

5. **Safe usage**

Lithium-based batteries can be built with high specific energy, but these systems are often reactive and unstable. Nickel-based Li-ion is such an example, so is metallic lithium. Most manufacturers stopped production of these systems because of safety issues. When used correctly, brand-name Li-ion is very safe.

6. **Wide operating range**

Batteries perform best at room temperature as cold temperatures slow the electrochemical reaction of all batteries. Li-ion cannot be charged below freezing, and heating blankets are often added to facilitate charging. High heat shortens battery life and compromises safety.

7. **Low toxicity**

Cadmium- and mercury-based batteries have been replaced with alternative metals for environmental reasons. Authorities in Europe are attempting to ban lead acid, but no economical replacement of similar performance is available. Nickel- and lithium-based batteries contain little toxic material, but they still pose a hazard if disposed carelessly.

8. **Fast charging**

Lithium- and nickel-based batteries should be charged at 1C or slower (See “What Is C-rate” on page 131.) At 1C, a nickel-based battery fully charges in about 90 minutes and Li-ion in 2–3 hours. Lead acid cannot be fast charged and the charge time is 8–16 hours. Fast charge times are possible for nickel and lithium, but the batteries must be built for it, be in good condition and be charged at room temperature. Aged and mismatched cells do not lend themselves to fast charging. Any charge above 1C causes undue stress, especially on the Energy Cell, and this should be avoided. (See “Ultra-fast Charging” on page 129.) NiCd is the only battery that accepts ultra-fast charge with minimal stress.

In addition to the eight basic requirements of the octagon battery, a battery must have low self-discharge to allow long storage and provide an instant start-up when needed. All batteries have self-discharge, and the loss increases with

temperature and age. Secondary batteries have a higher self-discharge rate than the primary equivalent. A further requirement is a long shelf life with little performance degradation. A battery is perishable, and like a food product it is only good for a time. While alkaline batteries can be stored for 10 years and still provide 70 percent charge, secondary batteries permanently lose capacity with age, even if not used.

Comparing the Battery with Other Power Sources

One hears of wonderful improvements in battery technologies, each offering distinct benefits, but none providing a fully satisfactory solution to all of today's energy needs. Though the battery has many advantages over other energy sources, it also has major limitations that need addressing.

Energy storage

Batteries store energy reasonably well and for a long time. Primary batteries (non-rechargeable) hold more energy than secondary (rechargeable) and self-discharge is lower. Lead-, nickel- and lithium-based batteries need periodic recharges to compensate for lost energy.

Specific energy (capacity)

Compared to fossil fuel, the energy storage capability of the battery is less impressive. The energy by mass of gasoline is over 12,000Wh/kg. In contrast a modern Li-ion battery carries only about 200Wh/kg. However, the battery has the advantage of delivering energy more effectively than a thermal engine.

Responsiveness

Batteries have a large advantage over other power sources by being ready to deliver on short notice — think of the quick action of the camera flash! There is no warm-up, as is the case with the internal combustion engine (ICE); battery power flows within a fraction of a second. In comparison, a jet engine takes several seconds to rev up, a fuel cell requires a few minutes to gain power, and the cold steam engine of a locomotive needs hours to build up steam.

Power bandwidth

Most rechargeable batteries have a wide power bandwidth, meaning that they can effectively handle small and large loads, a quality that is shared with the diesel engine. In comparison, the bandwidth of the fuel cell is narrow and works best within a specific load. So does the jet engine, which operates most efficiently at a defined revolution-per-minute (RPM).

Environment

The battery runs clean and stays reasonably cool. Most sealed cells have no vents, run quietly and do not vibrate. This is in sharp contrast with the ICE and large fuel cells that require compressors and cooling fans. The ICE also needs air intake and provision to exhaust toxic gases.

Efficiency

The battery is highly efficient. Li-ion has 99 percent charge efficiency, and the discharge loss is small. In comparison, the energy efficiency of the fuel cell is 20–60 percent, and the ICE is 25–30 percent. At optimal air intake speed and temperature, the GE90-115 on the Boeing 777 jetliner achieves an efficiency of 37 percent. (The charge efficiency of a battery is connected with the ability to accept charge. See also “Coulombic Efficiency” on page 255.)

Installation

The sealed battery operates in any position and offers good shock and vibration tolerance. Most ICEs must be positioned in the upright position and mounted on shock-absorbing dampers to reduce vibration. Thermal engines also need an air intake manifold and an exhaust muffler.

Operating cost

Lithium- and nickel-based batteries are best suited for portable devices; lead acid batteries are economical for wheeled mobility and stationary applications. Price and weight make batteries impractical for the electric powertrain in larger vehicles. The cost of drawing energy from a battery is about three times higher than getting it off the AC grid. The calculation includes the cost of the battery, charging it from the grid and budgeting for an eventual replacement. (See “Cost of Mobile Power” on page 321.)

Maintenance

With the exception of watering of flooded lead batteries and exercising NiCds to prevent “memory,” rechargeable batteries are low maintenance. Service includes cleaning the corrosion buildup on the outside terminals and applying periodic performance checks.

Service life

The rechargeable battery has a relatively short service life and ages even if not in use. The 3- to 5-year lifespan is satisfactory for consumer products, but this is not acceptable for larger batteries. Hybrid and electric vehicle batteries are guaranteed for 8–10 years; the fuel cell delivers 2,000–5,000 hours of service, and depending on temperature, large stationary batteries are good for 5–20 years.

Temperature extremes

Like molasses, cold temperatures slow the electrochemical reaction and batteries do not perform well below freezing. The fuel cell shares the same problem, but the internal combustion engine does well once warmed up. Fast charging must always be done above freezing. Operating at a high temperature provides a performance boost, but this causes rapid aging due to added stress.

Charge time

Here, the battery has an undisputed disadvantage. Lithium- and nickel-based systems take 1–3 hours to charge; lead acid typically takes 14 hours. In comparison, filling up a vehicle with fuel takes only a few minutes. Although some electric vehicles can be charged to 80 percent in less than one hour on a high-power outlet, Li-ion batteries get stressed on ultra-fast charges.

Disposal

Nickel-cadmium and lead acid batteries contain hazardous material and cannot be disposed of in landfills. Nickel-metal-hydride and lithium systems are environmentally friendly and can in small quantities be included with regular household items, but authorities recommend that all batteries be recycled.

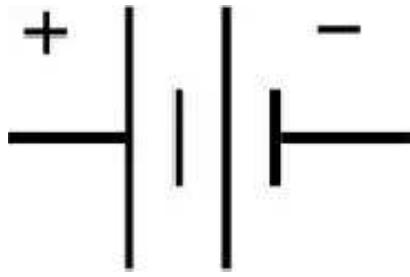
Battery Building Blocks

An electrochemical battery consists of a cathode, an anode and electrolyte that acts as a catalyst. When charging, a buildup of electrons forms on the cathode, creating a voltage potential between the cathode and the anode. Release is by a passing current from the positive cathode through an external load and back to the negative anode. On charge, the current flows in the other direction.

A battery has two separate pathways; one is the electric circuit through which electrons flow, feeding the load, and the other is the path where ions move between the electrodes through the separator that acts as an insulator for electrons. Ions are atoms that have lost or gained electrons and have become electrically charged. The separator electrically isolates the electrodes but allows the movement of ions.

Anode and Cathode

The electrode of a battery that releases electrons during discharge is called the *anode*; the electrode that absorbs the electrons is the *cathode*.



Battery symbol.

The cathode of a battery is positive; the anode is negative.

The battery anode is always negative and the cathode is positive. This seems to violate the convention as the anode is the terminal into which current flows. A vacuum tube, diode or a battery on charge follows this convention; however, taking power away from a battery on discharge turns the anode into negative. Since the battery is an electric storage device providing energy, the designation does not change between charging and discharging. The battery anode is always *negative*.

Tables 1-13a, b, c and d summarize the components of lead-, nickel- and lithium-based secondary batteries, including the primary alkaline.

Lead acid	Cathode (positive)	Anode (negative)	Electrolyte
Material	Lead dioxide (chocolate brown)	Porous lead, (spongy when formed)	Sulfuric acid (H_2SO_4)
Full charge	Lead oxide (PbO_2), electrons added to positive plate	Lead (Pb), electrons removed from plate	Strong sulfuric acid
Discharged	Lead turns into lead sulfate at the negative electrode, electrons driven from positive plate to negative plate		Weak sulfuric acid (water-like)

Table 1-13a: Composition of lead acid.

NiMH, NiCd	Cathode (positive)	Anode (negative)	Electrolyte
Material	Nickel oxyhydroxide	NiMH: Hydrogen-absorbing alloy NiCd: Cadmium	Potassium hydroxide

Table 1-13b: Composition of NiMH and NiCd.

Lithium-ion	Cathode (positive) on copper foil	Anode (negative) on aluminum foil	Electrolyte
Material	Metal oxides derived from cobalt, nickel, manganese, iron, aluminum	Carbon based	Lithium salt in an organic solvent
Full charge	Metal oxide with intercalation structure	Lithium ions migrate to the anode	
Discharged	Lithium ions move back to the positive electrode	Mainly carbon	

Table 1-13c: Composition of Li-ion.

Alkaline	Cathode (positive)	Anode (negative)	Electrolyte
Material	Manganese dioxide	Zinc	Aqueous alkaline

Table 1-13d: Composition of primary alkaline battery.

Electrolyte and Separator

Ion flow is made possible with an activator called the electrolyte. In a flooded battery system, the electrolyte moves freely between the inserted electrodes; in a sealed cell, the electrolyte is normally added to the separator in a moistened form. The separator segregates the anode from the cathode, forming an isolator for electrons but allowing ions to pass through. (See “Battery Separator” on page

114 and “Electrolyte” both on page 116.)

Battery Definitions

Batteries are specified by three main characteristics: chemistry, voltage and specific energy (capacity). A starter battery also provides cold cranking amps (CCA), which relates to the ability to provide high current at cold temperatures.

Chemistry: The most common battery chemistries are lead, nickel and lithium, and each system needs a designated charger. Charging a battery on a charger designed for a different chemistry may appear to work at first but might fail to terminate the charge correctly. Observe the chemistry when shipping and disposing of batteries as each chemistry has a different regulatory requirement.

Voltage: Batteries are marked with nominal voltage; however, the open circuit voltage (OCV) on a fully charged battery is 5–7 percent higher. Chemistry and the number of cells connected in series provide the OCV. The closed circuit voltage (CCV) is the operating voltage. Always check for the correct nominal voltage before connecting a battery.

Capacity: Capacity represents specific energy in ampere-hours (Ah). Ah is the discharge current a battery can deliver over time. You can install a battery with a higher Ah than specified and get a longer runtime; you can also use a slightly smaller pack and expect a shorter runtime. Chargers have some tolerance as to Ah rating (with same voltage and chemistry); a larger battery will simply take longer to charge than a smaller pack, but the Ah discrepancy should not exceed 25 percent. European starter batteries are marked in Ah; North America uses Reserve Capacity (RC). RC reflects the discharge time in minutes at a 25A discharge. (See “Reserve Capacity” in the Glossary on page 337.)

Cold cranking amps (CCA): Starter batteries, also known as SLI (starter light ignition) are marked with CCA. The number indicates the current in ampere that the battery can deliver at -18°C (0°F). American and European norms

differ slightly. (See definitions and specifications of BCI, DIN, IEC norms starting on page 340 under “Abbreviation / Conversion.” See also “How to Measure CCA” on page 268.)

Specific energy and energy density: Specific energy, or gravimetric energy density, defines battery capacity in weight (Wh/kg); energy density, or volumetric energy density, reflects volume in liters (Wh/l). Products requiring long runtimes at moderate load are optimized for high specific energy; the ability to deliver high current loads can be ignored.

Specific power: Specific power, or gravimetric power density, indicates loading capability. Batteries for power tools are made for high specific power and come with reduced specific energy (capacity). Figure 1-14 illustrates the relationship between specific energy (water in bottle) and specific power (spout opening).

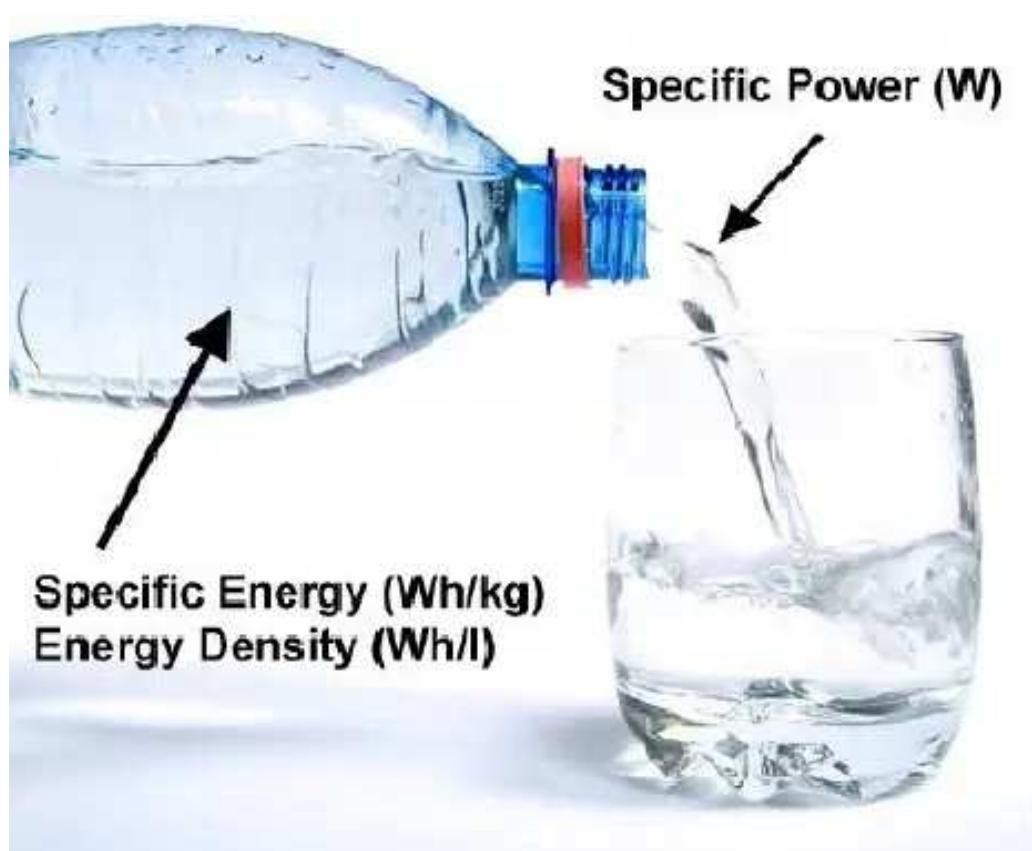


Figure 1-14: Relationship between specific energy and specific power.

The water in the bottle represents specific energy (capacity); the spout pouring the water governs specific power (loading).

A battery can have high specific energy but poor specific power as is the case with the alkaline battery, or low specific energy but high specific power as with the supercapacitor.

C-rate: The C-rate specifies the speed a battery is charged or discharged. At 1C, the battery charges and discharges at a current that is on par with the marked Ah rating. At 0.5C, the current is half and the time is doubled, and at 0.1C the current is one-tenth and the time is 10-fold. (More in “What Is C-rate?” on page 131.)

Load: A load defines the current that is drawn from the battery. Internal battery resistance and depleting state-of-charge (SoC) cause the voltage to drop under load, triggering end of discharge. *Power* relates to current delivery measured in watts (W); *energy* is the physical work over time measured in watt-hours (Wh).

Watts and Volt-amps (VA): Watt is *real power* that is being metered; VA is the *apparent power* that is affected by a reactive load. On a purely resistive load, watt and VA readings are alike; a reactive load such as an inductive motor or fluorescent light causes a phase shift between voltage and current that lowers the power factor (pf) from the ideal one (1) to 0.7 or lower. The sizing of electrical wiring and the circuit breakers must be based on VA power.

Primary Batteries

Primary batteries, also known as non-rechargeable batteries, tend to get overshadowed by the media attention secondary or rechargeable batteries receive. Heavy focus on one product over another may convince folks that primary batteries are old technology on the way out. Not so.

Primaries play an important role, especially when charging is impractical or impossible, such as in military combat, rescue missions and forest-fire services. Regulated under IEC 60086, primary batteries also service pacemakers in heart patients, tire pressure gauges in vehicles, smart meters, intelligent drill bits in mining, animal-tracking, remote light beacons, as well as wristwatches, remote controls, electric keys and children’s toys.

Most implantable pacemaker batteries are lithium-based, draw only 10–20

microamperes (μ A) and last 5–10 years. Many hearing aid batteries are also primary with a capacity from 70–600mAh, good for 5–14 days before a replacement is needed. The rechargeable version offers less capacity per size and lasts for about 20 hours. Cost-saving is the major advantage.

High specific energy, long storage times and instant readiness give primary batteries a unique advantage. They can be carried to remote locations and used instantly, even after long storage; they are also readily available and environmentally friendly when disposed.

The most popular primary battery is alkaline. It has a high specific energy and is cost effective, environmentally friendly and leak-proof even when fully discharged. Alkaline can be stored for up to 10 years, has a good safety record and can be carried on an aircraft without being subject to UN Transport and other regulations. The negative is low load currents, limiting its use to light loads such as remote controls, flashlights and portable entertainment devices.

Moving into higher capacities and better loading leads to lithium-metal batteries. These have very strict air shipping guidelines and are subject to Dangerous Good Regulations involving Class 9 hazardous material. Figure 1-15 compares the specific energy of lead acid, NiMH and Li-ion as secondary, as well as alkaline and lithium-metal serving as primary batteries.

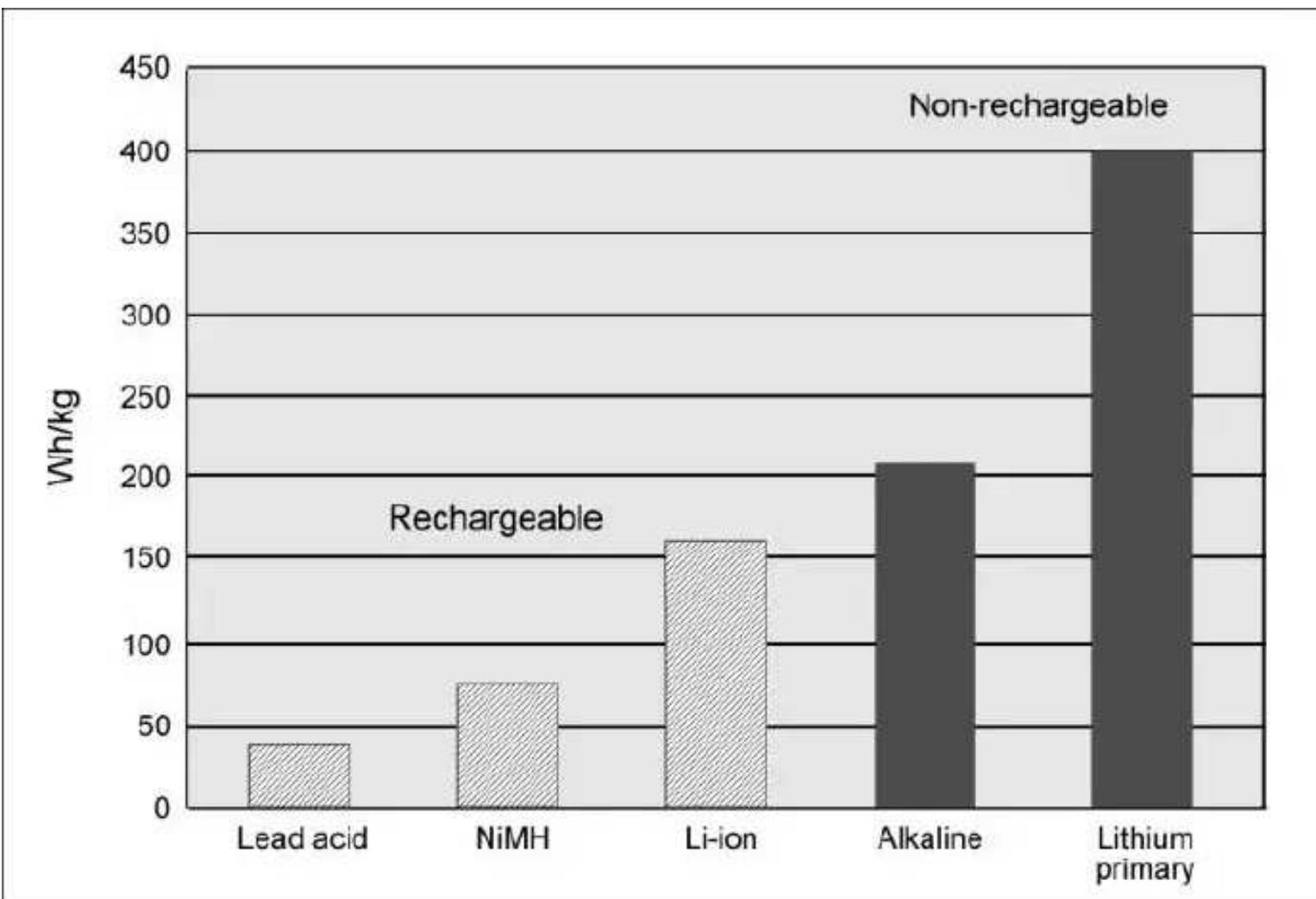


Figure 1-15: Specific energy comparison of secondary and primary batteries.

Secondary batteries are typically rated at 1C; alkaline uses lower discharge currents.

Courtesy of Cadex

Specific energy only indicates the capacity a battery can hold and does not include power delivery, a weakness with most primary batteries. Manufacturers

of primary batteries publish specific energy; specific power is seldom published. While most secondary batteries are rated at a 1C discharge current, the capacity on consumer-grade primary batteries is measured with a very low current of 25mA. In addition, the batteries are allowed to discharge from the nominal 1.5V for alkaline to 0.8V before deemed fully discharged. This provides impressive readings on paper, but the results are less flattering when applying loads that draw higher currents.

Figure 1-16 compares the performance of primary and secondary batteries as “Rated” and “Actual.” *Rated* refers to the specific energy when discharging at a very low current; *Actual* discharges at 1C, the way most secondary batteries

are rated. The figure clearly demonstrates that the primary alkaline performs well with light load typical to entertainment devices, while the secondary batteries represented by lead acid, NiMH and Li-ion have a lower rated capacity (Rated) but are better when being loaded with a 1C discharge (Actual).

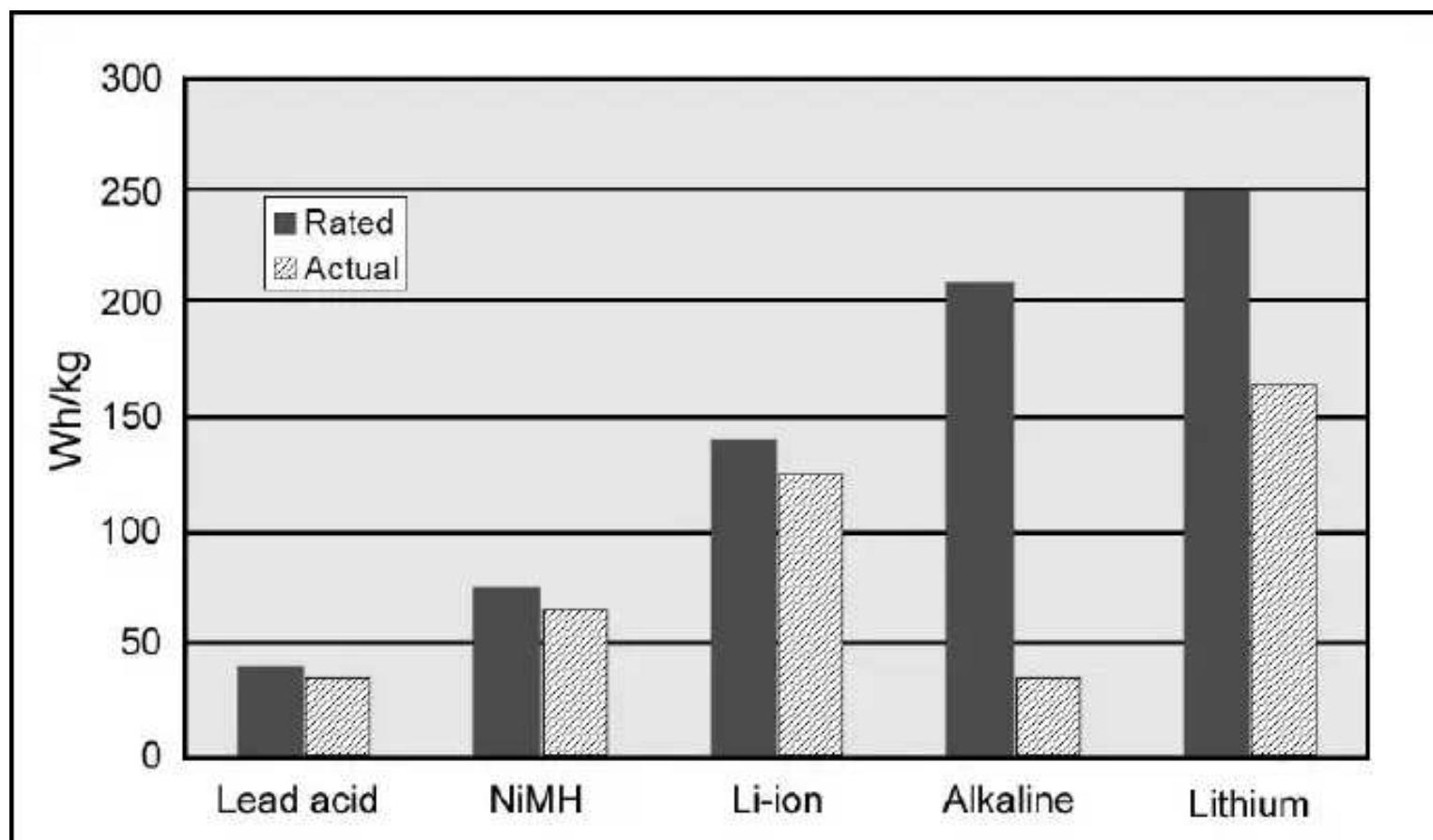


Figure 1-16: Comparing energy and power under load.

“Rated” refers to a mild discharge; “Actual” is a load at 1C. High internal resistance limits alkaline battery to light loads.

Courtesy of Cadex

One of the reasons for low performance under load conditions is the high internal resistance of primary batteries, which causes the voltage to collapse. Resistance determines how well electrical current flows through a material or device and is measured in ohms (Ω). As the battery depletes on discharge, the already elevated resistance increases further. Digital cameras with primary batteries are borderline cases — a power tool on alkaline would be impractical. A spent alkaline in a digital camera often leaves enough energy to run the kitchen clock for two years.

Table 1-17 illustrates the capacity of standard alkaline batteries with loads that run typical personal entertainment devices or small flashlights.

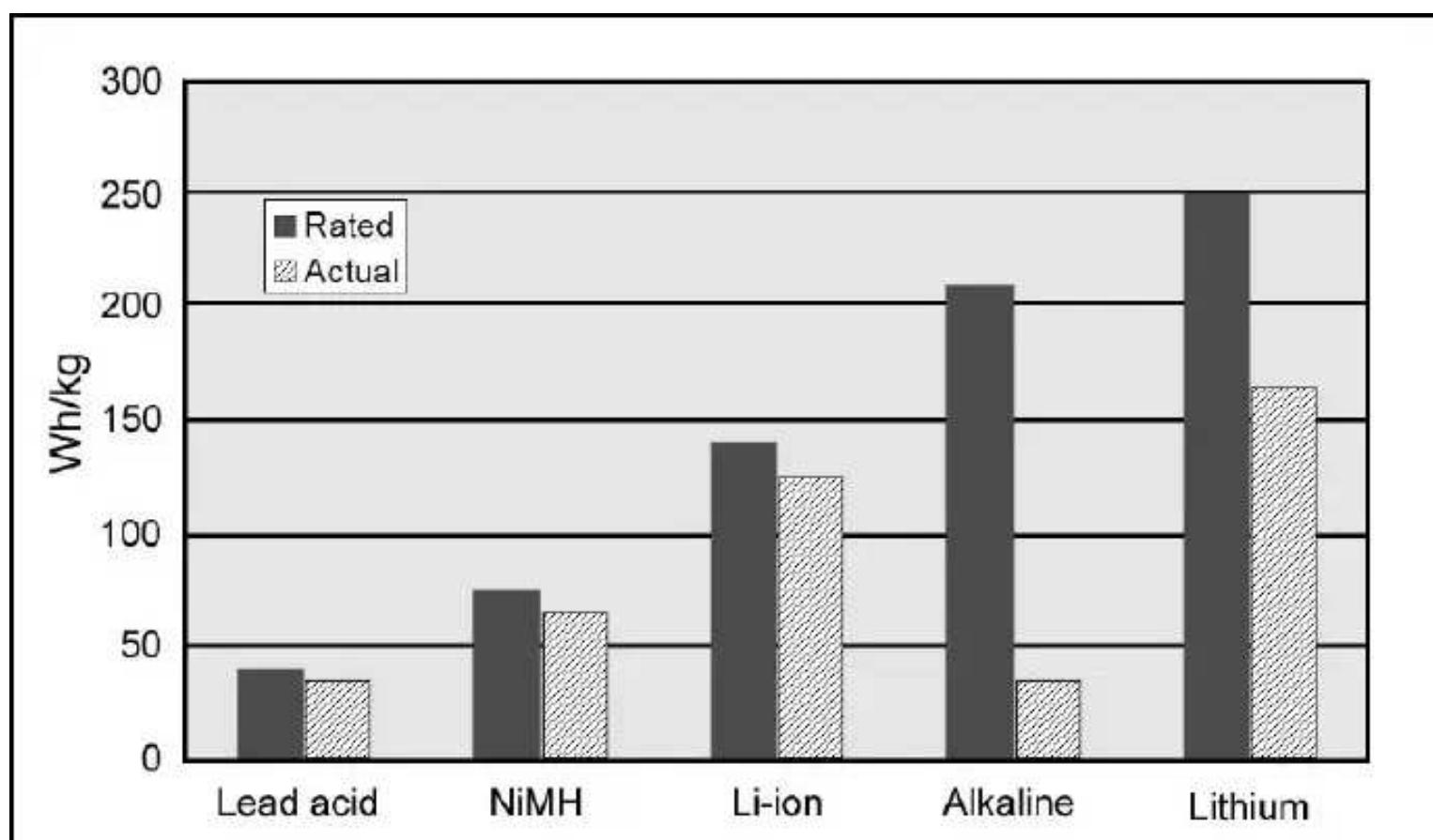


Table 1-17: Alkaline specifications. The discharge resembles entertainment devices with low loads.

Source: Panasonic

Note: Resistance can also be measured in siemens (s) units, which is equal to reciprocal ohm.

AA and AAA are the most common cell formats for primary batteries.

Known as penlight batteries for pocket lights, the AA became available to the public in 1915 and was used as a spy tool during World War I; the American National Standards Institute standardized the format in 1947. The AAA was developed in 1954 to reduce the size of the Kodak and Polaroid cameras and shrink other portable devices. In the 1990s, an offshoot of the 9V battery produced the AAAA for laser pointers, LED penlights, computer styli and headphone amplifiers. (The 9V uses six AAAA in series.) Table 1-18 compares common primary batteries.

	Zinc-carbon	Alkaline	Lithium (LiFeS ₂)	NiCd	NiMH
Capacity AA	400-1,700	1,800-2,600	2,500-3,400	600-1,000	800-2,700
AAA	~300	800-1,200	1,200	300-500	600-1,250
Nominal V	1.50	1.50	1.50	1.20	1.20
Discharge rate	Very low	Low	Medium	Very high	High
Rechargeable	No	No	No	Yes	Yes
Shelf life	1-2 years	7 years	10-15 years	5 years	5 years
Retail AA (2015) AAA	Not in all stores	\$0.75 \$1.00	\$3.00-5.00 \$4.00-5.00	Not in all stores	\$1.60-2.00 \$1.00

Table 1-18: Summary of batteries available in AA and AAA format

The AA cell contains roughly twice the capacity of the smaller AAA at a similar price. This doubles the energy cost of the AAA over the AA. Energy cost often takes second stage in preference to downsizing. This is the case with bicycle lights where the AA format would only increase the size of the light slightly but could deliver twice the runtime for the same cost.

To cut cost, cities often consolidate purchases and this includes bulk acquisitions of alkaline batteries. A city the size of Vancouver, Canada, with about 600,000 citizens would buy roughly 33,000 AA, 16,000 AAA, 4,500 C and 5,600 D size alkaline cells for general use.

Retail prices of the alkaline AA vary, so does performance. Exponent Inc. a US engineering firm, checked the capacity of eight brand-name alkaline batteries in AA packages and discovered an 800 percent discrepancy between the highest and lowest performers. The test standard was based on counting the shots of a digital camera until the batteries were depleted, a test that considered capacity and loading capability of a battery.

Figure 1-19 illustrates the number of shots a digital camera can take with discharge pulses of 1.3W using alkaline, NiMH and Lithium LiFeS₂ in an AA format. (With two cells in series at 3V, 1.3W draws 433mA.) The clear winner was LiFeS₂ (Lithium AA) with 690 pulses; the second was NiMH with 520 pulses; and the distant third was standard alkaline, producing only 85 pulses. Internal resistance rather than capacity governs the shot count. (See "How to

Rate Battery Runtime” on page 217.)

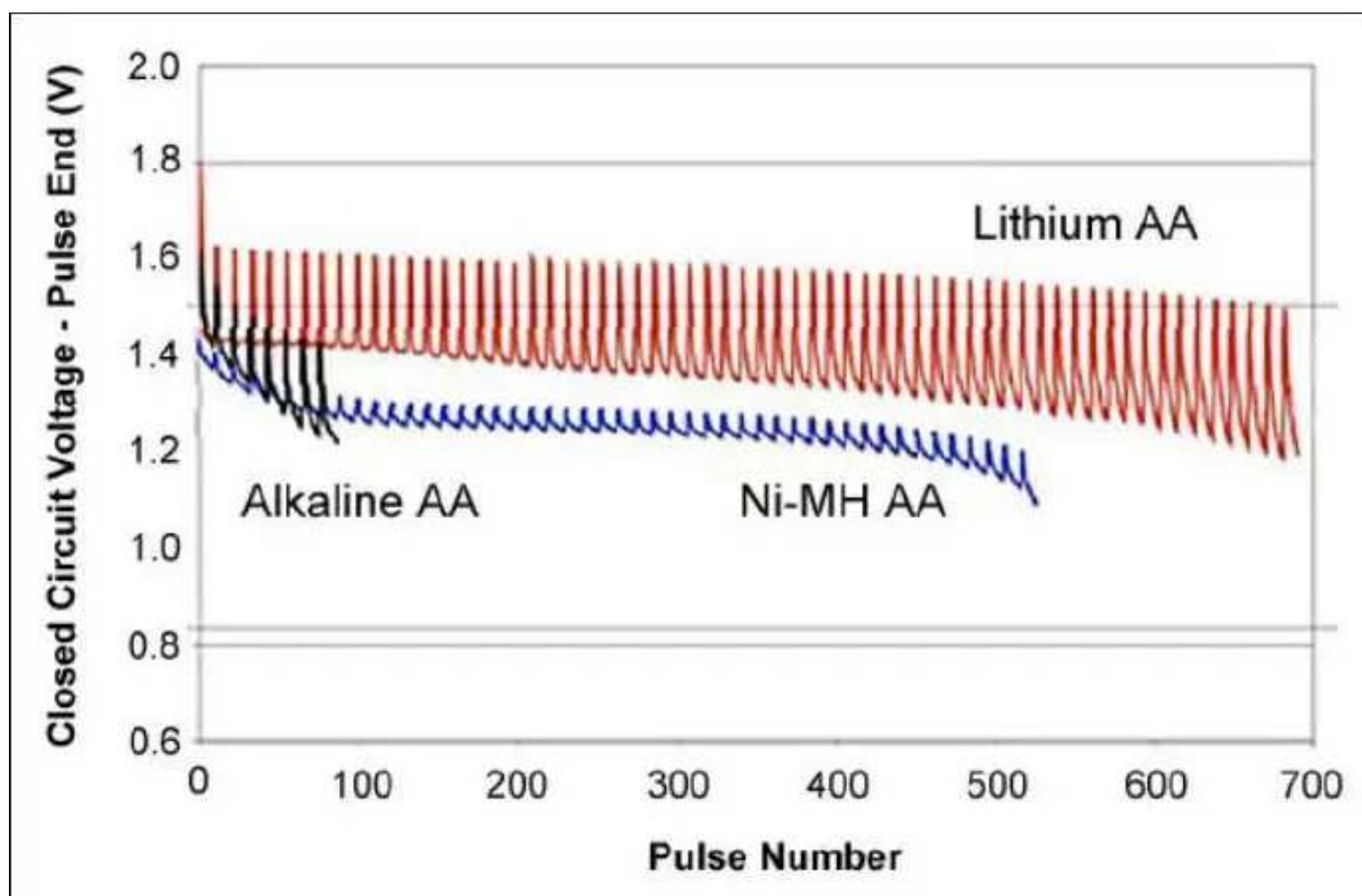


Figure 1-19: Number of shots a digital camera can take with alkaline, NiMH and lithium.

LiFeS₂, NiMH and alkaline have similar capacities; the internal resistance governs the shot count on a digital camera.

LiFeS₂, 3Ah, 690 pulses

NiMH, 2.5Ah, 520 pulses

Alkaline, 3Ah, 85 pulses
Test: ANSI C18.1

Source: Exponent Inc.

The relationship between battery capacity and current delivery is best illustrated with the Ragone chart. Named after David V. Ragone, the Ragone chart evaluates an energy storage device on energy and power. Energy in Ah presents the available storage capacity of a battery that is responsible for the runtime; power in watts governs the load current.

Figure 1-20 illustrates the Ragone chart with the 1.3W load of a digital

camera (indicated by the arrow and dotted line) using lithium (LiFeS_2), NiMH and alkaline. The horizontal axis displays energy in Wh and the vertical axis provides power in watts. The scale is logarithmic to allow a wide selection of battery sizes.

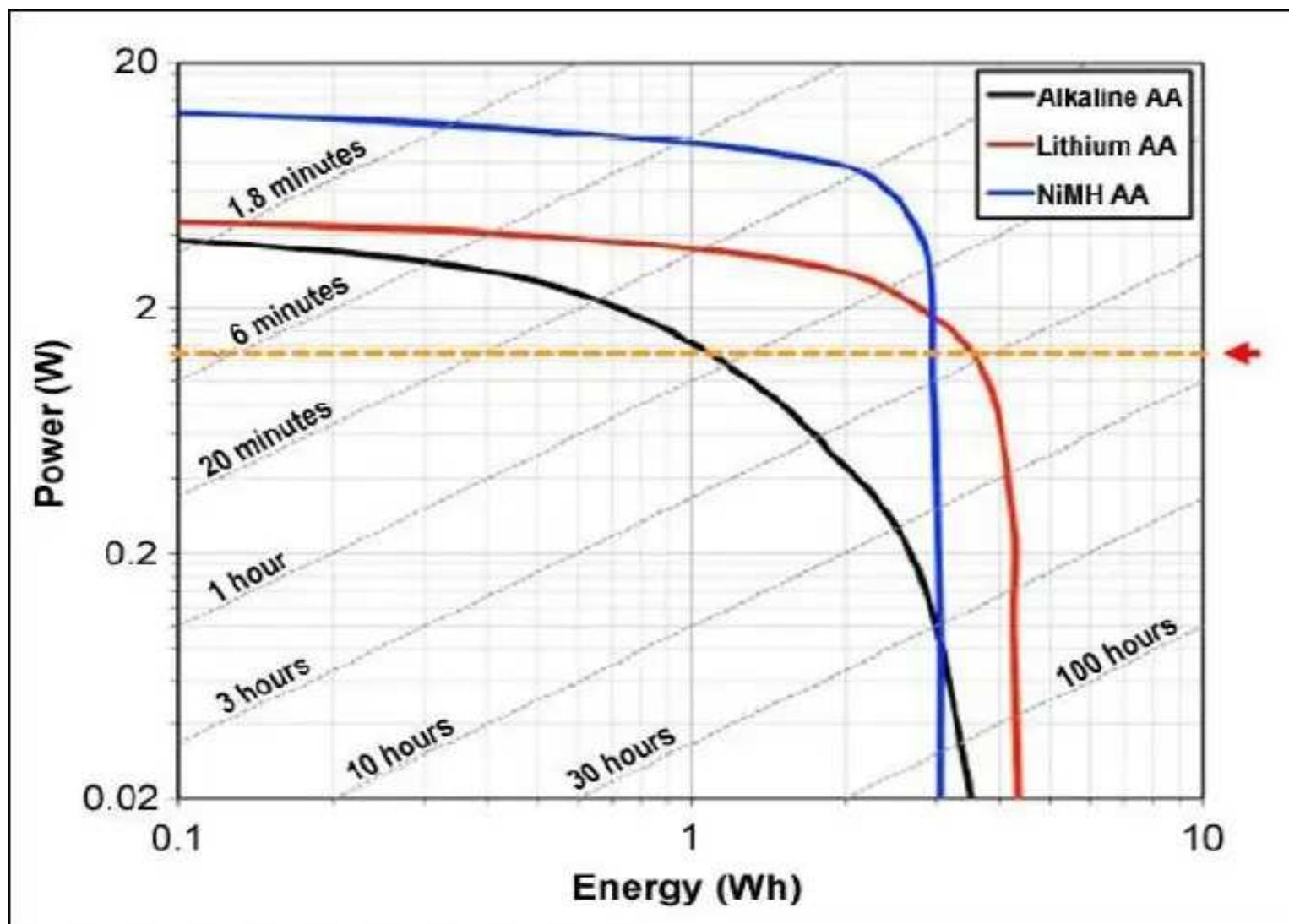


Figure 1-20: Ragone chart illustrates battery performance with various load conditions.
Digital camera loads NiMH, LiFeS_2 and alkaline with 1.3W pulses according to ANSI C18.1 (dotted line).
The results are:

- LiFeS_2 690 pulses
- NiMH 520 pulses
- Alkaline 85 pulses

$$\text{Energy} = \text{Capacity} \times V$$

$$\text{Power} = \text{Current} \times V$$

Source: Quinn Horn, Exponent Inc.

The performance of the battery chemistries varies according to the position of the Ragone line. NiMH delivers the highest power and works well at high

loads but it has the lowest specific energy. Lithium LiFeS₂ has the highest specific energy and satisfies moderate loading conditions, and alkaline offers an economic solution for lower current drains.

Summary

Primary batteries are practical for applications that draw occasional power, but they can get expensive when in continuous use. Price is a further issue when the packs are replaced after each mission, regardless of length of use. Discarding partially used batteries is common, especially in fleet applications and critical missions as it is convenient to simply issue fresh packs with each assignment rather than estimating the usage. At a battery conference a US Army general said that half of the batteries discarded still have 50 percent energy left.

The state-of-charge of primary batteries can be estimated by measuring the internal resistance. Each battery type needs its own look-up table as the resistive characteristics may differ. A more accurate method is coulomb counting that observes out-flowing energy, but this requires a more expensive circuit and is seldom done.

Choices of Primary Batteries

Zinc-carbon, also known as carbon-zinc or the Leclanché battery, is one of the earliest and least expensive primary batteries. It delivers 1.5V and often come with consumer devices. The first zinc-carbon invented by Georges Leclanché in 1859 was wet.

Alkaline. Alkaline-manganese, also known as alkaline, is an improved version of the zinc-carbon battery and delivers 1.5V. Lewis Urry (1927–2004) invented alkaline in 1949 while working with the Eveready Battery Company laboratory in Ohio, USA.

Alkaline delivers more energy at higher load currents than zinc-carbon. Furthermore, a regular household alkaline provides about 40 percent more energy than the average Li-ion but alkaline is not as strong as Li-ion on loading. Alkaline has very low self-discharge and does not leak electrolyte when depleted

as the old zinc-carbon does, but it is not totally leak-proof.

All primary batteries produce a small amount of hydroxide gas on discharge and battery-powered devices must make provision for venting. Pressure buildup in the cell can rupture the seal and cause corrosion. This is visible in form of a feathery crystalline structure that can develop and spread to neighboring parts in the device and cause damage.

Lithium iron disulfide (LiFeS_2) is a newcomer to the primary battery family and offers improved performance compared to alkaline. Lithium batteries normally deliver 3 volts and higher, but LiFeS_2 has 1.5 volts to be compatible with the AA and AAA formats. It has a higher capacity and a lower internal resistance than alkaline. This enables moderate to heavy loads and is ideal for digital cameras. Further advantages are improved low temperature performance, superior leakage resistance and low self-discharge, allowing 15 years of storage at ambient temperatures.

The disadvantages of the LiFeS_2 are a higher price and transportation issues due to the lithium-metal content in the anode. In 2004, the US DOT and the Federal Aviation Administration (FAA) banned bulk shipments of primary lithium batteries on passenger flights, but airline passengers can still carry them on board if the allotted lithium content is not exceeded. Each AA-sized LiFeS_2 contains 0.98 grams of lithium; the air limitation of primary lithium batteries is 2 grams (8 grams for rechargeable Li-ion). This restricts each passenger to two cells, but exceptions have been made in which 12 sample batteries can be carried. (See “Shipping Lithium-based Batteries by air” on page 204.)

The LiFeS_2 includes safety devices in the form of a *positive thermal coefficient (PTC)* that limits the current at high temperature and resets when normal. The LiFeS_2 cell cannot be recharged as is possible with NiMH in the AA and AAA formats. Recharging, putting a cell in backwards, mixing in a depleted cell or adding a foreign cell could cause a leak or explosion.

Figures 1-21 and 1-22 compare the discharge voltage and internal resistance of alkaline and LiFeS_2 at a 50mA pulsed load. Of interest is the flat voltage curve

and the low internal resistance of lithium; alkaline shows a rapid voltage drop and a permanent increase in resistance with use. This shortens the runtime, especially at an elevated load.

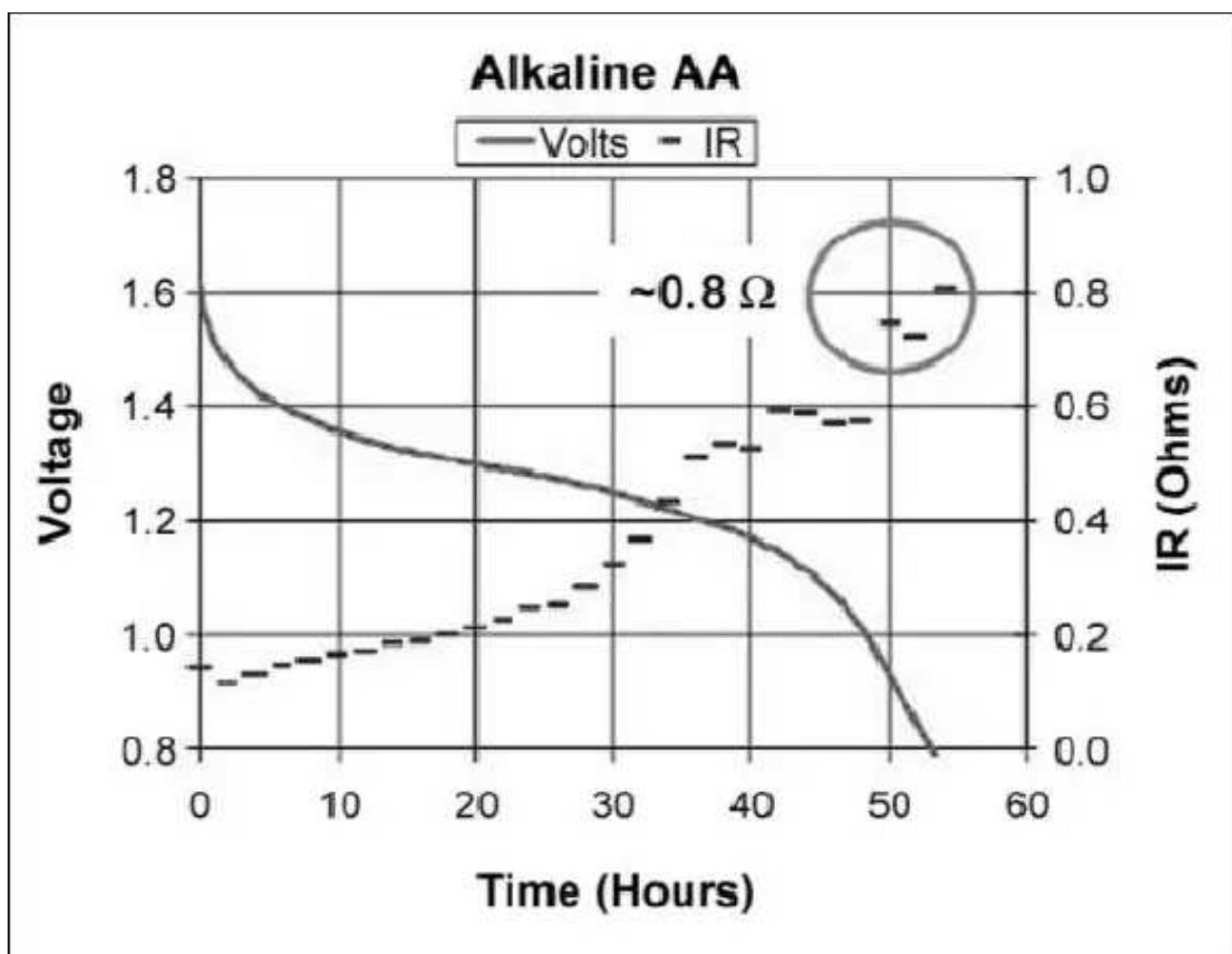


Figure 1-21: Voltage and internal resistance of alkaline on discharge. Voltage drops rapidly and causes the internal resistance to rise.

Source: Energizer

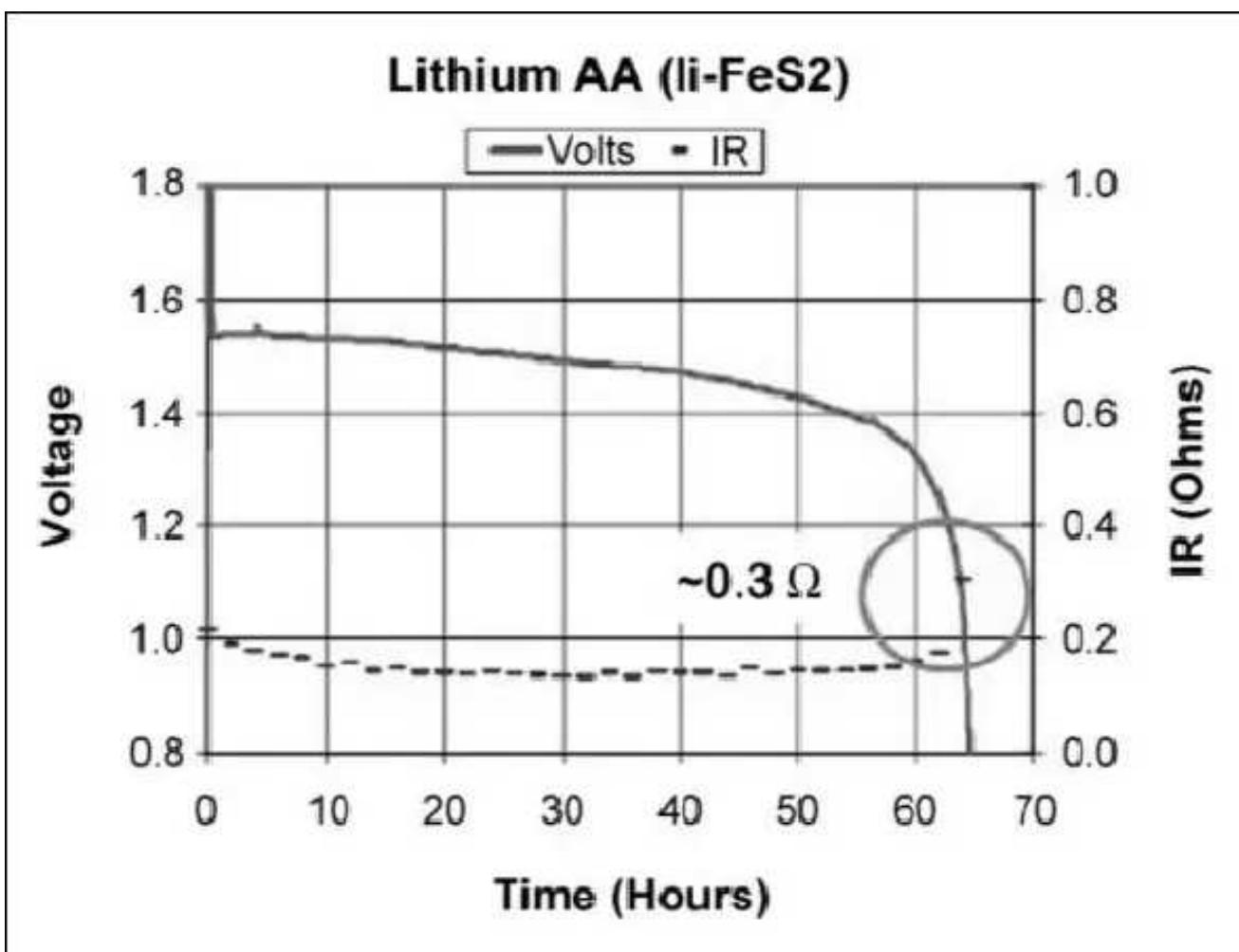


Figure 1-22: Voltage and internal resistance of lithium on discharge. Voltage stays flat and the internal resistance is low.

Source: Energizer

Lithium thionyl chloride (LiSOCl₂ or LTC) is one of the most rugged lithium-metal batteries. The ability to withstand high heat and strong vibration enables horizontal drilling, also known as fracking. Some LTC are said to operate from 0°C to 200°C (32°F to 392°F). Other uses are in medical and sensor applications.

With a specific energy of over 500Wh/kg, LTC offers twice the capacity of the best Li-ion. The nominal voltage is 3.6V/cell; the end-of-discharge cutoff voltage is 3.0V. The runtime is not based on capacity alone; thermal conditions and load pattern also have an effect. Constant current is more enduring than pulsed load; a phenomenon that applies to most batteries.

Like alkaline, LTC has a relatively high resistance and can only be used for moderate discharge loads. If stored for a time, a passivation layer forms between the lithium anode and the carbon-based cathode that dissipates when applying a load. This layer protects the battery by granting low self-discharge and a long

shelf life. (See “How to Prime Batteries” on page 191.)

LTC is one of the most powerful and potent battery chemistries and should only be used by trained workers. For safety reasons, this battery is not used in consumer devices.

Lithium manganese dioxide (LiMnO₂ or Li-M) is similar to LTC but has a lower specific capacity and is safe for public use. The voltage is 3.0–3.30V and the specific energy is about 280Wh/kg. Li-M is economically priced, has a long life and allows moderate loads but can deliver high pulse currents. Operational temperature ranges from -30°C to 60°C (-22°F to 140°F). Typical uses are meter sensing, medical devices, road toll sensors and cameras.

Lithium sulfur dioxide (LiSO₂) is a primary battery with a voltage of 2.8V and an energy density up to 330Wh/kg. It offers a wide temperature range of -54°C to 71°C (-65°F to 160°F) with a projected shelf life of 5–10 years at room temperature. LiSO₂ is inexpensive to make and is commonly used by the military. The Iraqi war used tons of these batteries, but it is giving way to the more superior Li-M.

Primary lithium batteries are also known as lithium-metal. The cathode is carbon and the anode holds the active material, the reverse of Li-ion, which features a carbon anode.

CAUTION LTC and Li-M are safe but workers handling these batteries must be familiar with safety precautions, transportation and disposal. Protect the batteries from heat, short circuit, and physical or electrical abuses.

Secondary Batteries

Rechargeable batteries play an important role in our lives and many daily chores would be unthinkable without the ability to recharge. The most common rechargeable batteries are lead acid, NiCd, NiMH and Li-ion. Here is a brief summary of their characteristics.

Lead acid – This is the oldest rechargeable battery system. Lead acid is rugged, forgiving if abused and is economically priced, but it has a low specific

energy and limited cycle count. Lead acid is used for wheelchairs, golf cars, personnel carriers, emergency lighting and uninterruptible power supply (UPS). Lead is toxic and cannot be disposed in landfills.

Nickel-cadmium – Mature and well understood, NiCd is used where long service life, high discharge current and extreme temperatures are required. NiCd is one of the most rugged and enduring batteries; it is the only chemistry that allows ultra-fast charging with minimal stress. Main applications are power tools, medical devices, aviation and UPS. Due to environmental concerns, NiCd is being replaced with other chemistries, but it retains its status in aircraft due to its good safety record.

Nickel-metal-hydride – Serves as a replacement for NiCd as it has only mild toxic metals and provides higher specific energy. NiMH is used for medical instruments, hybrid cars and industrial applications. NiMH is also available in AA and AAA cells for consumer use.

Lithium-ion – Li-ion is replacing many applications that were previously served by lead and nickel-based batteries. Due to safety concerns, Li-ion needs a protection circuit. It is more expensive than most other batteries, but high cycle count and low maintenance reduce the cost per cycle over many other chemistries.

Table 1-23 compares the characteristics of the four commonly used rechargeable battery systems, showing average performance ratings at time of publication. Li-ion is divided into different types, named by their active materials, which are cobalt, manganese, phosphate and titanate. (See “Types of Lithium-ion Batteries” on page 61.)

Missing from the list is the popular lithium-ion-polymer that gets its name from the unique separator and electrolyte system. Most are a hybrid version that shares performance with other Li-ion. Also missing is the rechargeable lithium-metal, a battery that, once the safety issues are resolved, has the potential of becoming a battery choice with extraordinarily high specific energy and good specific power. The table only addresses portable batteries and excludes large

systems that resemble a refinery.

Comments to Table 1-23

1. Combining cobalt, nickel, manganese and aluminum raises energy density up to 250Wh/kg.
2. Cycle life is based on the depth of discharge (DoD). Shallow DoD prolongs cycle life.
3. Cycle life is based on battery receiving regular maintenance to prevent memory.
4. Ultra-fast charge batteries are made for a special purpose. (See “Ultra-fast Charging” on page 129.)
5. Self-discharge is highest immediately after charge. NiCd loses 10% in the first 24 hours, then declines to 10% every 30 days. High temperature and age increase self-discharge.
6. 1.25V is traditional; 1.20V is more common. (See “Confusion with Voltages” on page 105.)
7. Manufacturers may rate voltage higher because of low internal resistance (marketing).
8. Capable of high current pulses; needs time to recuperate.
9. Do not charge Li-ion below freezing. (See “Charging at High and Low Temperatures” on page 148.)
10. Maintenance may be in the form of equalizing or topping charge to prevent sulfation.
11. Protection circuit cuts off below about 2.20V and above 4.30V on most Li-ion; different voltage settings apply for lithium iron phosphate.
12. Coulombic efficiency is higher with quicker charge (in part due to self-discharge error).
13. Li-ion may have lower cost-per-cycle than lead acid.

Specifications	Lead Acid	NiCd	NiMH	Cobalt	Li-ion ¹	Manganese	Phosphate
Specific energy Wh/kg)	30–50	45–80	60–120	150–250	100–150	90–120	
Internal resistance	Very Low	Very low	Low	Moderate	Low	Very low	
Cycle life² (80%DoD)	200–300	1,000 ³	300–500 ³	500–1,000	500–1,000	1,000–2,000	
Charge time⁴	8–16h	1–2h	2–4h	2–4h	1–2h	1–2h	
Charge tolerance	High	Moderate	Low	Low. No trickle charge			
Self-discharge/ month (room temp)	5%	20% ⁵	30% ⁵	<5% Protection circuit consumes 3%/month			
Cell voltage nominal	2V	1.2V ⁶	1.2V ⁶	3.6V ⁷	3.7V ⁷	3.2–3.3V	
Charge cutoff voltage (V/cell)	2.40 Float 2.25	Full charge detection by voltage signature		4.20 typical Some go to higher V		3.60	
Discharge voltage	1.75V	1.0V		2.5–3.0V		2.5V	
Peak load current Best result	5C ⁸ 0.2C	20C 1C	5C 0.5C	2C <1C	>30C <10C	>30C <10C	
Charge temperature	–20 to 50°C (-4 to 122°F)	0 to 45°C (32 to 113°F)		0 to 45°C ⁹ (32 to 113°F)			
Discharge temperature	–20 to 50°C (-4 to °F)	–20 to 65°C (-4 to 49°F)		–20 to 60°C (-4 to 140°F)			
Maintenance requirement	3-6 months ¹⁰ (toping chg.)	Full discharge every 90 days when in full use		Maintenance-free			
Safety requirements	Thermally stable	Thermally stable, fuse protection		Protection circuit mandatory ¹¹			
In use since	Late 1800s	1950	1990	1991	1996	1999	
Toxicity	Very high	Very high	Low	Low			
Coulombic efficiency¹²	~90%	~70% slow charge ~90% fast charge		99%			
Cost	Low	Moderate		High ¹³			

Table 1-23: Characteristics of common rechargeable batteries. The figures are average ratings of commercial batteries at time of publication. Specialty batteries with above-average ratings are excluded.

Chapter 2 | Battery Types

Lead-based Batteries

Invented by the French physician Gaston Planté in 1859, lead acid was the first rechargeable battery for commercial use. Despite its advanced age, the lead chemistry continues to be in wide use today. There are good reasons for its popularity; lead acid is dependable and inexpensive on a cost-per-watt base.

There are few other batteries that deliver bulk power as cheaply as lead acid, and this makes the battery cost-effective for automobiles, golf cars, forklifts, marine and uninterrupted power supplies (UPS).

The grid structure of the lead acid battery is made from a lead alloy. Pure lead is too soft and would not support itself, so small quantities of other metals are added to get the mechanical strength and improve electrical properties. The most common additives are antimony, calcium, tin and selenium. These batteries are often known as “lead-antimony” and “lead-calcium.”

Adding antimony and tin improves deep cycling, but this increases water consumption and escalates the need to equalize. Calcium reduces self-discharge, but the positive lead-calcium plate has the side effect of growing due to grid oxidation when being over-charged. Modern lead acid batteries also make use of doping agents such as selenium, cadmium, tin and arsenic to lower the antimony and calcium content.

Lead acid is heavy and is less durable than nickel- and lithium-based systems when deep cycled. A full discharge causes strain and each discharge/charge cycle permanently robs the battery of a small amount of capacity. This loss is small while the battery is in good operating condition, but

the fading increases once the performance drops.

Depending on the depth of discharge, lead acid for deep-cycle applications provides 200 to 300 discharge/charge cycles. The primary reasons for its relatively short cycle life are grid corrosion on the positive electrode, depletion of the active material and expansion of the positive plates. This aging phenomenon is accelerated at elevated operating temperatures and when drawing high discharge currents. (See “How to Prolong Lead Acid Batteries” on page 235.)

Charging a lead acid battery is simple, but the correct voltage limits must be observed. Choosing a low voltage limit shelters the battery, but this produces poor performance and causes a buildup of sulfation on the negative plate. A high voltage limit improves performance but forms grid corrosion on the positive plate. While sulfation can be reversed if serviced in time, corrosion is permanent. (See “Charging Lead Acid” on page 133.)

Lead acid does not lend itself to fast charging and with most types, a full charge takes 14–16 hours. The battery must always be stored at full state-of-charge. Low charge causes sulfation, a condition that robs the battery of performance. Adding carbon on the negative electrode reduces this problem but this lowers the specific energy.

Lead acid has a moderate life span, but it is not subject to memory as nickel-based systems are, and the charge retention is best among rechargeable batteries. While nickel-based batteries lose approximately 40 percent of their stored energy in three months, lead acid self-discharges the same amount in one year. The lead acid battery works well at cold temperatures and is superior to lithium-ion when operating in subzero conditions.

Sealed Lead Acid

The first sealed, or maintenance-free, lead acid emerged in the mid-1970s. Engineers argued that the term “sealed lead acid” was a misnomer because no lead acid battery can be totally sealed. To control venting during stressful charge

and rapid discharge, valves have been added that release gases if pressure builds up. Rather than submerging the plates in a liquid, the electrolyte is impregnated into a moistened separator, a design that resembles nickel- and lithium-based systems. This enables operating the battery in any physical orientation without leakage.

The sealed battery contains less electrolyte than the flooded type, hence the term “acid-starved.” Perhaps the most significant advantage of sealed lead acid is the ability to combine oxygen and hydrogen to create water and prevent dry out during cycling. The recombination occurs at a moderate pressure of 0.14 bar (2psi). The valve serves as a safety vent if the gas buildup rises. Repeated venting should be avoided as this will lead to an eventual dry-out.

Several types of sealed lead acid have emerged and the most common are *gel*, also known as *valve-regulated lead acid* (VRLA), and *absorbent glass mat* (AGM). The gel cell contains a silica type gel that suspends the electrolyte in a paste. Smaller packs with capacities of up to 30Ah are often called SLA (sealed lead acid). Packaged in a plastic container, these batteries are used for small UPS, emergency lighting and wheelchairs. Because of low price, dependable service and low maintenance, the SLA remains the preferred choice for healthcare in hospitals and retirement homes. The larger VRLA is used as power backup for cellular repeater towers, Internet hubs, banks, hospitals, airports and more.

The AGM suspends the electrolyte in a specially designed glass mat. This offers several advantages to lead acid systems, including faster charging and instant high load currents on demand. AGM works best as a mid-range battery with capacities of 30 to 100Ah and is less suited for large systems, such as UPS. Typical uses are starter batteries for motorcycles, start-stop function for micro-hybrid cars, as well as marine and RV that need some cycling.

With cycling and age, the capacity of AGM fades gradually; gel, on the other hand, has a dome shaped performance curve and stays in the high performance range longer but then drops suddenly towards the end of life. AGM

is more expensive than flooded, but is cheaper than gel. See “Absorbent Glass Mat (AGM)” on page 50.)

Unlike the flooded, the sealed lead acid battery is designed with a low over-voltage potential to prohibit the battery from reaching its gas-generating potential during charge. Excess charging causes gassing, venting and subsequent water depletion and dry-out. Consequently, gel, and in part also AGM, cannot be charged to their full potential and the charge voltage limit must be set lower than that of a flooded. This also applies to the float charge on full charge. In respect to charging, the gel and AGM are no direct replacements for the flooded type. If no designated charger is available for AGM with lower voltage settings, disconnect the charger after 24 hours of charge. This prevents gassing due to a float voltage that is set too high.

The optimum operating temperature for a VRLA battery is 25°C (77°F); every 8°C (15°F) rise above this temperature threshold cuts battery life in half. Lead acid batteries are rated at a 5-hour (0.2C) and 20-hour (0.05C) discharge rate. The battery performs best when discharged slowly; the capacity readings are substantially higher at a slower discharge than at the 1C-rate. Lead acid can, however, deliver high pulse currents of several C if done for only a few seconds. This makes the lead acid well suited as a starter battery, also known as starter-light-ignition (SLI). The high lead content and the sulfuric acid make lead acid environmentally unfriendly.

Lead acid batteries are commonly classified into three usages: Automotive (starter or SLI), motive power (traction or deep cycle) and stationary (UPS).

Starter Battery

The starter battery is designed to crank an engine with a momentary high-power load lasting a second or so. For its size, the battery is able to deliver high current but it cannot be deep-cycled. Starter batteries are rated with Ah or RS (Reserve Capacity) to indicate energy storage capability, as well as CCA (cold cranking amps) to signify the current a battery can deliver at cold temperature. SAE J537 specifies 30 seconds of discharge at -18°C (0°F) at the rated CCA ampere

without the battery voltage dropping below 7.2 volts. RC reflects the runtime in minutes at a steady discharge of 25A. (SAE stands for Society of Automotive Engineers; see page 337.)

Starter batteries have a very low internal resistance that is achieved by adding extra plates for maximum surface area (Figure 2-1). The plates are thin and the lead is applied in a sponge-like form that has the appearance of fine foam, expanding the surface area further. Plate thickness, which is important for a deep-cycle battery is less important because the discharge is short and the battery is recharged while driving; the emphasis is on power rather than capacity.

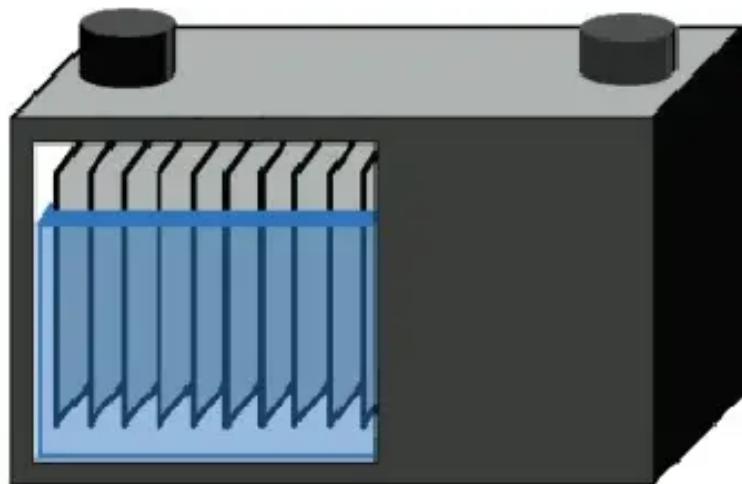


Figure 2-1: Starter battery

The starter battery has many thin plates in parallel to achieve low resistance with high surface area. The starter battery does not allow deep cycling.

Courtesy of Cadex

Deep-cycle Battery

The deep-cycle battery is built to provide continuous power for wheelchairs, golf cars, forklifts and more. This battery is built for maximum capacity and a reasonably high cycle count. This is achieved by making the lead plates thick (Figure 2-2). Although the battery is designed for cycling, full discharges still induce stress and the cycle count relates to the depth-of-discharge (DoD). Deep-cycle batteries are marked in Ah or minutes of runtime. The capacity is typically rated as a 5-hour and 20-hour discharge.

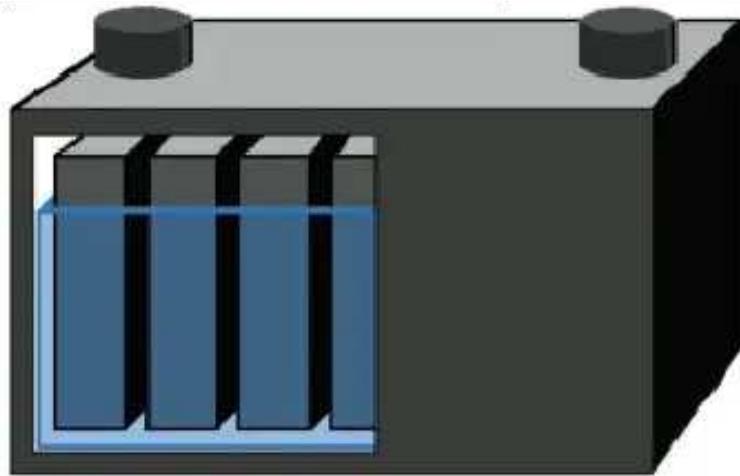


Figure 2-2: Deep-cycle battery

The deep-cycle battery has thick plates for improved cycling abilities. The deep-cycle battery generally allows about 300 cycles.

Courtesy of Cadex

A starter battery cannot be swapped with a deep-cycle battery or vice versa.

While an inventive senior may be tempted to install a starter battery rather than the more expensive deep-cycle on his wheelchair to save money, the starter battery would not last because the thin sponge-like plates would quickly dissolve with repeated deep cycling.

There are hybrid starter/deep-cycle batteries available for trucks, buses, public safety and military vehicles, but these units are big and heavy. As a simple guideline, the heavier the battery is, the more lead it contains, and the longer it will last. Table 2-3 compares the typical life of starter and deep-cycle batteries when deep cycled.

Batteries are expensive and have a relatively short life span. As discarded batteries grow by the tonnage, entrepreneurs are enticed to start a business in recycling. With an annual world market of \$33 billion, lead acid is the most common battery in use. This is followed by Li-ion at \$16.6 billion, NiMH at \$2 billion and NiCd at \$1 billion. All other chemistries only make up \$1 billion. Table 7-13 lists the material cost per ton to build these batteries.

Depth of discharge	Starter battery	Deep-cycle battery
100%	12–15 cycles	150–200 cycles
	100–120 cycles	400–500 cycles

30%	130–150 cycles	1,000 and more cycles
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Table 2-3: Cycle performance of starter and deep-cycle batteries. A discharge of 100% refers to a full discharge; 50% is half and 30% is a moderate discharge with 70% remaining.

Lead is toxic and environmentalists would like to replace the lead acid battery with an alternative chemistry. Europe succeeded in keeping NiCd out of consumer products, and similar efforts are being made with the starter battery. The choices are NiMH and Li-ion, but the price is too high and low temperature performance is poor. With a 99 percent recycling rate, the lead acid battery poses little environmental hazard and will likely continue to be the battery of choice. Table 2-4 lists advantages and limitations of common lead acid batteries in use today.

Advantages	<ul style="list-style-type: none"> Inexpensive and simple to manufacture; lowest cost per watt-hour Mature and well-understood technology; provides dependable service Low self-discharge; lowest among rechargeable batteries High specific power, capable of high discharge currents
Limitations	<ul style="list-style-type: none"> Low specific energy; poor weight-to-energy ratio Slow charge; fully saturated charge takes 14–16 hours Must always be stored in charged condition Limited cycle life; repeated deep-cycling reduces battery life Flooded version requires watering Not environmentally friendly Transportation restrictions on the flooded type

Table 2-4: Advantages and limitations of lead acid batteries. Dry systems have advantages over flooded

but are less rugged. The table does not include new lead acid chemistries.

Absorbent Glass Mat (AGM)

AGM technology became popular in the early 1980s as a sealed lead acid battery for military aircraft, vehicles and UPS to reduce weight and improve reliability. The sulfuric acid is absorbed by a very fine fiberglass mat, making the battery spill-proof. This enables shipment without hazardous material restrictions. The plates can be made flat to resemble a standard flooded lead acid pack in a rectangular case; they can also be wound into a cylindrical cell.

AGM has very low internal resistance, is capable of delivering high currents on demand and offers a relatively long service life, even when deep cycled. AGM is maintenance free, has good electrical reliability and is lighter than the flooded lead acid type. While regular lead acid batteries need a topping charge every six months to prevent the buildup of sulfation, AGM batteries are less prone to sulfation and can sit in storage for longer before a charge becomes necessary. The battery stands up well to cold temperatures and has low self-discharge.

The leading advantages are a charge that is up to five times faster than the flooded version and the ability to deep cycle. AGM offers a depth-of-discharge of 80 percent; the flooded, on the other hand, is specified at 50 percent DoD to attain the same cycle life. The negatives are slightly lower specific energy and higher manufacturing costs than the flooded.

Most AGM batteries are mid-sized and range from 30 to 100Ah. They are commonly built to size and are found in high-end vehicles to run power-hungry accessories such as heated seats, steering wheels, mirrors and windshields. NASCAR and other auto racing leagues choose AGM products because they are vibration resistant.

AGM is the preferred battery for upscale motorcycles. Being sealed, AGM reduces acid spilling in an accident, lowers the weight for the same performance and allows installation at odd angles. Because of good performance at cold

temperatures, AGM batteries are also used for marine, motor home and robotic applications.

AGM is making inroads into the start-stop function of cars. The classic flooded type is simply not robust enough and repeated cycling causes a sharp capacity fade after only two years of use. (See “How Heat and Loading Affects Battery Life” on page 244.)

As with all gelled and sealed units, AGM batteries are sensitive to overcharging. A charge to 2.40V/cell (and higher) is fine; however, the float charge should be reduced to between 2.25 and 2.30V/cell when fully charged. Summer temperatures may require lower voltages. Automotive charging systems for flooded lead acid often have a fixed float voltage setting of 14.40V (2.40V per cell); a direct replacement with a sealed unit could overcharge the battery on a long drive.

AGM and other sealed batteries do not like heat and should be installed away from the engine compartment. Manufacturers recommend halting charge if the battery core reaches 49°C (120°F). Table 2-5 spells out the advantages and limitations of AGM.

Advantages	Spill-proof through acid encapsulation in matting technology High specific power, low internal resistance, responsive to load Up to 5 times faster charge than with flooded lead acid Better cycle life than with flooded systems Water retention (oxygen and hydrogen combine to produce water) Vibration resistance; stands up well to cold temperature Less prone to sulfation if not regularly topping charged
Limitations	Higher manufacturing cost than flooded (but cheaper than gel)

Sensitive to overcharging (gel has tighter tolerances than AGM)
Capacity has gradual decline (gel has a performance dome)
Low specific energy
Must be stored in charged condition (less critical than flooded)
Not environmentally friendly (has less electrolyte and lead than flooded)

Table 2-5: Advantages and limitations of AGM.

New Lead Acid Systems

Most battery systems allow reasonably fast charging of one hour or so. The energy can also be withdrawn in about the same time, meaning that the charge and discharge times can be made similar. Lead acid is unique in that the battery can be discharged at a very high rate but requires more than 14 hours to fully charge. Lead acid also needs periodic equalization to de-sulfate the plates and correct other ills.

The answer to the inherent low charge acceptance relates to the formation and dissolution of lead sulfate on the negative electrode, which is pure lead. On discharge, lead sulfate adheres to the surface and dissolves again on charge. The process is sluggish and when trying to hasten the charge, excess electrons have nowhere to go; this leads to hydrogen generation and water loss. With age, the lead sulfate crystals engrain, which reduces the charge acceptance even further.

The positive electrode also contains lead sulfate, but it supports a high charge rate. It is clear that the negative electrode is the problem with lead acid batteries. New lead acid systems try to solve this problem by adding carbon to this electrode with promising results.

Advanced Lead-carbon

Scientists have known for years that sulfate accumulation prevents the classic lead acid from delivering sustained performance; partial charge and aging are the

main culprits because the negative lead plate is not sufficiently scrubbed. The advanced lead-carbon (ALC) battery solves this by adding carbon to the negative plate (cathode). This turns the battery into a quasi-asymmetric supercapacitor to improve charge and discharge performance.

Figure 2-6 illustrates the classic lead acid cell with the lead negative plate being replaced with a carbon electrode to benefit from the qualities of a supercapacitor.

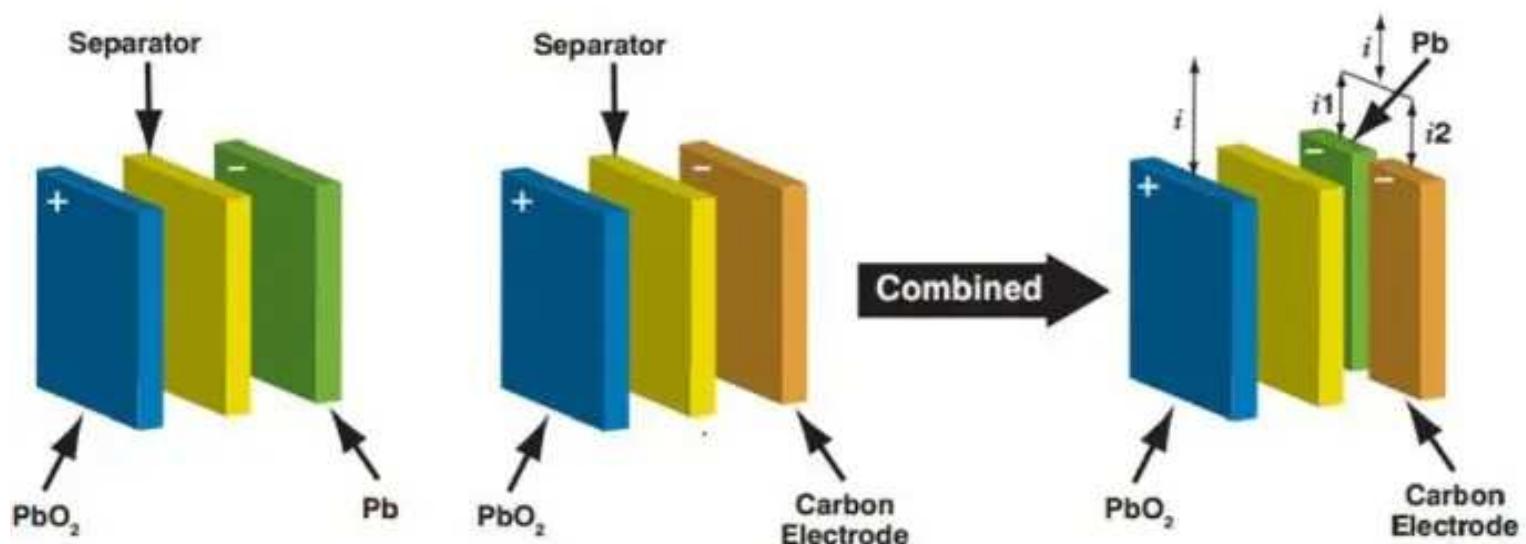


Figure 2-6: The classic lead acid develops into an advanced lead-carbon battery.

The negative plate is replaced with a carbon electrode that shares the qualities of a supercapacitor.

Source: Advanced Lead-Acid Battery Consortium (ALABC)

The ALC is being tested as a replacement for the classic starter battery in start-stop applications and in 48V micro and mild hybrid systems. Rapid charging on regenerative braking is a decisive advantage with these batteries, a task that is difficult to achieve with regular lead acid. Although larger and heavier than Li-ion, the ALC is low-cost, operates at subfreezing temperatures and does not need active cooling — advantages Li-ion cannot claim. Unlike regular lead acid, lead carbon can operate between 30 and 70 percent state-of-charge without fear of becoming sulfated. The ALC is said to outlive the regular lead acid battery, but the negative is a rapid voltage drop on discharge, resembling that of a supercapacitor.

The composite plate material of the Firefly Energy battery is based on a lead acid variant, and the maker claims that the battery is lighter, longer living and offers a higher active material utilization than current lead acid systems. It is also one of the few lead acid batteries that can operate for extended time in partial-states-of-charge. The battery includes carbon-foam electrodes for the negative plates, which gives it a performance that is comparable to NiMH but at lower manufacturing costs. Firefly Energy was a spin-off of Caterpillar, and in 2010 it went into bankruptcy. The company was revived later under separate ownership. Today, Firefly International Energy manufactures the Oasis line of batteries in limited quantities in the US.

Altraverda Bipolar

Similar to the Firefly Energy battery, the Altraverda battery is based on lead. It

®

uses a proprietary titanium sub-oxide ceramic structure called Ebonex[®] for the grid and an AGM separator. The un-pasted plate contains Ebonex[®] particles in a polymer matrix that holds a thin lead alloy foil on the external surfaces. At a specific energy of 50–60Wh/kg, the battery is comparable with NiCd and is said to be well suited for high voltage applications. Based in the UK, Altraverda works with East Penn in the USA.

Axion Power

The Axion Power e3 Supercell is a hybrid battery/supercapacitor in which the positive electrode is made of standard lead dioxide and the negative electrode is activated carbon. The assembly process is similar to lead acid. The Axion Power battery offers faster recharge times and longer cycle life on repeated deep discharges than what is possible with regular lead acid systems, opening the door for the start-stop application in micro-hybrid cars. The lead-carbon combination lowers the lead content on the negative plate, which results in a weight reduction of 30 percent compared to a regular lead acid. This, however, also decreases the specific energy to 15–25Wh/kg instead of the 30–50Wh/kg with a regular lead acid. Another negative is a steep voltage decline on discharge that shares similarities with the supercapacitor.

CSIRO Ultrabattery

The Ultrabattery by Commonwealth Scientific and Industrial Research Organisation (CSIRO) of Australia combines the asymmetric ultracapacitor with the lead acid battery, sharing similarities with the advanced lead-carbon described above. The capacitor enhances the power and lifetime of the battery by acting as a buffer during charging and discharging. This is said to prolong battery lifetime by a factor of four over regular lead acid systems while boosting the power by 50 percent. The manufacturer further claims a 70 percent cost reduction over current batteries in hybrid electric vehicles. CSIRO batteries were tested in a Honda Insight HEV, and the results were said to be positive. The battery is also being tested for start-stop applications in micro-hybrid cars. Unlike other advanced lead acid, the ability to rapid-charge is a decisive advantage over the regular lead acid. Furukawa Battery in Japan licensed the technology and also makes the battery.

EEStor

This is the mystery battery/supercapacitor combination that has received much media attention. The battery is based on a modified barium titanate ceramic powder and claims a specific energy of up to 280Wh/kg, higher than lithium-ion. The company is very secretive about their invention and releases only limited information. Some of their astonishing claims include: One-tenth of the weight of a NiMH battery in a hybrid application; no deep-cycle wear down; 3–6 minute charge time; no hazardous material; similar manufacturing costs to lead acid; and a self-discharge of 0.02 percent per month, a fraction of that of lead acid and Li-ion. Tests conducted in 2013 did not find meaningful levels of energy because of high resistance between the layers. Research is continuing.

Enhanced Flooded Battery (EFB)

Car manufacturers are aware of the added stress when a regular starter battery is in start-stop mode. AGM (absorbent glass mat) batteries can withstand the repeat start function, but car manufacturers looking for a lower cost solution came up with the enhanced flooded battery (EFB). Tests reveal that the EFB performs better than the regular flooded version, but it is not as good as AGM. Performance appears to be directly related with battery cost.

Nickel-based Batteries

For 50 years, portable devices relied almost exclusively on nickel-cadmium (NiCd). This generated a large amount of data, but in the 1990s, nickel-metal-hydride (NiMH) took over the reign to solve the toxicity problem of the otherwise robust NiCd. Many of the characteristics of NiCd were transferred to the NiMH camp, offering a quasi-replacement as these two systems are similar. Because of environmental regulations, NiCd is limited to specialty applications today.

Nickel-cadmium (NiCd)

Invented by Waldemar Jungner in 1899, the nickel-cadmium battery offered several advantages over lead acid, then the only other rechargeable battery; however, the materials for NiCd were expensive. Developments were slow, but in 1932, advancements were made to deposit the active materials inside a porous nickel-plated electrode. Further improvements occurred in 1947 by absorbing the gases generated during charge, which led to the modern sealed NiCd battery.

For many years, NiCd was the preferred battery choice for two-way radios, emergency medical equipment, professional video cameras and power tools. In the late 1980s, the ultra-high capacity NiCd rocked the world with capacities that were up to 60 percent higher than the standard NiCd. Packing more active material into the cell achieved this, but the gain was shadowed by higher internal resistance and reduced cycle count.

The standard NiCd remains one of the most rugged and forgiving batteries, and the airline industry stays true to this system, but it needs proper care to attain longevity. NiCd, and in part also NiMH, have *memory effect* that causes a loss of capacity if not given a periodic full discharge cycle. The battery appears to remember the previous energy delivered and once a routine has been established, it does not want to give more. (See “Memory: Myth or Fact?” on page 246.) Table 2-7 lists the advantages and limitations of the standard NiCd.

Advantages	Rugged, high cycle count with proper maintenance Only battery that can be ultra-fast charged with little stress Good load performance; forgiving if abused Long shelf life; can be stored in a discharged state, needs priming before use Simple storage and transportation; not subject to regulatory control Good low-temperature performance Economically priced; NiCd is the lowest in terms of cost per cycle Available in a wide range of sizes and performance options
Limitations	Relatively low specific energy compared with newer systems Memory effect; needs periodic full discharges and can be rejuvenated Cadmium is a toxic metal. Cannot be disposed of in landfills High self-discharge; needs recharging after storage Low cell voltage of 1.20V requires many cells to achieve high voltage

Table 2-7: Advantages and limitations of NiCd batteries.

Nickel-metal-hydride (NiMH)

Research on nickel-metal-hydride started in 1967; however, instabilities with the metal-hydride led to the development of the nickel-hydrogen (NiH) instead. New hydride alloys discovered in the 1980s eventually improved the stability issues and today NiMH provides 40 percent higher specific energy than the standard NiCd.

Nickel-metal-hydride is not without drawbacks. The battery is more delicate and trickier to charge than NiCd. With 20 percent self-discharge in the first 24 hours after charge and 10 percent per month thereafter, NiMH ranks among the highest in the class. Modifying the hydride materials lowers the self-discharge and reduces corrosion of the alloy, but this decreases the specific energy. Batteries for the electric powertrain make use of this modification to achieve the needed robustness and long life span.

Consumer Applications

NiMH has become one of the most readily available rechargeable batteries for consumer use. Battery manufacturers, such as Panasonic, Energizer, Duracell and Rayovac, have recognized the need for a durable and low-cost rechargeable battery and offer NiMH in AA, AAA and other sizes. The battery manufacturers want to lure buyers away from disposable alkaline to rechargeable batteries.

The NiMH battery for the consumer market is an alternative for the failed reusable alkaline that appeared in the 1990s. Limited cycle life and poor loading characteristics hindered its success. (See “Reusable Alkaline” on page 89.)

Table 2-8 compares the specific energy, voltage, self-discharge and runtime of over-the-counter batteries. Available in AA, AAA and other sizes, these cells can be used in portable devices designed for these norms. Even though the cell voltages may vary, the end-of-discharge voltages are common, which is typically 1V/cell. Portable devices have some flexibility in terms of voltage range. It is important not to mix cells and to always use the same type of batteries in the holder. Safety concerns and voltage incompatibility prevent the sale of most lithium-ion batteries in AA and AAA formats.

Battery type	Capacity AA cell	Voltage	Self-discharge Capacity after 1 year storage	Runtime Estimated photos on digital camera
NiMH	2,700mAh, rechargeable	1.2V	50%	600 shots
Eneloop*	2,400mAh, rechargeable	1.2V	85%	500 shots
Regular alkaline	2,800mAh; non-rechargeable	1.5V	95% 10 year shelf life	100 shots
Reusable alkaline	2,000mAh; lower on subsequent recharge	1.4V	95%	100 shots
Lithium (LiFeS ₂)	2,500–3,400mAh (non-rechargeable)	1.5V	Very low 10 year shelf life	690 shots

Table 2-8: Comparison of alkaline, reusable alkaline, Eneloop and NiMH.

* Eneloop is a Sanyo trademark, based on NiMH

High self-discharge is of ongoing concern to consumers using rechargeable batteries, and NiMH behaves like a leaky basketball or bicycle tire. A flashlight or portable entertainment device with a NiMH battery gets “flat” when put away for only a few weeks. Having to recharge the device before each use does not sit well with many consumers, especially for flashlights that sit on standby for the occasional power-outage; alkaline keeps the charge for 10 years.

The Eneloop NiMH by Panasonic and Sanyo has reduced the self-discharge by a factor of six. This means you can store the charged battery six times longer than a regular NiMH before a recharge becomes necessary. The drawback of the Eneloop to regular NiMH is a slightly lower specific energy.

Table 2-9 summarizes the advantages and limitations of industrial-grade NiMH. The table does not include the Eneloop and other consumer brands.

Advantages 30–40 percent higher capacity than a standard NiCd

Less prone to memory than NiCd, can be rejuvenated

Simple storage and transportation; not subject to regulatory control

	<p>Environmentally friendly; contains only mild toxins</p> <p>Nickel content makes recycling profitable</p> <p>Wide temperature range</p>
Limitations	<p>Limited service life; deep discharge reduces service life</p> <p>Discharge load current not as good as NiCd</p> <p>Requires complex charge algorithm. Sensitive to overcharge.</p> <p>Does not absorb overcharge well; trickle charge must be kept low</p> <p>Generates heat during fast charge and high-load discharge</p> <p>High self-discharge</p> <p>Coulombic efficiency only about 65% (99% with Li-ion)</p>

Table 2-9: Advantages and limitations of NiMH batteries

Nickel-iron (NiFe)

After inventing nickel-cadmium in 1899, Sweden's Waldemar Jungner tried to substitute iron for cadmium to save money; however, poor charge efficiency and gassing (hydrogen formation) prompted him to abandon the development without securing a patent.

In 1901, Thomas Edison continued the development of the nickel-iron battery as a substitute to lead acid for electric vehicles. He claimed that nickel-iron was "far superior to batteries using lead plates and acid" and counted on the emerging electric vehicle market. He lost out when gasoline-powered cars took over and was deeply disappointed when the auto industry did not adopt nickel-iron as the starter, lighting and ignition battery (SLI) for cars.

The nickel-iron battery (NiFe) uses an oxide-hydroxide cathode and an iron anode with potassium hydroxide electrolyte that produces a nominal cell voltage

of 1.20V. NiFe is resilient to overcharge and over-discharge and can last for more than 20 years in standby applications. Resistance to vibrations and high temperatures made NiFe the preferred battery for mining in Europe; during World War II the battery powered German V-1 flying bombs and V-2 rockets. Other uses are railroad signaling, forklifts and stationary applications.

NiFe has a low specific energy of about 50Wh/kg, has poor low-temperature performance and exhibits high self-discharge of 20–40 percent a month. This, together with high fabrication cost, prompted the industry to stay faithful to lead acid.

Improvements are being made, and NiFe is becoming a viable alternative to lead acid in off-grid power systems. Pocket plate technology lowered the self-discharge; the battery is virtually immune to over- and under-charging and should last for over 50 years. This compares to less than 12 years with deep cycle lead acids in cycling mode. NiFe costs about four times as much as lead acid and is comparable with Li-ion in purchase price.

Nickel-iron batteries use a taper charge similar to NiCd and NiMH. Do not use constant voltage charge as with lead acid and lithium-ion batteries, but allow the voltage to float freely. Similar to nickel-based batteries, the cell voltage begins to drop at full charge as the internal gas builds up and the temperature rises. Avoid overcharging as this causes water evaporation and dry-out.

Low capacity can often be improved by applying a high discharge current of up to three times the C-rate for periods of 30 minutes. Assure that the temperature of the electrolyte does not exceed 46°C (115°F).

Nickel-zinc (NiZn)

Nickel-zinc is similar to nickel-cadmium in that it uses an alkaline electrolyte and a nickel electrode, but it differs in voltage; NiZn provides 1.65V/cell rather than 1.20V, which NiCd and NiMH deliver. NiZn charges at a constant current to 1.9V/cell and cannot take trickle charge, also known as maintenance charge. The specific energy is 100Wh/kg and can be cycled 200–300 times. NiZn has no

heavy toxic materials and can easily be recycled. Some packaging is available in the AA cell format.

In 1901, Thomas Edison was awarded the U.S. patent for a rechargeable nickel-zinc battery system that was installed in rail cars between 1932 and 1948. NiZn suffered from high self-discharge and short cycle life caused by dendrite growth, which often led to an electrical short. Improvements in the electrolyte have reduced this problem, and NiZn is being considered again for commercial uses. Low cost, high power output and good temperature operating range make this chemistry attractive.

Nickel-hydrogen (NiH)

When research for nickel-metal-hydride began in 1967, problems with metal instabilities caused a shift towards the development of the nickel-hydrogen battery (NiH). NiH uses a steel canister to store hydrogen at a pressure of 8,270kPa (1,200psi). The cell includes solid nickel electrodes, hydrogen electrodes, gas screens and electrolyte that are encapsulated in the pressurized vessel.

NiH has a nominal cell voltage of 1.25V and the specific energy is 40–75Wh/kg. The advantages are long service life, even with full discharge cycles, good calendar life due to low corrosion, minimal self-discharge, and a remarkable temperature performance of –28°C to 54°C (–20°F to 130°F). These attributes make NiH ideal for satellite use. Scientists tried to develop NiH batteries for terrestrial use, but low specific energy and high cost worked against this endeavor. A single cell for a satellite application costs thousands of dollars. As NiH replaced NiCd in satellites, there is a move towards long-life Li-ion.

Lithium-based Batteries

Pioneering work of the lithium battery began in 1912 under G.N. Lewis, but it was not until the early 1970s that the first non-rechargeable lithium batteries became commercially available. Attempts to develop rechargeable lithium

batteries followed in the 1980s but failed because of instabilities in the metallic lithium used as anode material. (The metal-lithium battery uses lithium as anode; Li-ion uses graphite as anode and active materials in the cathode.)

Lithium is the lightest of all metals, has the greatest electrochemical potential and provides the largest specific energy per weight. Rechargeable batteries with lithium-metal on the anode could provide extraordinarily high energy densities; however, it was discovered in the mid-1980s that cycling produced unwanted dendrites on the anode. These growth particles penetrate the separator and cause an electrical short. The cell temperature would rise quickly and approach the melting point of lithium, causing thermal runaway, also known as “venting with flame.” A large number of rechargeable metallic lithium batteries sent to Japan were recalled in 1991 after a battery in a mobile phone

released flaming gases and inflicted burns to a man’s face.

The inherent instability of lithium-metal, especially during charging, shifted research to a non-metallic solution using lithium ions. In 1991, Sony commercialized the first Li-ion, and today this chemistry has become the most promising and fastest growing battery on the market. Although lower in specific energy than lithium-metal, Li-ion is safe, provided the voltage and currents limits are being respected.

Credit for the pioneering work leading to the lithium-cobalt-oxide battery goes to John B. Goodenough (1922). It is said that during the developments, a graduate student employed by Nippon Telephone & Telegraph (NTT) worked with Goodenough in the USA. Shortly after the breakthrough, the student traveled back to Japan, taking the discovery with him. Then in 1991, Sony announced an international patent on a lithium-cobalt-oxide cathode. Years of litigation ensued, but Sony was able to keep the patent and Goodenough received nothing for his efforts. In recognition of contributions made in Li-ion developments, the U.S. National Academy of Engineering awarded Goodenough and other contributors the Charles Stark Draper Prize in 2014. In 2015, Israel awarded Goodenough a \$1 million prize, which he will donate to the Texas Materials Institute to assist in materials research.

The key to the superior specific energy is the high cell voltage of 3.60V. Improvements in the active materials and electrolytes have the potential to further boost the energy density. Load characteristics are good and the flat discharge curve offers effective utilization of the stored energy in a desirable and flat voltage spectrum of 3.70–2.80V/cell.

In 1994, the cost to manufacture Li-ion in the 18650 cylindrical cell was over US\$10 and the capacity was 1,100mAh. In 2001, the price dropped to below \$3 while the capacity rose to 1,900mAh. Today, high energy-dense 18650 cells deliver over 3,000mAh and the costs are dropping. Cost reduction, increased specific energy and the absence of toxic material paved the road to make Li-ion the universally accepted battery for portable applications, heavy industries, electric powertrains and satellites. The 18650 cell measures 18mm in diameter and 65mm in length. (See “A Look at Old and New Battery Formats” on page 93.)

Li-ion is a low-maintenance battery, an advantage that most other chemistries cannot claim. The battery has no memory and does not need exercising (deliberate full discharge) to keep it in good shape. Self-discharge is less than half that of nickel-based systems and this helps fuel the gauge applications. The nominal cell voltage of 3.60V can directly power mobile phones, tablets and digital cameras, offering simplifications and cost reductions over multi-cell designs. The drawbacks are the need for protection circuits to prevent abuse, as well as high price.

Lithium-ion Architecture

Lithium-ion uses a cathode (positive electrode), an anode (negative electrode) and electrolyte as conductor. The cathode is metal oxide and the anode consists of porous carbon. During discharge, the ions flow from the anode to the cathode through the electrolyte and separator; charge reverses the direction and the ions flow from the cathode to the anode. Figure 2-10 illustrates the process.

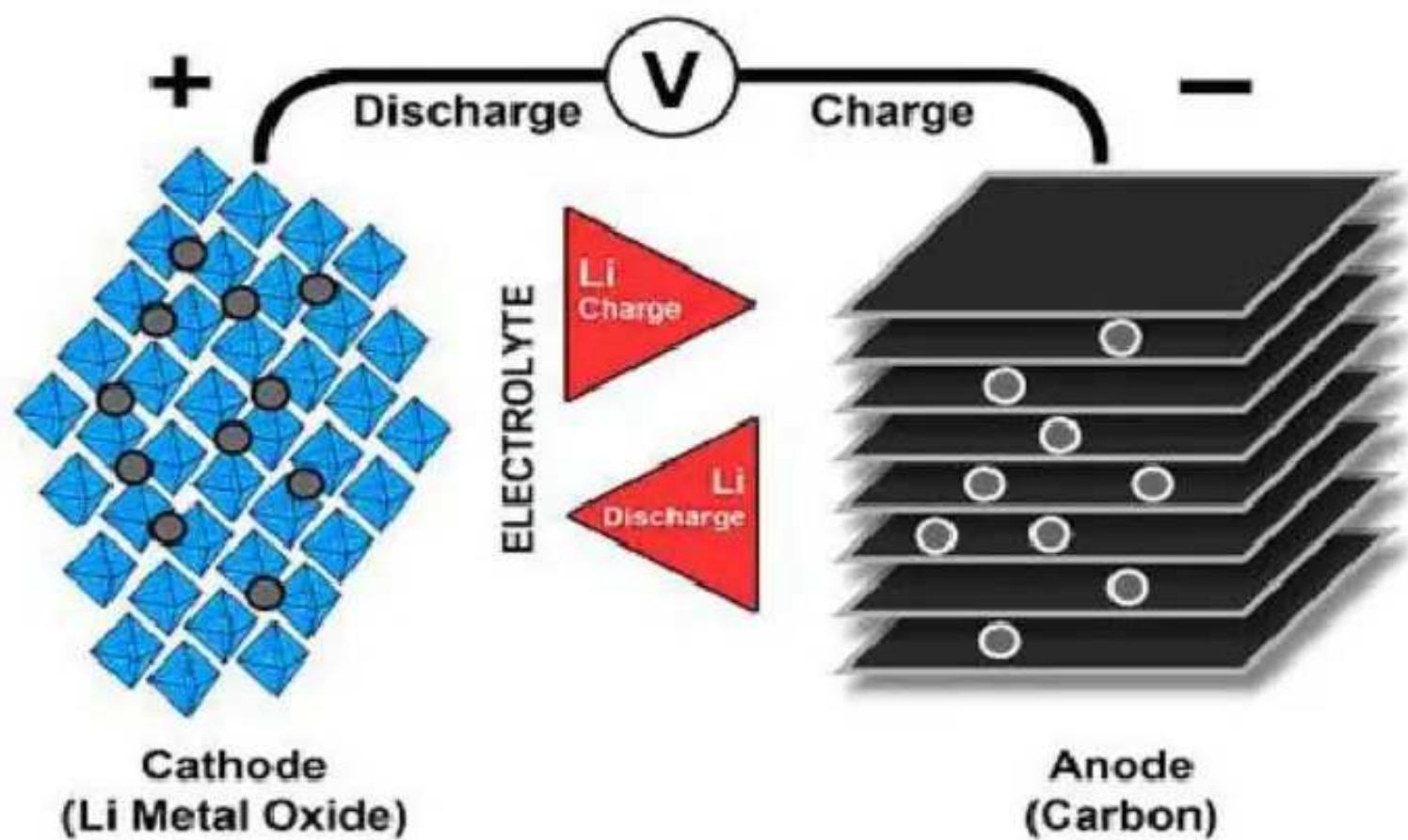


Figure 2-10: Ion flow in lithium-ion battery.

On charge and discharge, ions shuttle between the cathode (positive electrode) and anode (negative electrode). On discharge the anode undergoes oxidation or loss of electrons and the cathode sees a reduction or a gain of electrons. Charge reverses the movement.

Li-ion batteries come in many varieties but all have one thing in common – the “lithium-ion” catchword. Although strikingly similar at first glance, these batteries vary in performance and the choice of active materials gives them unique personalities.

Sony’s original lithium-ion battery used coke as the anode (coal product). Since 1997, most Li-ion manufacturers, including Sony, shifted to graphite to attain a flatter discharge curve. Graphite is a form of carbon that has long-term cycle stability and is used in lead pencils. It is the most common carbon material, followed by hard and soft carbons. Nanotube carbons have not yet found commercial use in Li-ion as they tend to entangle and affect performance. A future material that promises to enhance the performance of Li-ion is graphene.

Figure 2-11 illustrates the voltage discharge curve of a modern Li-ion with graphite anode and the early coke version.

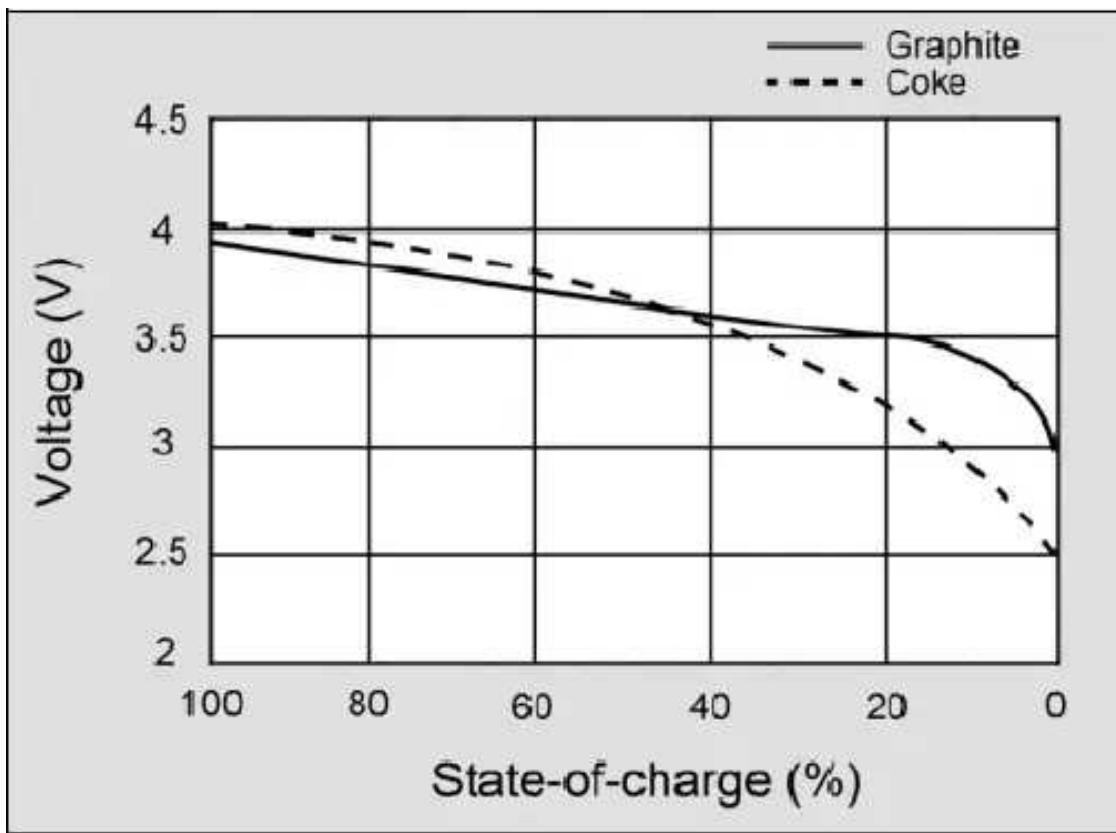


Figure 2-11: Voltage discharge curve of lithium-ion.

A battery should have a flat voltage curve in the usable discharge range. The modern graphite anode does this better than the early coke version.

Courtesy of Cadex

Several additives have been tried, including silicon-based alloys, to enhance the performance of the graphite anode. It takes six carbon (graphite) atoms to bind to a single lithium ion; a single silicon atom can bind to four lithium ions. This means that the silicon anode could theoretically store over 10 times the energy of graphite, but expansion of the anode during charge is a problem. Pure silicone anodes are therefore not practical and only 3–5 percent of silicon is typically added to the anode of a silicon-based to achieve good cycle life.

Using nano-structured lithium-titanate as an anode additive shows promising cycle life, good load capabilities, excellent low-temperature performance and superior safety, but the specific energy is low and the cost is high.

Experimenting with cathode and anode material allows manufacturers to strengthen intrinsic qualities, but one enhancement may compromise another. The so-called “Energy Cell” optimizes the specific energy (capacity) to achieve

long runtimes but at lower specific power; the “Power Cell” offers exceptional specific power but at lower capacity. The “Hybrid Cell” is a compromise and offers a little bit of both.

Manufacturers can attain a high specific energy and low cost relatively easily by adding nickel in lieu of the more expensive cobalt, but this makes the cell less stable. While a start-up company may focus on high specific energy and low price to gain quick market acceptance, reputable manufacturers place high integrity on safety and longevity.

Types of Lithium-ion Batteries

Lithium-ion is named for its active materials; the words are either written in full or shortened by their chemical symbols. A series of letters and numbers strung together can be hard to remember and even harder to pronounce, and battery chemistries are also identified in abbreviated letters.

For example, lithium cobalt oxide, one of the most common Li-ions, has the chemical symbols LiCoO_2 and the abbreviation LCO. For reasons of simplicity, the short form Li-cobalt can also be used for this battery. Cobalt is the main active material that gives this battery character. Other Li-ion chemistries are given similar short-form names. This section lists six of the most common Li-ions. All readings are average estimates at time of writing.

Lithium Cobalt Oxide (LiCoO_2)

Its high specific energy makes Li-cobalt the popular choice for mobile phones, laptops and digital cameras. The battery consists of a cobalt oxide cathode and a graphite carbon anode. The cathode has a layered structure and during discharge, lithium ions move from the anode to the cathode. The flow reverses on charge. Figure 2-12 illustrates the structure.

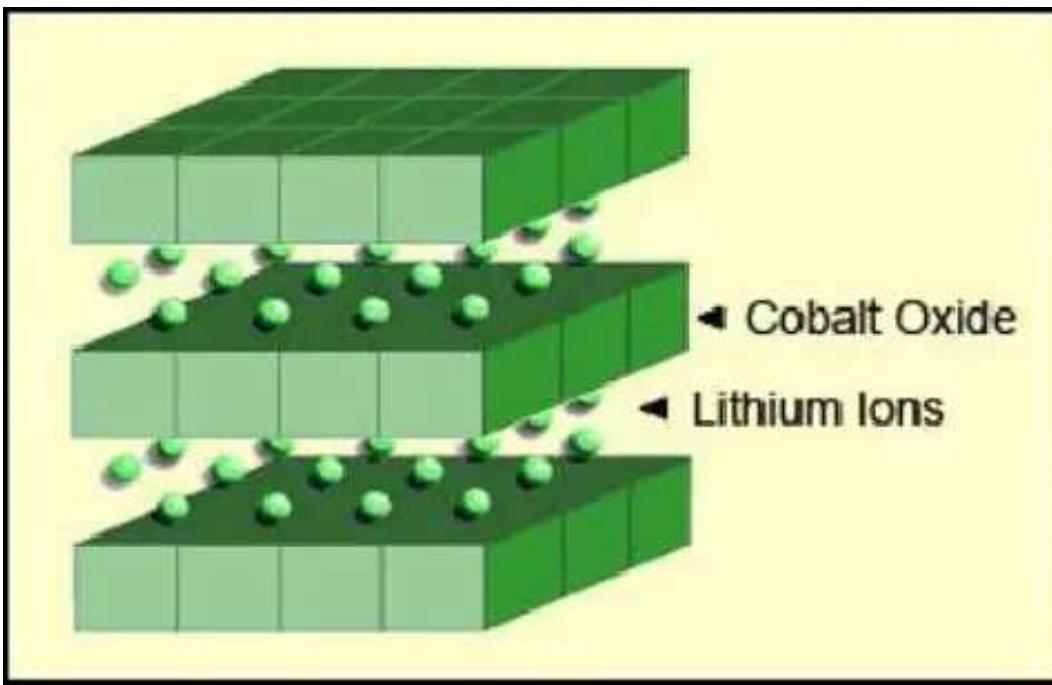


Figure 2-12: Li-cobalt structure.

The cathode has a layered structure. During discharge the lithium ions move from the anode to the cathode; on charge the flow is from cathode to anode.

Courtesy of Cadex

The drawback of Li-cobalt is a relatively short life span, low thermal stability and limited load capabilities (specific power). Li-cobalt is maturing and newer systems include nickel, manganese and/or aluminum to improve longevity, loading capabilities and cost.

Li-cobalt should not be charged and discharged at a current higher than its C-rate. This means that an 18650 cell with 2,400mAh can only be charged and discharged at 2,400mA. Forcing a fast charge or applying a load higher than 2,400mA causes overheating and undue stress. For optimal fast charge, the manufacturer recommends a C-rate of 0.8C or about 2,000mA. (See “What Is C-rate” on page 131.) The mandatory battery protection circuit limits the charge and discharge rate to a safe level of about 1C for the Energy Cell.

The hexagonal spider graphic (Figure 2-13) summarizes the performance of Li-cobalt in terms of specific energy or capacity that relates to runtime; specific power or the ability to deliver high current; safety; performance at hot and cold temperatures; life span reflecting cycle life and longevity; and cost. Other characteristics of interest not shown in the spider webs are toxicity, fast charge

capabilities, self-discharge and shelf life.

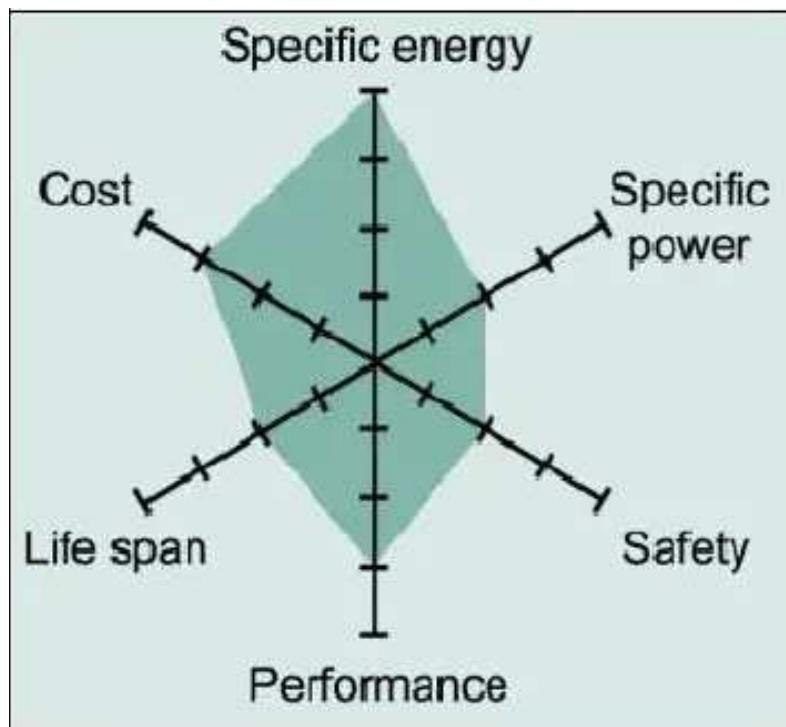


Figure 2-13: Snapshot of an average Li-cobalt battery.

Li-cobalt excels on high specific energy but offers only moderate performance on specific power, safety and life span.

Courtesy of Cadex

Lithium Cobalt Oxide: LiCoO ₂ cathode (~60% Co), graphite anode Short form: LCO or Li-cobalt.		Since 1991
Voltages	3.60V nominal; typical operating range 3.0–4.2V/cell	
Specific energy (capacity)	150–200Wh/kg. Specialty cells provide up to 240Wh/kg.	
Charge (C-rate)	0.7–1C, charges to 4.20V (most cells); 3h charge typical. Charge current above 1C shortens battery life.	
Discharge (C-rate)	1C; 2.50V cut off. Discharge current above 1C shortens battery life.	
Cycle life	500–1000, related to depth of discharge, load, temperature	
Thermal runaway	150°C (302°F). Full charge promotes thermal runaway	
Applications	Mobile phones, tablets, laptops, cameras	
Comments	Very high specific energy, limited specific power. Cobalt is expensive. Serves as <i>Energy Cell</i> . Market share has stabilized.	

Summary Table 2-14: Characteristics of lithium cobalt oxide.

Lithium Manganese Oxide (LiMn_2O_4)

Li-ion with manganese spinel was first published in the *Materials Research Bulletin* in 1983. In 1996, Moli Energy commercialized a Li-ion cell with lithium manganese oxide as cathode material. The architecture forms a three-dimensional spinel structure that improves ion flow on the electrode, which results in lower internal resistance and improved current handling. A further advantage of spinel is high thermal stability and enhanced safety, but the cycle and calendar life are limited.

Figure 2-15 illustrates the formation of a three-dimensional crystalline framework on the cathode of a Li-manganese battery. This spinel structure, which is usually composed of diamond shapes connected into a lattice, appears after initial formation.

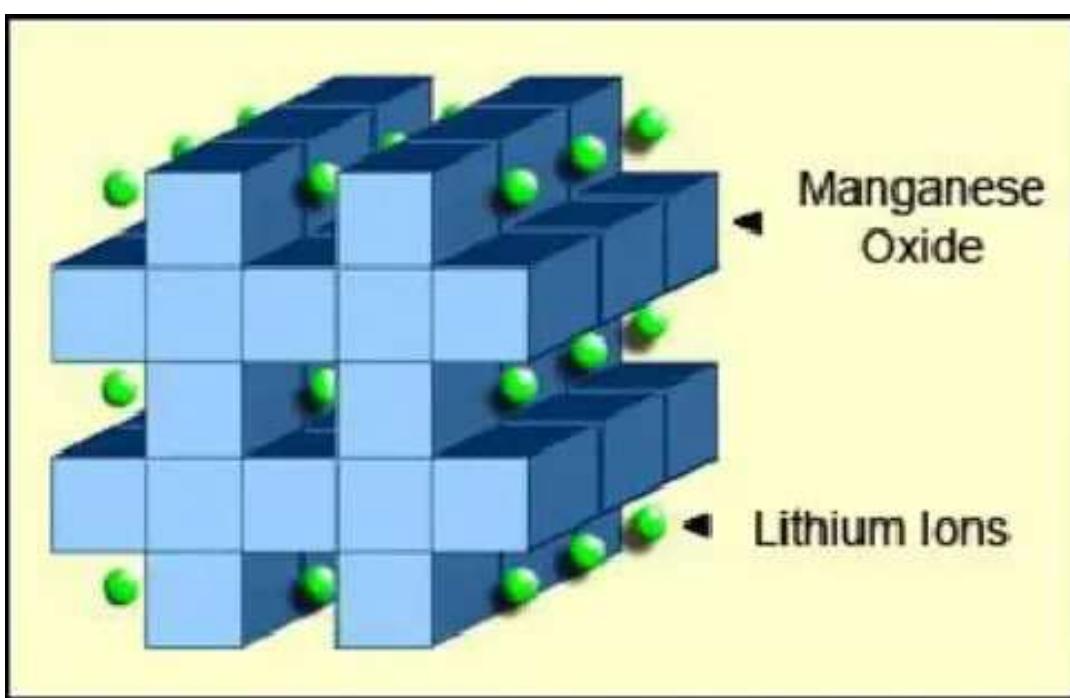


Figure 2-15: Li-manganese structure.

The cathode crystalline formation of lithium manganese oxide has a three-dimensional framework structure that appears after initial formation. Spinel provides low resistance but has more moderate specific energy than cobalt.

Courtesy of Cadex

Low internal cell resistance enables fast charging and high-current discharging. In an 18650 package, Li-manganese can be discharged at currents of 20–30A with moderate heat buildup. It is also possible to apply one-second

load pulses of up to 50A. A continuous high load at this current would cause heat buildup and the cell temperature cannot exceed 80°C (176°F). Li-manganese is used for power tools, medical instruments, as well as hybrid and electric vehicles.

Li-manganese has a capacity that is roughly one-third lower than Li-cobalt. Design flexibility allows engineers to maximize the battery for either optimal longevity (life span), maximum load current (specific power) or high capacity (specific energy). For example, the long-life version in the 18650 cell has a moderate capacity of only 1,100mAh; the high-capacity version is 1,500mAh.

Figure 2-16 shows the spider web of a typical Li-manganese battery. The characteristics appear marginal but newer designs have improved in terms of specific power, safety and life span. Pure Li-manganese batteries are no longer common today; they may only be used for special applications.

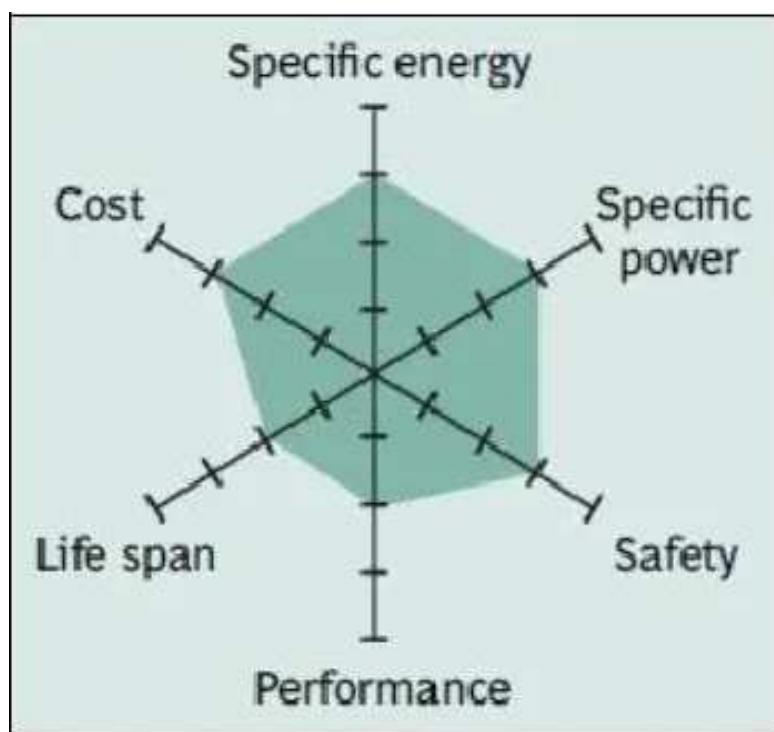


Figure 2-16: Snapshot of a typical Li-manganese battery.

Although moderate in overall performance, newer designs of Li-manganese offer improvements in specific power, safety and life span.

Source: Boston Consulting Group

Most Li-manganese batteries blend with lithium nickel manganese cobalt oxide (NMC) to improve the specific energy and prolong the life span. This

combination brings out the best in each system, and the LMO (NMC) is chosen for most electric vehicles, such as the Nissan Leaf, Chevy Volt and BMW i3. The LMO part of the battery, which can be about 30 percent, provides high current boost on acceleration; the NMC part gives the long driving range.

Li-ion research gravitates heavily towards combining Li-manganese with cobalt, nickel, manganese and/or aluminum as active cathode material. In some architecture, a small amount of silicon is added to the anode. This provides a 25 percent capacity boost; however, the gain is commonly connected with a shorter cycle life as silicon grows and shrinks with charge and discharge, causing mechanical stress.

These three active metals, as well as the silicon enhancement can conveniently be chosen to enhance the specific energy (capacity), specific power (load capability) or longevity. While consumer batteries go for high capacity, industrial applications require battery systems that have good loading capabilities, deliver a long life and provide safe and dependable service.

Lithium Manganese Oxide: LiMn_2O_4 cathode. graphite anode <i>Short form:</i> LMO or Li-manganese (spinel structure)		Since 1996
Voltages	3.70V (3.80V) nominal; typical operating range 3.0–4.2V/cell	
Specific energy (capacity)	100–150Wh/kg	
Charge (C-rate)	0.7–1C typical, 3C maximum, charges to 4.20V (most cells)	
Discharge (C-rate)	1C; 10C possible with some cells, 30C pulse (5s), 2.50V cutoff	
Cycle life	300–700 (related to depth of discharge, temperature)	
Thermal runaway	250°C (482°F) typical. High charge promotes thermal runaway	
Applications	Power tools, medical devices, electric powertrains	
Comments	High power but less capacity; safer than Li-cobalt; commonly mixed with NMC to improve performance.	

Summary Table 2-17: Characteristics of lithium manganese oxide.

Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO² or NMC)
One of the most successful Li-ion systems is a cathode combination of nickel-

manganese-cobalt (NMC). Similar to Li-manganese, these systems can be tailored to serve as Energy Cells or Power Cells. For example, NMC in an 18650 cell for moderate load condition has a capacity of about 2,800mAh and can deliver 4–5A; NMC in the same cell optimized for specific power has a capacity of only about 2,000mWh but delivers a continuous discharge current of 20A. A silicon-based anode will go to 4,000mAh and higher but at reduced loading capability and shorter cycle life. Silicon added to graphite has the drawback that the anode grows and shrinks with charge and discharge, making the cell mechanically unstable.

The secret of NMC lies in combining nickel and manganese. An analogy of this is table salt in which the main ingredients, sodium and chloride, are toxic on their own but mixing them serves as seasoning salt and food preserver. Nickel is known for its high specific energy but poor stability; manganese has the benefit of forming a spinel structure to achieve low internal resistance but offers a low specific energy. Combining the metals enhances each other strengths.

NMC is the battery of choice for power tools, e-bikes and other electric powertrains. The cathode combination is typically one-third nickel, one-third manganese and one-third cobalt, also known as 1-1-1. This offers a unique blend that also lowers the raw material cost due to reduced cobalt content. Another successful combination is NCM with 5 parts nickel, 3 parts cobalt and 2 parts manganese. Further combinations using various amounts of cathode materials are possible. New electrolytes and additives enable charging to 4.4V/cell and higher to boost capacity. Figure 2-18 demonstrates the characteristics of the NMC.

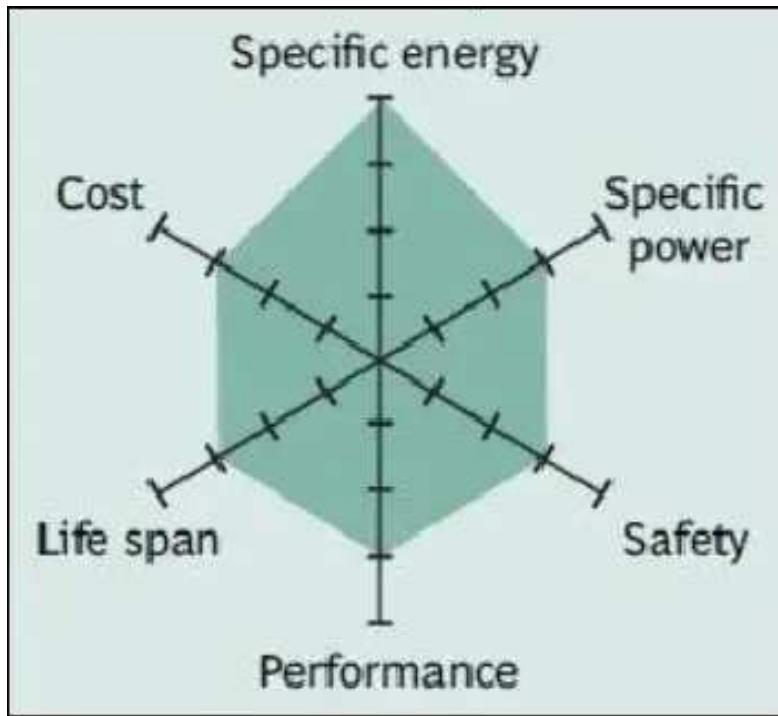


Figure 2-18: Snapshot of NMC.

NMC has good overall performance and excels on specific energy. This battery is the preferred candidate for the electric vehicle and has the lowest self-heating rates.

Source: Boston Consulting Group

There is a move towards NMC-blended Li-ion as the system can be built economically and it achieves a good performance. The three active materials of nickel, manganese and cobalt can easily be blended to suit a wide range of applications for automotive and energy storage systems (EES) that need frequent cycling. The NMC family is growing in its diversity.

Lithium Nickel Manganese Cobalt Oxide: LiNiMnCoO_2 cathode, graphite anode <i>Short form: NMC (NCG, CMN, CNM, MNC, MCN similar with different metal combinations)</i> Since 2008	
Voltages	3.60V, 3.70V nominal; typical operating range 3.0–4.2V/cell, or higher
Specific energy (capacity)	150–220Wh/kg
Charge (C-rate)	.7–1C, charges to 4.20V, some go to 4.30V; 3h charge typical. Charge current above 1C shortens battery life.
Discharge (C-rate)	1C; 2C possible on some cells; 2.50V cutoff
Cycle life	1000–2000 (related to depth of discharge, temperature)
Thermal runaway	210°C (410°F) typical. High charge promotes thermal runaway
Applications	E-bikes, medical devices, EVs, industrial

Comments	Provides high capacity and high power. Serves as Hybrid Cell. Favorite chemistry for many uses; market share is increasing.
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Summary Table 2-19: Characteristics of lithium nickel manganese cobalt oxide (NMC).

Lithium Iron Phosphate (LiFePO_4)

In 1996, the University of Texas (and other contributors) discovered phosphate as cathode material for rechargeable lithium batteries. Li-phosphate offers good electrochemical performance with low resistance. This is made possible with nano-scale phosphate cathode material. The key benefits are high current rating and long cycle life, besides good thermal stability, enhanced safety and tolerance if abused.

Li-phosphate is more tolerant to full charge conditions and is less stressed than other lithium-ion systems if kept at high voltage for a prolonged time. (See “How to Prolong Lithium-based Batteries” on page 249.) As a trade-off, the lower voltage of 3.2V/cell reduces the specific energy to less than that of Li-manganese. With most batteries, cold temperature reduces performance and elevated storage temperature shortens the service life, and Li-phosphate is no exception. Li-Phosphate has a higher self-discharge than other Li-ion batteries, which can cause balancing issues with aging. Figure 2-20 summarizes the attributes of Li-phosphate.

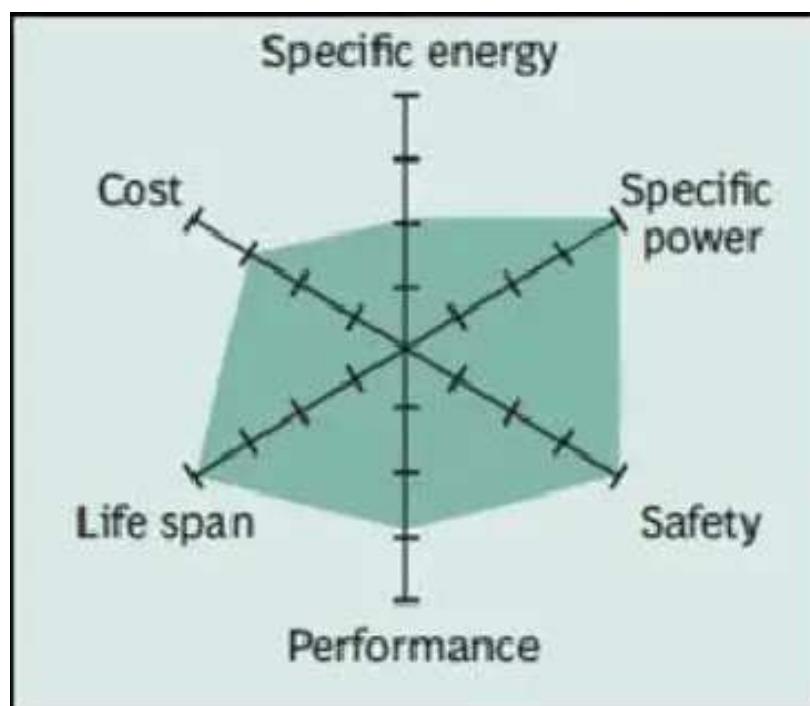


Figure 2-20 Snapshot of a typical Li-phosphate battery.

Li-phosphate has excellent safety and long life span but moderate specific energy and elevated self-discharge.

Courtesy of Cadex

Lithium Iron Phosphate: LiFePO ₄ cathode, graphite anode <i>Short form:</i> LFP or Li-phosphate		Since 1996
Voltages	3.20, 3.30V nominal; typical operating range 2.5–3.65V/cell	
Specific energy (capacity)	90–120Wh/kg	
Charge (C-rate)	1C typical, charges to 3.65V; 3h charge time typical	
Discharge (C-rate)	1C, 25C on some cells; 40A pulse (2s); 2.50V cutoff (lower than 2V causes damage)	
Cycle life	1000–2000 (related to depth of discharge, temperature)	
Thermal runaway	270°C (518°F) Very safe battery even if fully charged	
Applications	Portable and stationary needing high load currents and endurance	
Comments	Very flat voltage discharge curve but low capacity. One of safest Li-ions. Used for special markets. Elevated self-discharge.	

Summary Table 2-21: Characteristics of lithium iron phosphate.

Li-phosphate is often used to replace the lead acid starter battery. Four cells in series produce 12.80V, a similar voltage to six 2V lead acid cells in series. Vehicles charge lead acid to 14.40V (2.40V/cell) and maintain a topping charge.

With four Li-phosphate cells in series, each cell tops at 3.60V, which is the correct full-charge voltage. At this point, the charge should be disconnected but the topping charge continues while driving. Li-phosphate is tolerant to some overcharge; however, keeping the voltage at 14.40V for a prolonged time, as most vehicles do on a long drive, could stress Li-phosphate. Cold temperature operation starting could also be an issue with Li-phosphate as a starter battery.

Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO₂)

Lithium nickel cobalt aluminum oxide battery, or NCA, has been around since 1999 for special applications. It shares similarities with NMC by offering high specific energy, reasonably good specific power and a long life span. Less

flattering are safety and cost. Figure 2-22 summarizes the six key characteristics. NCA is a further development of lithium nickel oxide; adding aluminum gives the chemistry greater stability.

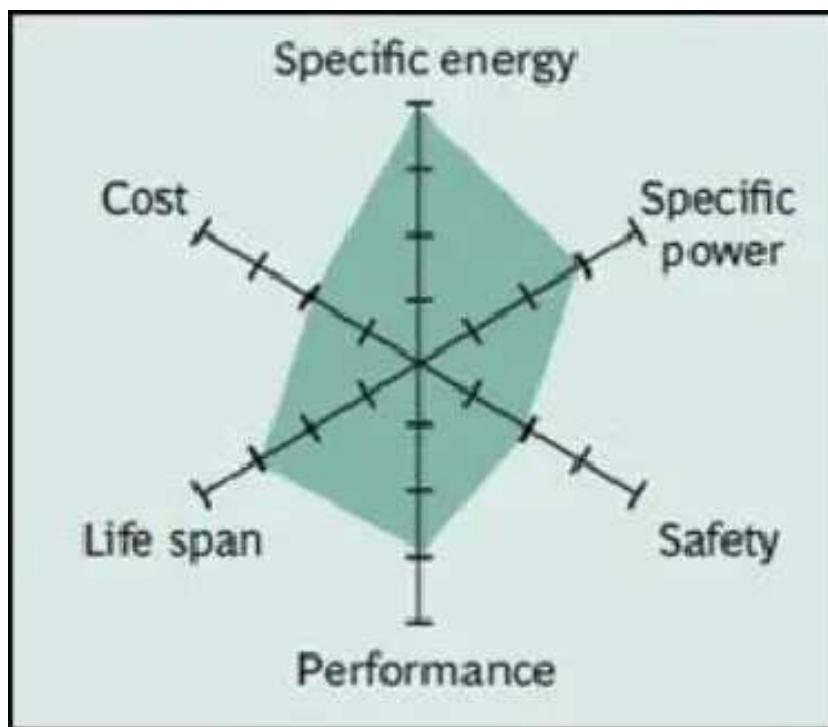


Figure 2-22: Snapshot of NCA.

High energy and power densities, as well as good life span, make NCA a candidate for EV powertrains. High cost and marginal safety are negatives.

Courtesy of Cadex

Lithium Nickel Cobalt Aluminum Oxide: LiNiCoAlO ₂ cathode (~9% Co), graphite anode <i>Short form:</i> NCA or Li-aluminum.		Since 1999
Voltages	3.60V nominal; typical operating range 3.0–4.2V/cell	
Specific energy (capacity)	200-260Wh/kg; 300Wh/kg predictable	
Charge (C-rate)	0.7C, charges to 4.20V (most cells), 3h charge typical, fast charge possible with some cells	
Discharge (C-rate)	1C typical; 3.0V cutoff; high discharge rate shortens battery life	
Cycle life	500 (related to depth of discharge, temperature)	
Thermal runaway	150°C (302°F) typical, High charge promotes thermal runaway	
Applications	Medical devices, industrial, electric powertrain (Tesla)	
Comments	Shares similarities with Li-cobalt. Serves as <i>Energy Cell</i> .	

Summary Table 2-23: Characteristics of lithium nickel cobalt aluminum oxide.

Lithium Titanate ($\text{Li}_4\text{Ti}_5\text{O}_{12}$)

Batteries with lithium titanate anodes have been known since the 1980s. Li-titanate replaces the graphite in the anode of a typical lithium-ion battery and the material forms into a spinel structure. The cathode can be lithium manganese oxide or NMC. Li-titanate has a nominal cell voltage of 2.40V, can be fast charged and delivers a high discharge current of 10C, or 10 times the rated capacity. The cycle count is said to be higher than that of a regular Li-ion. Li-titanate is safe, has excellent low-temperature discharge characteristics and obtains a capacity of 80 percent at -30°C (-22°F). However, the battery is expensive and at 65Wh/kg the specific energy is low, rivalling that of NiCd. Li-titanate charges to 2.80V/cell, and the end of discharge is 1.80V/cell. Figure 2-24 illustrates the characteristics of the Li-titanate battery. Typical uses are electric powertrains, UPS and solar-powered street lighting.

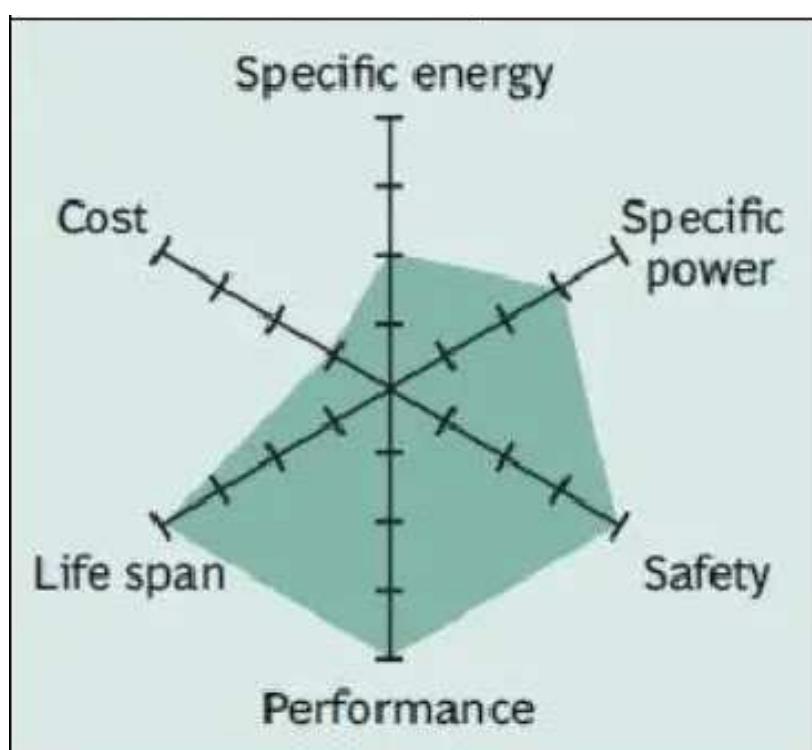


Figure 2-24: Snapshot of Li-titanate.

Li-titanate excels in safety, low-temperature performance and life span. Efforts are being made to improve the specific energy and lower cost.

Source: Boston Consulting Group

Lithium Titanate: Can be lithium manganese oxide or NMC; $\text{Li}_4\text{Ti}_5\text{O}_{12}$ (titanate) anode
Short form: LTO or Li-titanate Commercially available since about 2008

Voltages	2.40V nominal; typical operating range 1.8–2.85V/cell
Specific energy (capacity)	70–80Wh/kg
Charge (C-rate)	1C typical; 5C maximum, charges to 2.85V,
Discharge (C-rate)	10C possible, 30C 5s pulse; 1.80V cutoff on LCO/LTO
Cycle life	3,000–7,000
Thermal runaway	One of safest Li-ion batteries
Applications	UPS, electric powertrain, solar-powered street lighting
Comments	Long life, fast charge, wide temperature range but low specific energy and expensive. Among safest Li-ion batteries.

Summary Table 2-25: Characteristics of lithium titanate.

Figure 2-26 compares the specific energy of lead-, nickel- and lithium-based systems. While Li-aluminum (NCA) is the clear winner by storing more capacity than other systems, this only applies to specific energy. In terms of specific power and thermal stability, Li-manganese (LMO) and Li-phosphate (LFP) are superior. Li-titanate (LTO) may have low capacity but this chemistry outlives most other batteries in terms of life span and also has the best cold temperature performance. Moving towards the electric powertrain, safety and cycle life will gain dominance over capacity. (LCO stands for Li-cobalt, the original Li-ion.

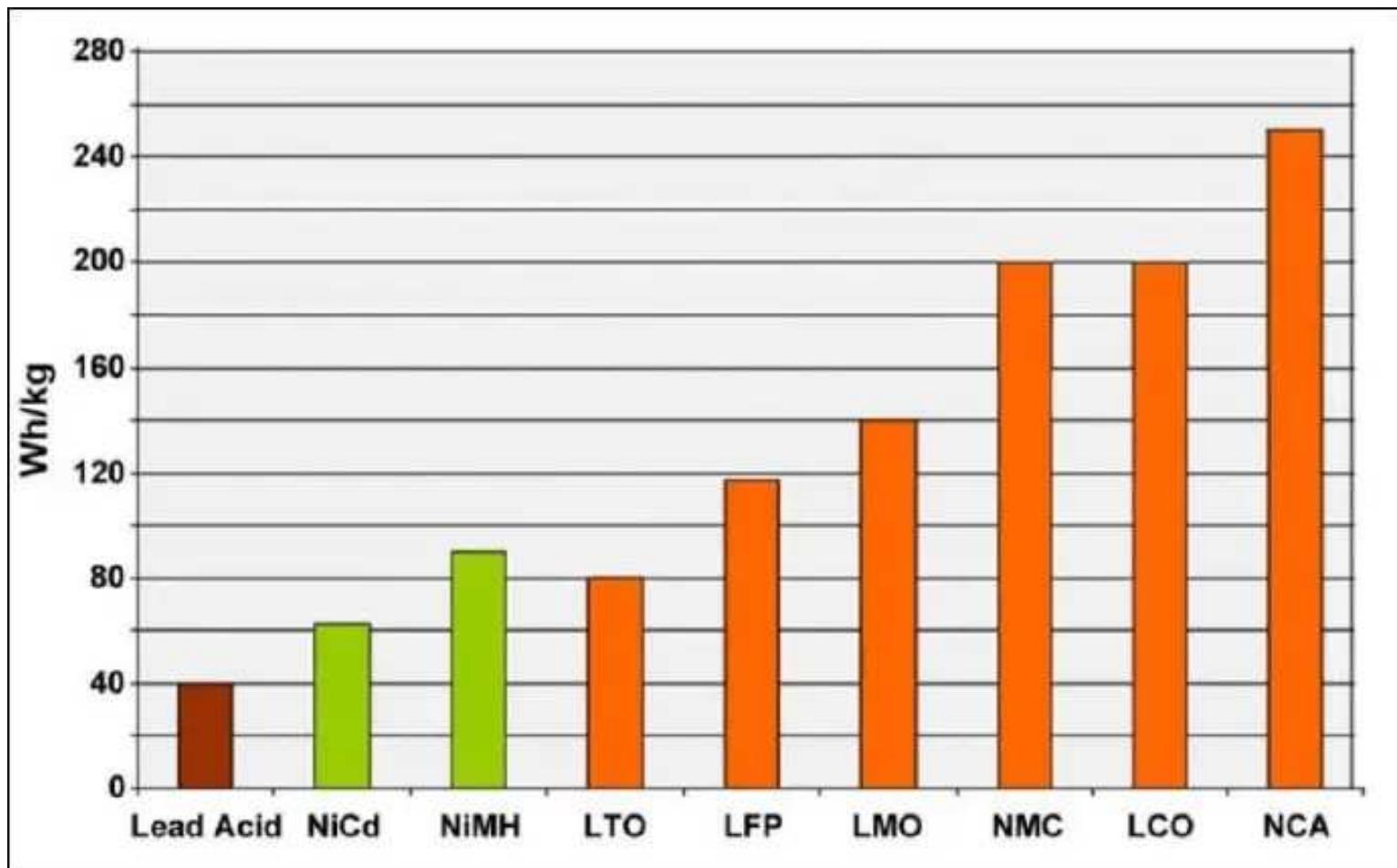


Figure 2-26: Specific energy of lead-, nickel- and lithium-based batteries.

NCA enjoys the highest specific energy; however, manganese and phosphate are superior in terms of specific power and thermal stability. Li-titanate has the best life span.

Courtesy of Cadex

Lithium-polymer: Substance or Hype?

The term *polymer* is commonly mentioned when describing a lithium-based battery, yet users cannot distinguish between regular Li-ion and a pack with the polymer architecture. Adding another battery type has little benefit and only confuses the market further. While the word “polymer” is perceived as a plastic, polymers range from synthetic plastics to natural biopolymers and proteins that form fundamental biological structures.

Lithium-polymer differs from other battery systems in the type of electrolyte used. The original polymer design dating back to the 1970s used a solid (dry) polymer electrolyte that resembles a plastic-like film. This insulator allows the exchange of ions (electrically charged atoms) and replaces the traditional porous separator that is soaked with electrolyte.

A solid polymer has poor conductivity at room temperature, and the battery must be heated to 60°C (140°F) and higher to enable current flow. Large polymer batteries for stationary applications were installed that needed heating, but these have since disappeared. The much anticipated hype of the “true plastic battery” promised in the early 2000s did not materialize as conductivity could not be attained at ambient temperature.

To make the modern Li-polymer battery conductive at room temperature, gelled electrolyte has been added. Most Li-ion polymer cells today incorporate a micro porous separator with some moisture. Li-polymer can be built on many systems, the likes of Li-cobalt, NMC, Li-phosphate and Li-manganese, and is not considered a unique battery chemistry. The majority of Li-polymer packs are cobalt based; other active material may also be added.

With gelled electrolyte, what is the difference between a normal Li-ion and Li-ion polymer? As far as the user is concerned, lithium polymer is essentially the same as lithium-ion. Both systems use identical cathode and anode material and contain a similar amount of electrolyte.

Li-polymer is unique in that a micro porous electrolyte replaces the traditional porous separator. Li-polymer offers slightly higher specific energy and can be made thinner than conventional Li-ion, but the manufacturing cost is said to be higher than cylindrical design. For the purpose of discussion, pouch cells are often identified as being Li-polymer.

Li-polymer cells also come in a flexible foil-type case that resembles a food package. While a standard Li-ion needs a rigid case to press the electrodes together, Li-polymer uses laminated sheets that do not need compression. A foil-type enclosure reduces the weight by more than 20 percent over the classic hard shell. Thin film technology liberates the design as the battery can be made into any shape, fitting neatly into stylish mobile phones and tablets. Li-polymer can also be made very slim to resemble a credit card. (See “Pouch Cell” page 98.) Light weight and high specific power make Li-polymer the preferred choice for hobbyists.

Charge and discharge characteristics of Li-polymer are identical to other Li-ion systems and do not require a dedicated charger. Safety issues are also similar in that protection circuits are needed. Gas buildup during charge can cause some prismatic and pouch cells to swell, and equipment manufacturers must make allowances for expansion. Li-polymer in a foil package may be less durable than Li-ion in the cylindrical package. Table 2-27 compares the advantages and limitations of Li-ion.

Advantages	High specific energy and high load capabilities with Power Cells Long cycle and extended shelf-life; maintenance-free High capacity, low internal resistance, good coulombic efficiency Simple charge algorithm and reasonably short charge times Nickel content makes recycling profitable Low self-discharge (less than half that of NiCd and NiMH)
Limitations	Requires protection circuit to prevent thermal runaway if stressed Degrades at high temperature and when stored at high voltage No rapid charge possible at freezing temperatures (<0°C, <32°F) Transportation regulations required when shipping in larger quantities

Table 2-27: Advantages and limitations of Li-ion batteries

Cycling Performance

To compare older and newer battery systems, Cadex tested a large volume of

nickel-cadmium, nickel-metal-hydride and lithium-ion batteries used in portable communication devices. Preparations included an initial charge, followed by a regime of full discharge/charge cycles at a 1C rate. The following tables show the capacity in percent, DC resistance measurement and self-discharge obtained from time to time by reading the capacity loss incurred during a 48-hour rest period. The tests were carried out on Cadex 7000 Series battery analyzers with a 1C charge and discharge and a 100 percent depth-of-discharge (DoD).

Nickel-cadmium

In terms of life cycling, NiCd is the most enduring battery. Figure 2-28 illustrates capacity, internal resistance and self-discharge of a 7.2V, 900mA pack with standard NiCd cell. The internal resistance stayed low at $75\text{m}\Omega$ and the self-discharge was stable. Due to time constraints, the test was terminated after 2,300 cycles.

This battery receives a grade “A” rating for almost perfect performance in terms of minimal capacity loss when cycling with a 100 percent DoD and rock-solid internal resistance over the entire test. NiCd is the only chemistry that can be ultra-fast charged with little stress. Due to its safe operation, NiCd remains the preferred choice of battery on board aircrafts.

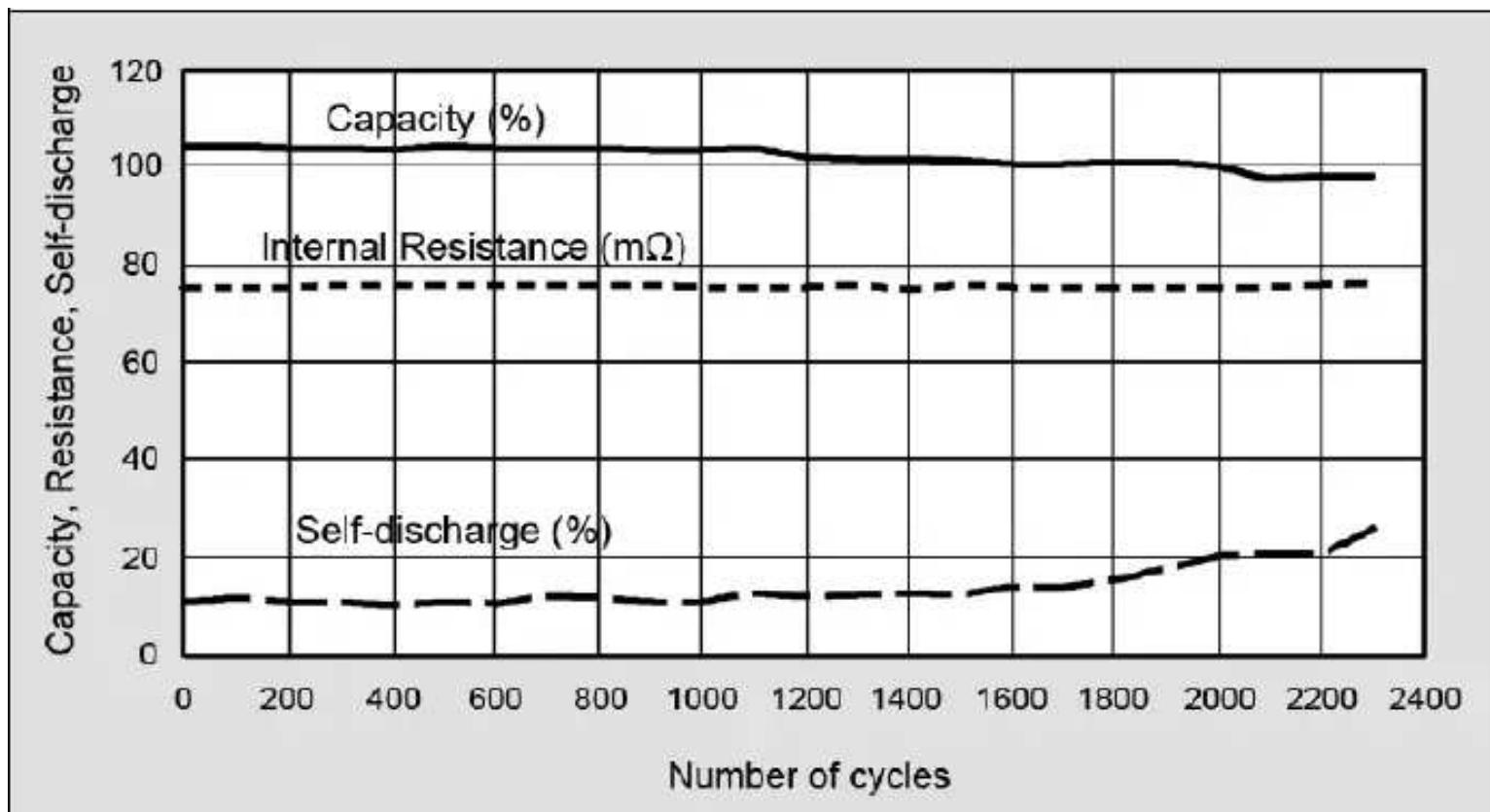


Figure 2-28: Performance of standard NiCd. (7.2V, 900mAh)

This battery receives an “A” rating for stable capacity and low internal resistance over many cycles.

Courtesy of Cadex

The ultra-high capacity nickel-cadmium offers up to 60 percent higher specific energy compared to the standard version, but this comes at the expense of reduced cycle life. Figure 2-29 observes a steady drop of capacity during 2,000 cycles, a slight increase in internal resistance and a notable rise in self-discharge after 1,000 cycles.

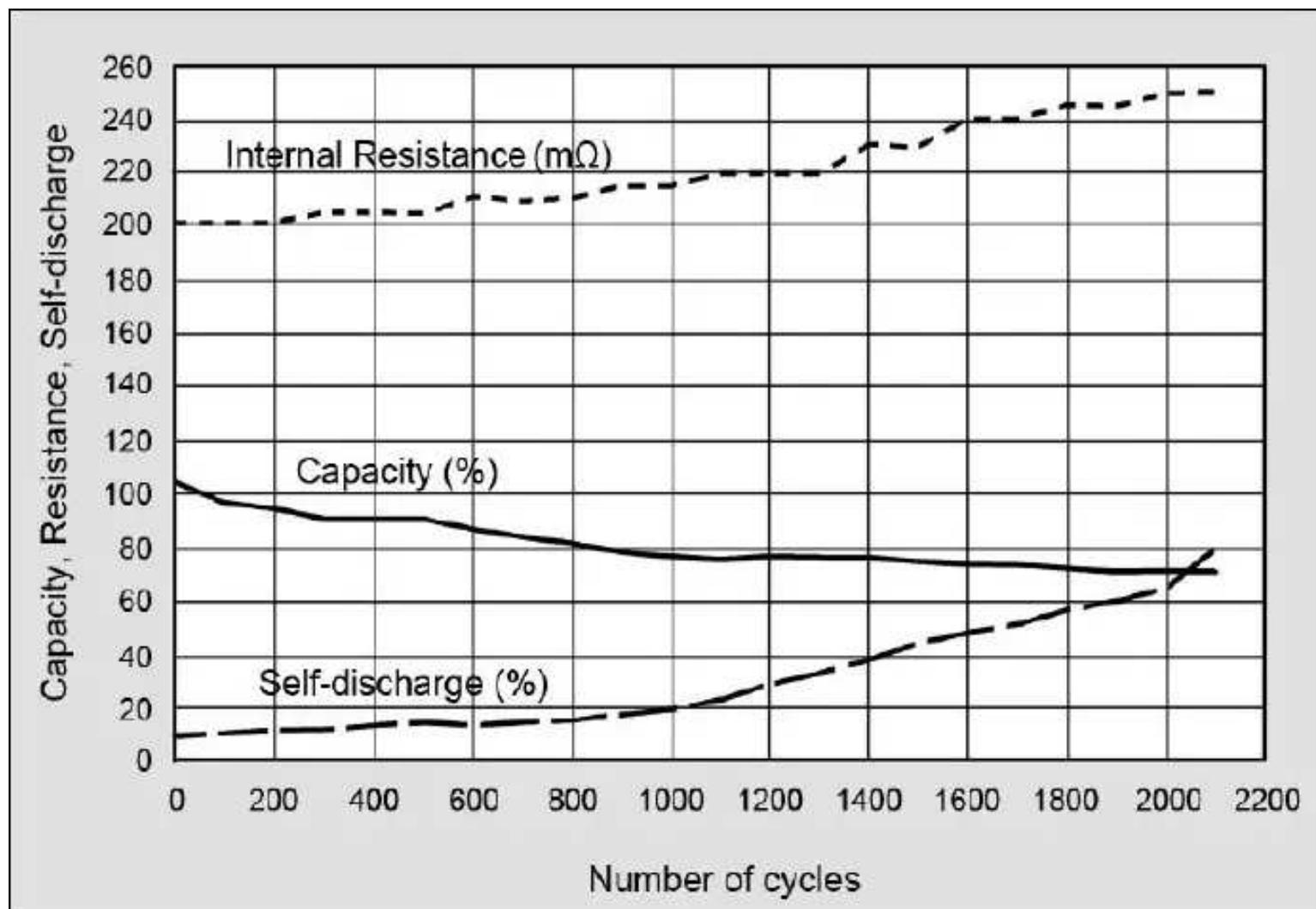


Figure 2-29: Performance of ultra-high-capacity NiCd. (6V, 700mAh)

This battery offers higher specific energy than the standard version at the expense of reduced cycle life.

Courtesy of Cadex

Nickel-metal-hydride

Figure 2-30 examines NiMH, a battery that offers high specific energy but loses capacity after the 300-cycle mark. There is also a rapid increase in internal resistance after a cycle count of 700 and a rise in self-discharge after 1000 cycles. The test was done on an older generation NiMH.

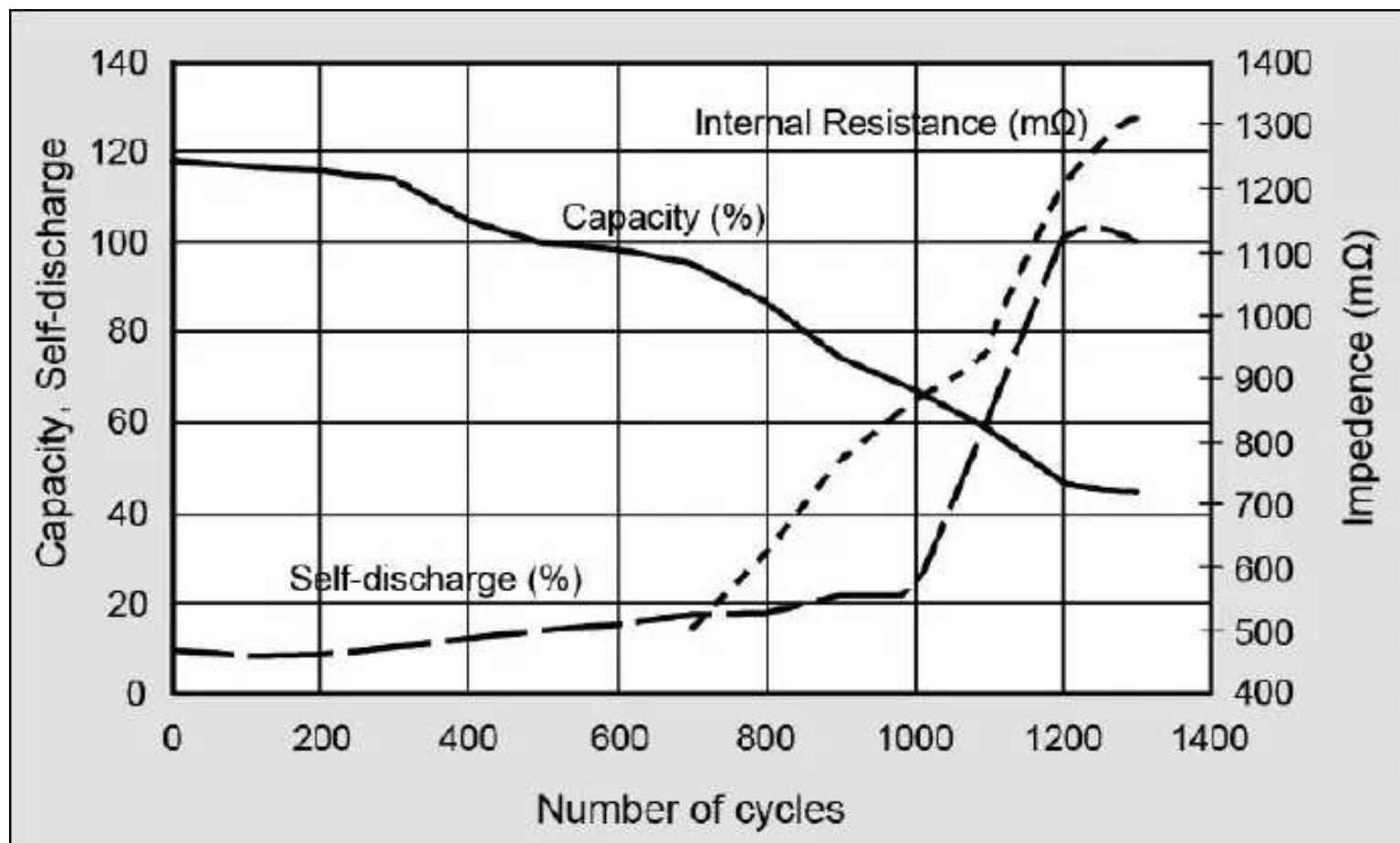


Figure 2-30: Performance of NiMH. (6V, 950mAh)

This battery offers good performance at first but past 300 cycles, the capacity, internal resistance and self-discharge start to increase rapidly.

Courtesy of Cadex

Lithium-ion

Figure 2-31 examines the capacity fade of a modern Li-ion Power Cell at a 2A, 10A, 15A and 20A discharge. Stresses increase with higher load currents and this also applies to fast charging. The rugged Power Cell is more enduring than the more delicate Energy Cell.

Li-ion manufacturers seldom specify the rise of internal resistance and self-discharge as a function of cycling. Advancements have been made with electrolyte additives that keep the resistance low through most of the battery life. The self-discharge of Li-ion is normally low but it can increase if misused or if exposed to deep discharges.

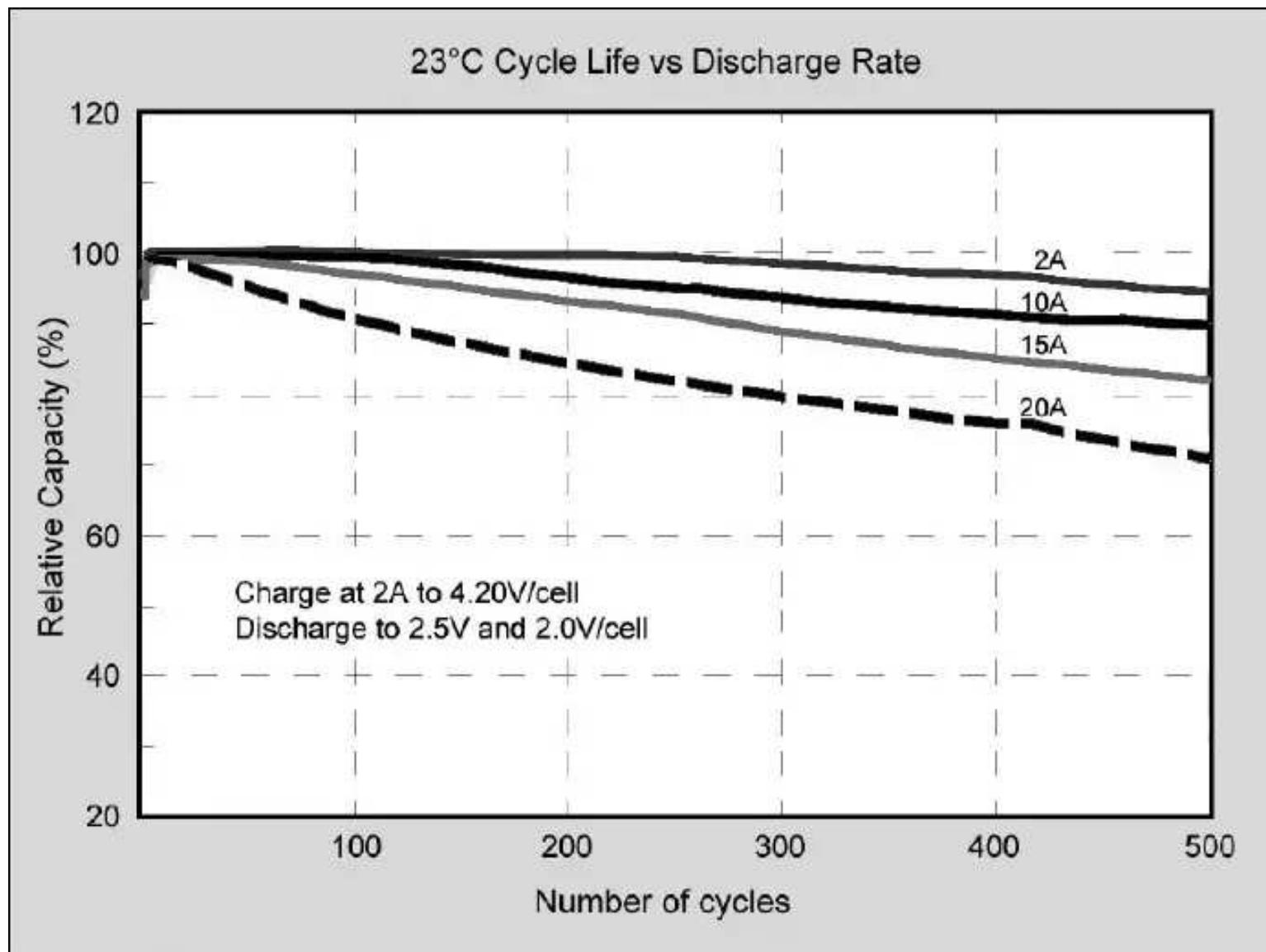


Figure 2-31: Cycle characteristics of IHR18650C by E-One Moli. (3.6V, 2,000mA)

18650 Power Cell was charged with 2A and discharged at 2, 10, 15 and 20A. The internal resistance and self-discharge are N/A.

Source: E-One Moli Energy

Batteries tested in a laboratory tend to provide better results than in the field. Elements of stress in everyday use do not always transfer well into a test laboratory. Aging plays a negligible role in a lab because the batteries are cycled over a period of a few months rather than the expected service life of several years. The temperature is often moderate and the batteries are charged under controlled charging condition and with approved chargers.

The load signature also plays a role as all batteries were discharged with a DC load. Batteries tend to have a lower cycle life if discharged with pulses. (See “Basics about Discharging” on page 165.) Do not overstress a battery as this will

shorten the life. If a battery must repeatedly be loaded at peak currents, choose a pack with increased Ah rating.

Alternate Battery Systems

The media promotes wonderful new batteries that promise long runtimes, charge in minutes, are paper-thin and will one day power the electric car. While these experimental batteries produce a voltage, the downsides are seldom mentioned. The typical shortcomings are low load capacity and short cycle life.

As a lemon can be made into a battery, so also has seawater been tried as electrolyte, but the retrieved energy is only good to light an incandescent flashlight for a short time before corrosion buildup renders the battery unusable. Many chemical processes are being tried to generate electricity but only a few promise to surpass today's lead, nickel and lithium systems.

There is much media hype, and this may be done in part to attract venture capitalists to fund research projects. Few products have incubation periods that are as long as a battery's. Although glamorous and promising at first, especially if the battery promises to power the electric vehicle, investment firms are beginning to realize the high development costs, uncertainties and long gestation periods before a return can be realized. Meanwhile, universities continue publishing papers about battery breakthroughs to keep receiving government funding while private companies throw in a paper or two to appease investors and boost their own stock value.

Supercapacitor

The supercapacitor, also known as ultracapacitor or double-layer capacitor, differs from a regular capacitor in that it has very high capacitance. A capacitor stores energy by means of a static charge as opposed to an electrochemical reaction. Applying a voltage differential on the positive and negative plates charges the capacitor. This is similar to the buildup of electrical charge when walking on a carpet. Touching an object releases the energy through the finger.

There are three types of capacitors and the most basic is the *electrostatic capacitor* with a dry separator. This classic capacitor has very low capacitance and is mainly used to tune radio frequencies and filtering. The size ranges from a few pico-farads (pf) to low microfarad (μF).

The *electrolytic capacitor* provides higher capacitance than the electrostatic capacitor and is rated in microfarads (μF), which is a million times larger than a pico-farad. These capacitors deploy a moist separator and are used for filtering, buffering and signal coupling. Similar to a battery, the electrostatic capacity has a positive and negative that must be observed.

The third type is the supercapacitor, rated in farads, which is thousands of times higher than the electrolytic capacitor. The supercapacitor is used for energy storage undergoing frequent charge and discharge cycles at high current and short duration.

Farad is a unit of capacitance named after the English physicist Michael Faraday (1791–1867). One farad stores one coulomb of electrical charge when applying one volt. One microfarad is one million times smaller than a farad, and one pico-farad is again one million times smaller than the microfarad.

Engineers at General Electric first experimented with an early version of supercapacitor in 1957, but there were no known commercial applications. In 1966, Standard Oil rediscovered the effect of the double-layer capacitor by accident while working on experimental fuel cell designs. The double-layer greatly improved the ability to store energy. The company did not commercialize the invention and licensed it to NEC, who in 1978 marketed the technology as “supercapacitor” for computer memory backup. It was not until the 1990s that advances in materials and manufacturing methods led to improved performance and lower cost.

The supercapacitor has evolved and crosses into battery technology by using special electrodes and electrolyte. While the basic *Electrochemical Double Layer Capacitor (EDLC)* depends on electrostatic action, the *Asymmetric Electrochemical Double Layer Capacitor (AEDLC)* uses battery-like electrodes

to gain higher energy density, but this has a shorter cycle life and other burdens that are shared with the battery. Graphene electrodes promise improvements to supercapacitors and batteries but such developments are 15 years away.

Several types of electrodes have been tried and the most common systems today are built on the electrochemical double-layer capacitor that is carbon-based, has an organic electrolyte and is easy to manufacture.

All capacitors have voltage limits. While the electrostatic capacitor can be made to withstand high volts, the supercapacitor is confined to 2.5–2.7V. Voltages of 2.8V and higher are possible, but at a reduced service life. To get higher voltages, several supercapacitors are connected in series. Series connection reduces the total capacitance and increases the internal resistance. Strings of more than three capacitors require voltage balancing to prevent any cell from going into over-voltage. Lithium-ion batteries share a similar protection circuit.

The specific energy of the supercapacitor ranges from 1Wh/kg to 30Wh/kg, 10–50 times less than Li-ion. The discharge curve is another disadvantage. Whereas the electrochemical battery delivers a steady voltage in the usable power band, the voltage of the supercapacitor decreases on a linear scale, reducing the usable power spectrum.

Take a 6V power source that is allowed to discharge to 4.5V before the equipment cuts off. By the time the supercapacitor reaches this voltage threshold, a linear discharge only delivers 44% of the energy; the remaining 56% is reserved. An optional DC-DC converter helps to recover the energy dwelling in the low voltage band, but this adds costs and introduces loss. A battery with a flat discharge curve, in comparison, delivers 90 to 95 percent of its energy reserve before reaching the voltage threshold.

Figures 2-32 and 2-33 demonstrate voltage and current characteristics on charge and discharge of a supercapacitor. On charge, the voltage increases linearly and the current drops by default when the capacitor is full without the need of a full-charge detection circuit. On discharge, the voltage drops linearly.

To maintain a steady wattage level as the voltage drops, the DC-DC converter begins drawing more and more current. The end of discharge is reached when the load requirements can no longer be met.

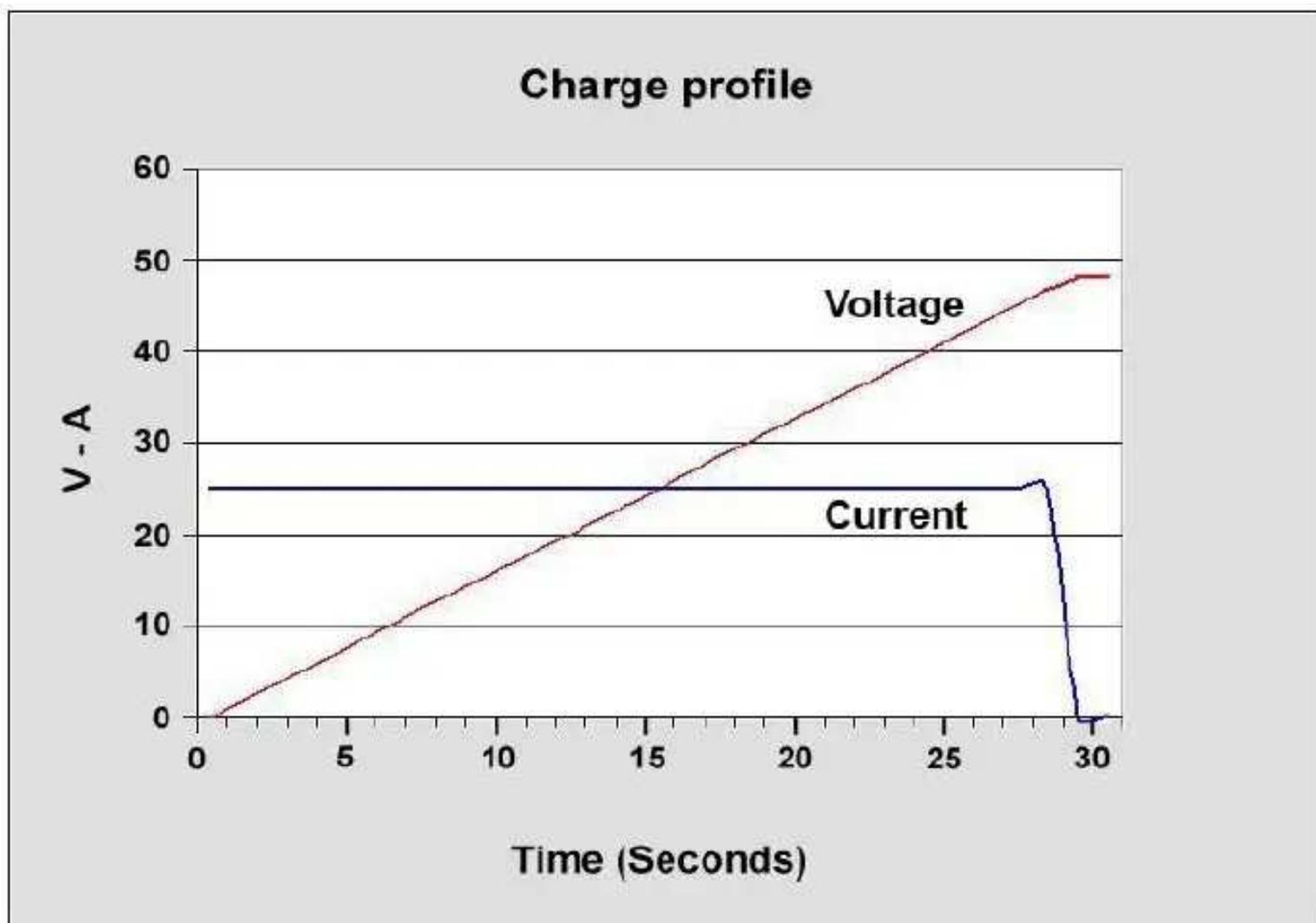


Figure 2-32: Charge profile of a supercapacitor.

The voltage increases linearly during a constant current charge. When the capacitor is full, the current drops by default.

Source: PPM Power

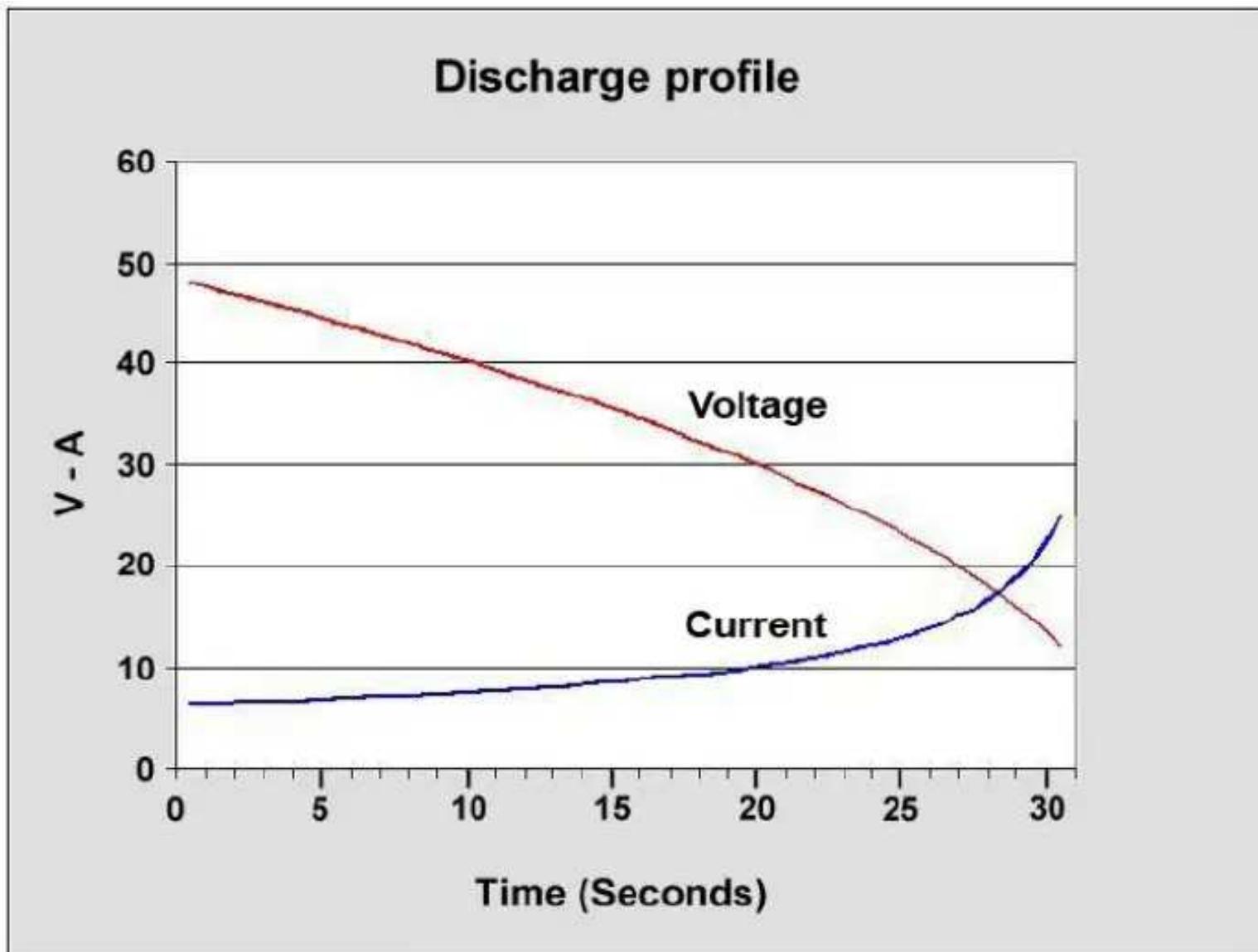


Figure 2-33: Discharge profile of a supercapacitor.

The voltage drops linearly on discharge. The optional DC-DC convertor maintains the wattage level by drawing higher current with dropping voltage.

Source: PPM Power

The charge time of a supercapacitor is 1–10 seconds. The charge characteristic is similar to an electrochemical battery and the charge current is, to a large extent, limited by the charger's current handling capability. The initial charge can be made very fast, and the topping charge will take extra time. Provision must be made to limit the inrush current when charging an empty supercapacitor as it will suck up all it can. The supercapacitor is not subject to overcharge and does not require full-charge detection; the current simply stops flowing when full.

Table 2-34 compares the supercapacitor with a typical Li-ion.

Function	Supercapacitor	Lithium-ion (general)
Charge time	1–10 seconds	1–3 hours
Cycle life	1 million or 30,000h	500 and higher
Cell voltage	2.30–2.75V	3.60V nominal
Specific energy (Wh/kg)	5 (typical)	120–240
Specific power (W/kg)	Up to 10,000	1,000–3,000
Cost per kWh	\$10,000 (typical)	\$250–\$1,000 (large system)
Service life (industrial)	10–15 years	5–10 years
Charge temperature	–40 to 65°C (–40 to 149°F)	0 to 45°C (32° to 113°F)
Discharge temperature	–40 to 65°C (–40 to 149°F)	–20 to 60°C (–4 to 140°F)

Table 2-34: Performance comparison between supercapacitor and Li-ion.

Source: Maxwell Technologies, Inc.

The supercapacitor can be charged and discharged a virtually unlimited number of times. Unlike the electrochemical battery, which has a defined cycle life, there is little wear and tear by cycling a supercapacitor. Age is also kinder to the supercapacitor than a battery. Under normal conditions, a supercapacitor fades from the original 100 percent capacity to 80 percent in 10 years. Applying higher voltages than specified shortens the life. The supercapacitor is forgiving in hot and cold temperatures, an advantage that batteries cannot meet equally well.

The self-discharge of a supercapacitor is substantially higher than that of an electrostatic capacitor and somewhat higher than an electrochemical battery; the organic electrolyte contributes to this. The supercapacitor discharges from 100 to 50 percent in 30 to 40 days. Lead and lithium-based batteries, in comparison, self-discharge about 5 percent per month.

Applications

Supercapacitors are ideal when a quick charge is needed to fill a short-term power need; whereas batteries are chosen to provide long-term energy.

Combining the two into a hybrid battery satisfies both needs and reduces battery stress, which reflects in a longer service life. Such batteries are being made

available today in the lead acid family.

Supercapacitors are most effective to bridge power gaps lasting from a few seconds to a few minutes and can be recharged quickly. A flywheel offers similar qualities, and an application where the supercapacitor competes against the flywheel is the Long Island Rail Road (LIRR) trial in New York. LIRR is one of the busiest railroads in North America.

To prevent voltage sag during acceleration of a train and to reduce peak power usage, a 2MW supercapacitor bank is being tested in New York against flywheels that deliver 2.5MW of power. Both systems must provide continuous power for 30 seconds at their respective megawatt capacity and fully recharge in the same time. The goal is to achieve a regulation that is within 10 percent of the nominal voltage; both systems must have low maintenance and last for 20 years. (Authorities believe that flywheels are more rugged and energy efficient for this application than batteries. Time will tell.)

Japan also employs large supercapacitors. The 4MW systems are installed in commercial buildings to reduce grid consumption at peak demand times and ease loading. Other applications are to start backup generators during power outages and provide power until the switch-over is stabilized.

Supercapacitors have also made critical inroads into electric powertrains. The virtue of ultra-rapid charging during regenerative braking and delivery of high current on acceleration makes the supercapacitor ideal as a peak-load enhancer for hybrid vehicles as well as for fuel cell applications. Its broad temperature range and long life offers an advantage over the battery.

Supercapacitors have low specific energy and are expensive in terms of cost per watt. Some design engineers argue that the money for the supercapacitor would be spent better on a larger battery. Table 2-35 summarizes the advantages and limitations of the supercapacitor.

Advantages	Virtually unlimited cycle life; can be cycled millions of time
-------------------	----------------------------------------------------------------

	<p>High specific power; low resistance enables high load currents</p> <p>Charges in seconds; no end-of-charge termination required</p> <p>Simple charging; draws only what it needs; not subject to overcharge</p> <p>Safe; forgiving if abused</p> <p>Excellent low-temperature charge and discharge performance</p>
Limitations	<p>Low specific energy; holds a fraction of a regular battery</p> <p>Linear discharge voltage prevents using the full energy spectrum</p> <p>High self-discharge; higher than most batteries</p> <p>Low cell voltage; requires series connections with voltage balancing</p> <p>High cost per watt</p>

Table 2-35: Advantages and limitations of supercapacitors.

Fuel Cell

A fuel cell is an electrochemical device that combines hydrogen fuel with oxygen to produce electricity, heat and water. The fuel cell is similar to a battery in that an electrochemical reaction occurs as long as fuel is available. Hydrogen is stored in a pressurized container and oxygen is taken from the air. Because of the absence of combustion, there are no harmful emissions and the only by-product is fresh water. So pure is the water emitted from the proton exchange membrane fuel cell (PEMFC) that visitors to Vancouver's Ballard Power Systems were served hot tea made from this clean water.

Fundamentally, a fuel cell is electrolysis in reverse, using two electrodes separated by an electrolyte. The anode (negative electrode) receives hydrogen and the cathode (positive electrode) collects oxygen. A catalyst at the anode

separates hydrogen into positively charged hydrogen ions and electrons. The oxygen is ionized and migrates across the electrolyte to the anodic compartment, where it combines with hydrogen. A single fuel cell produces 0.6–0.8V under load. Figure 2-36 illustrates the concept of a fuel cell.

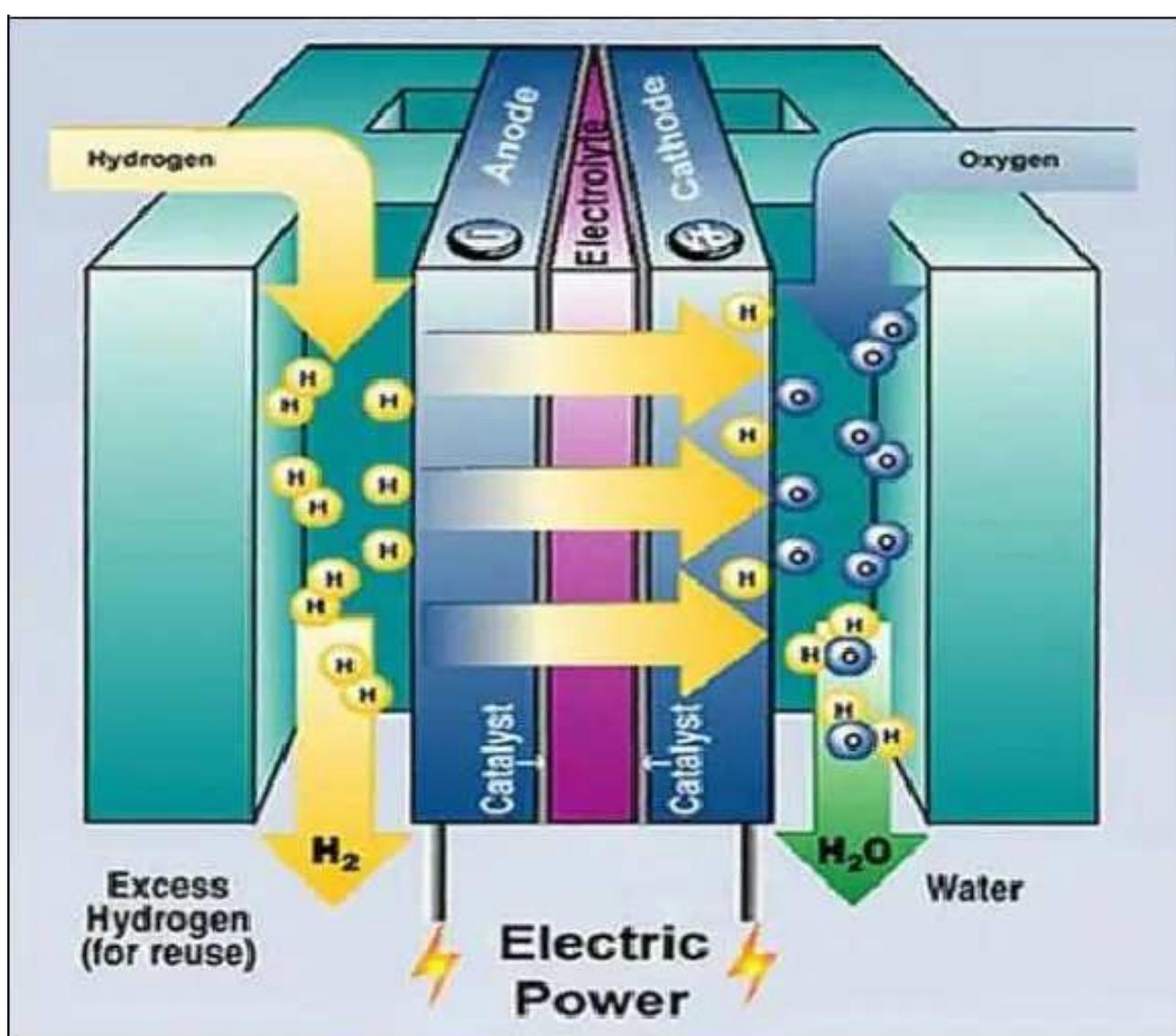


Figure 2-36: Concept of a fuel cell.

The anode (negative electrode) receives the hydrogen and the cathode (positive electrode) collects the oxygen.

Source: US Department of Energy, Office of Energy Efficiency and Renewable Energy

Fuel cell technology is twice as efficient as combustion in turning carbon fuel to energy. Hydrogen, the simplest chemical element (one proton and one electron), is plentiful and exceptionally clean as a fuel. Hydrogen makes up 90 percent of the universe and is the third most abundant element on the earth's surface. Such a wealth of fuel would provide an almost unlimited pool of clean

energy at relatively low cost. But there is a hitch.

In most fuels, hydrogen is bonded to other substances and “unleashing” the gas takes energy. In terms of net calorific value (NCV), hydrogen is more costly to produce than gasoline. Some say that hydrogen is nearly *energy neutral*, meaning that it takes as much energy to produce as it delivers at the end destination.

Storage of hydrogen poses a further disadvantage. Pressurized hydrogen requires heavy steel tanks, and the NCV by volume is about 24 times lower than a liquid petroleum product. In liquid form, which is much denser, hydrogen needs extensive insulation for cold storage.

Hydrogen can also be produced with a reformer by means of extraction from methanol, propane, butane and natural gas. Converting fossil fuel into pure hydrogen releases some leftover carbon, but it is 90 percent less harmful than what comes from the tailpipe of a car. Carrying a reformer would increase cost and add to vehicle weight; reformers are also sluggish. Hydrogen conversion is in question because it does not solve the energy problem.

Sir William Grove, a Welsh judge and gentleman scientist, developed the fuel cell concept in 1839, but the invention never took off. This was during the development of the internal combustion engine (ICE) that showed promising results. It was not until the 1960s that the fuel cell was put to practical use during the Gemini space program. NASA preferred this power source to nuclear or solar power. The alkaline fuel cell system that was chosen generated electricity and also produced drinking water for the astronauts.

High material costs made the fuel cell prohibitive for commercial use. The fuel cell core (stack) is expensive and has a limited life span. Burning fossil fuel in a combustion engine is the simplest and most effective means to harness energy, but it pollutes.

High cost did not discourage the late Karl Kordesch, the co-inventor of the alkaline battery, from converting his car to an alkaline fuel cell in the early 1970s. He mounted the hydrogen tank on the roof and placed the fuel cell and

1970s. He mounted the hydrogen tank on the roof and placed the fuel cell and

backup batteries in the trunk. According to Kordesch, there was enough room for four people and a dog. He drove his car for many years in Ohio, USA, but the only problem, Kordesch told me in person, was that the car did not pass inspections because it had no tail pipe. Here are the most common fuel cell concepts.

Proton Exchange Membrane Fuel Cell (PEMFC)

The proton exchange membrane, also known as PEM, uses a polymer electrolyte. PEM is one of the furthest developed and most commonly used fuel cell systems; it powers cars, serves as a portable power source and provides backup power in lieu of stationary batteries in offices. The PEM system allows compact design and achieves a high energy-to-weight ratio. Another advantage is a relatively quick start-up when applying hydrogen. The stack runs at a moderate temperature of 80°C (176°F) and is 50 percent efficient. (The ICE is 25–30 percent efficient.)

On the negative, the PEM fuel cell has high manufacturing costs and a complex water management system. The stack contains hydrogen, oxygen and water, and if dry, water must be added to get the system started; too much water causes flooding. The stack requires chemical grade hydrogen; lower fuel grades can cause decomposition and clogging of the membrane. Testing and repairing a stack is difficult, given that a 150V stack requires 250 cells.

Freezing water can damage the stack and heating elements may be added to prevent ice formation. Start-up is slow when cold and the performance is poor at first. Excessive heat can also cause damage. Controlling temperatures and supplying oxygen requires compressors, pumps and other accessories that consume about 30 percent of the energy generated.

Operating a PEMFC in a vehicle provides a stack life of 2,000–4,000 hours. Wetting and drying caused by short distance driving contributes to membrane stress. Running continuously, the stationary stack is good for about 40,000 hours. The stack does not die suddenly but fades similar to a battery. Stack replacement is a major expense.

Alkaline Fuel Cell (AFC)

The alkaline fuel cell is the choice for aerospace, including the space shuttle. Manufacturing and operating costs are low. While the separator for the PEM costs between \$800 and \$1,100 per square meter, the same for the alkaline system is almost negligible. (The separator for a lead acid battery costs about \$5 per square meter.) Water management is simple and does not need compressors and other peripherals; efficiency is in the 60 percent range. A negative is that the AFC is larger in physical size than the PEM and needs pure oxygen and hydrogen as fuels. The amount of carbon dioxide present in a polluted city can poison the stack and this limits the AFC to specialized applications.

Solid Oxide Fuel Cell (SOFC)

Electric utilities deploy three types of fuel cells, *molten carbonate*, *phosphoric acid* and *solid oxide fuel cells*. Among these, the solid oxide (SOFC) is the least developed, but it has received renewed attention because of breakthroughs in cell material and stack design. Rather than operating at a very high operating temperature of 800–1,000°C (1,472–1,832°F), a new generation of ceramic material has brought the core temperature down to a more manageable 500–600°C (932–1,112°F). This allows the use of conventional stainless steel rather than expensive ceramics for auxiliary parts.

High temperature allows direct extraction of hydrogen from natural gas through a catalytic reforming process. Carbon monoxide, a contaminant for the PEM, is a fuel for the SOFC. Being able to accept carbon-based fuels without a designated reformer and delivering high efficiency poses significant advantages for this type of fuel cell. Co-generation by running steam generators from the heat by-product raises the efficiency to 60 percent, one of the highest among fuel cells. As a negative, high stack temperature requires exotic materials for the core that adds to manufacturing costs and reduces longevity.

Direct Methanol Fuel Cell (DMFC)

Portable fuel cells have gained attention and the most promising development is the *direct methanol fuel cell*. This small unit is inexpensive to manufacture, convenient to use and does not require pressurized hydrogen gas. The DMFC

convenient to use and does not require pressurized hydrogen gas. The DMFC

has good electrochemical performance and refilling is done by squirting in liquid or replacing the cartridge. This enables continued operation without downtime.

Manufacturers admit that a direct battery replacement by the fuel cell is years away. To bridge the gap, the micro fuel cell serves as a charger to provide continuous operation for the onboard battery. Furthermore, methanol is toxic and flammable, and there are limitations to how much fuel passengers can carry on an aircraft. In 2008 the Department of Transportation issued a ruling to permit passengers and crew to carry an approved fuel cell with an installed methanol cartridge and up to two additional spare cartridges of 200 ml (6.76 fl oz). This provision does not yet extend to bottled hydrogen. Figure 2-37 shows a micro fuel cell by Toshiba and Figure 2-38 demonstrates refueling with methanol that is 99.5 percent pure.

Improvements are being made, and Toshiba unveiled prototype fuel cells for laptops and other applications generating 20 to 100 watts. The units are compact and the specific energy is comparable with that of a NiCd battery. Meanwhile, Panasonic claims to have doubled the power output with a similar size, specifying a calendar life of 5,000 hours if the fuel cell is used intermittently for 8 hours per day. The low longevity of these fuel cell is used intermittently for 8 hours per day. The low longevity of these fuel cells has been an issue to be reckoned with.

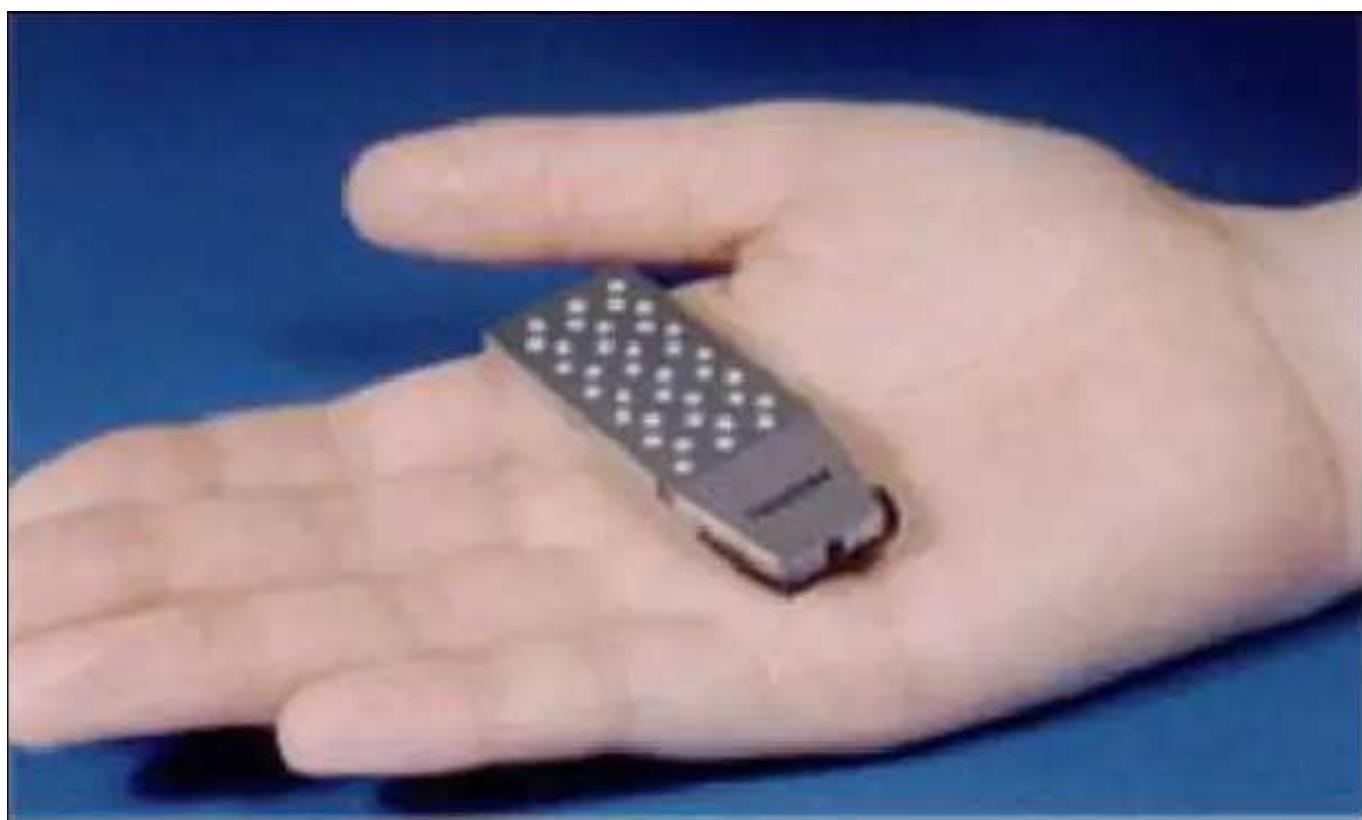


Figure 2-37: Micro fuel cell. This prototype micro fuel cell is capable of providing 300mW of continuous power. Both courtesy of Toshiba

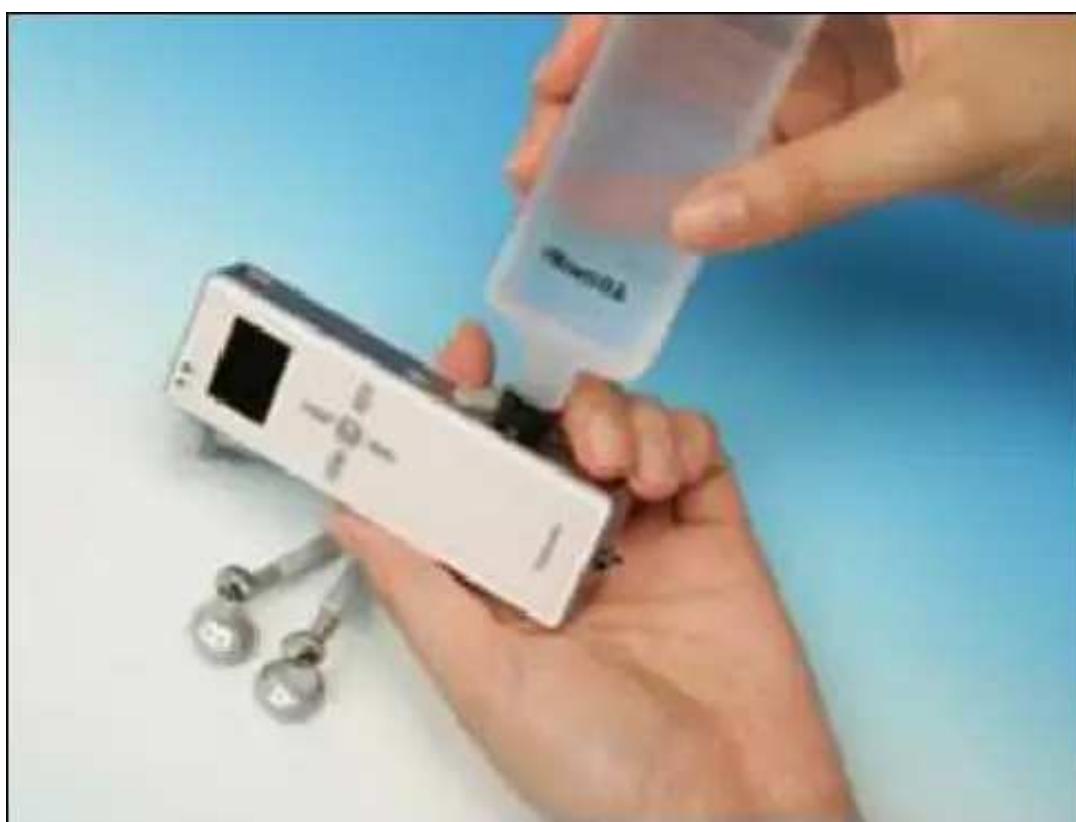


Figure 2-38: Toshiba fuel cell with refueling cartridge. The fuel in a 10ml tank is 99.5 percent pure methanol.

Attempts are being made with small fuel cells running on stored hydrogen. Increased efficiency and smaller size are the advantages of pure hydrogen over

methanol. These miniature systems have no pumps and fans and are totally silent. A 21cc cartridge is said to provide the equivalent energy of about 10 AA alkaline batteries with a runtime between refueling of 20 hours. This lends itself to portable computing, wireless communications and flashlights for the lone bicycle rider.

Military and recreational users are also experimenting with the miniature fuel cell. Figure 2-39 illustrates a portable fuel cell made by SFC Smart Fuel Cell. The EFOY fuel cell comes in different capacities that ranges from 600 to 2,160 watt-hours per day.



Figure 2-39: Portable fuel cell for consumer market.

The fuel cell converts hydrogen and oxygen to electricity and clean water is the only by-product. Fuel cells can be used indoors as an electricity generator.

Source: SFC Smart Fuel Cell AG (2010)

Table 2-40 describes the applications and summarizes the advantages and limitations of common fuel cells. The table also includes the molten carbonate (MCFC) and phosphoric acid (PAFC), classic fuel cell systems that have been around for a while and have unique advantages.

Type of fuel cell	Applications	Core temperature, efficiency	Advantages	Limitations
Proton Exchange Membrane (PEMFC)	Portable, stationary and automotive	50–100°C; 80°C typical; 35–60% efficient	Compact design, long operating life, quick start-up, well developed	Expensive catalyst; needs chemical grade fuel; complex heat and water control
Alkaline (AFC)	Space, military, submarines, transport	90–100°C; 60% efficient	Low parts and operation costs; no compressor; fast cathode kinetics	Large size; sensitive to hydrogen and oxygen impurities
Molten Carbonate (MCFC)	Large power generation	600–700°C; 45–50% efficient	High efficiency, flexible to fuel, co-generation	High heat causes corrosion, long startup, short life
Phosphoric Acid (PAFC)	Medium to large power generation	150–200°C; 40% efficient	Good tolerance to fuel impurities; co-generation	Low efficiency; limited service life; expensive catalyst
Solid Oxide (SOFC)	Medium to large power generation	700–1000°C; 60% efficient	Lenient to fuels; can use natural gas, high efficient	High heat causes corrosion, long startup, short life
Direct Methanol (DMFC)	Portable, mobile and stationary use	40–60°C; 20% efficient	Compact; feeds on methanol; no compressor	Complex stack; slow response; low efficiency

Table 2-40: Advantages and limitations of various fuel cell systems. Fuel cell developments have been gradual; the specific power is low and a direct battery replacement may never be feasible.

Developments

Limitations involve slow start-up times, low power output, sluggish response on power demand, poor loading capabilities, narrow power bandwidth, short service life and high cost. Similar to batteries, the performance of all fuel cells degrades with age, and the stack gradually loses efficiency. Such performance losses are much less apparent with the ICE.

Fuel cells below 1kW are normally non-pressurized and only use a fan to aid in oxygen supply; fuel cells above 1kW are pressurized and include a compressor that lowers efficiency and the system can get rather noisy. The relatively high internal resistance of fuel cells poses a further challenge. Each cell of a stack produces about 1 volt in open circuit; a heavy load causes a notable voltage drop. Similar to the battery, the power bandwidth decreases with age. Individual cells in the stack are also known to cause failures and contaminants are large contributors. Figure 2-41 illustrates the voltage and

power output of a fuel cell stack over time.

power bandwidth as a function of load.

Fuel cells operate best at a 30 percent load factor; higher loads reduce efficiency. This and poor throttle response place the fuel cell into a support mode or a charger to keep batteries charged. A stand-alone power source, as the developers had hoped, has not materialized.

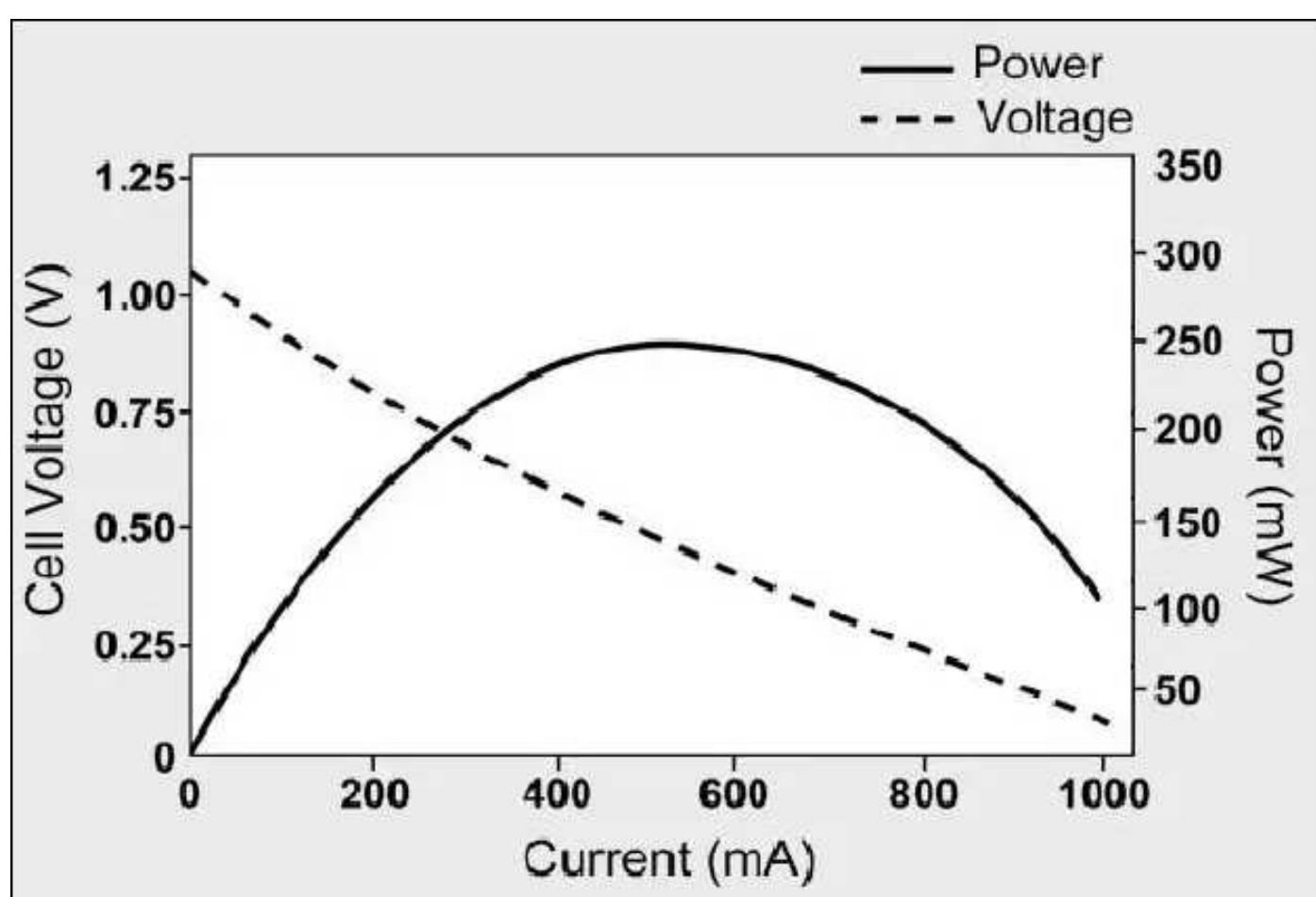


Figure 2-41: Power band of a portable fuel cell.

High internal resistance causes the cell voltage to drop rapidly with load. The power band is limited to between 300 and 800mA.

Courtesy of Cadex

Paradox of the fuel cell

The fuel cell enjoyed the height of popularity in the 1990s, when scientists and stock promoters envisioned a world running on a clean and inexhaustible resource — hydrogen. They predicted that cars would run on fuel cells, and that household electricity would also be generated by fuel cells. The stock prices skyrocketed but marginal performance, high manufacturing costs and limited

service life moderated the hydrogen dream.

It was said that the fuel cell would transform the world as the microprocessor did in the 1970s. A clean and inexhaustible source of energy would become available that would solve the environmental concerns of burning fossil fuel. From 1999 through 2001, more than 2,000 organizations got actively involved in fuel cell development, and four of the largest public fuel cell companies in North America raised over a billion US dollars in public stock offerings. What went wrong?

Hydrogen is not a source of energy per se but a medium to transport and store energy similar to electricity that charges a battery. To envision “burning an endless supply of hydrogen,” the fuel must first be produced, because hydrogen cannot be pumped from the earth as is possible with oil. While fossil fuel lends itself well to producing hydrogen, taking this valuable fuel to unleash hydrogen makes little sense when it costs as much or more for extraction as burning it directly. The only benefit is reduced greenhouse gases.

Just as the attempt to fly airplanes on steam failed in the mid-1800s, it is conceivable that the fuel cell will never be the powerhouse scientists had hoped for. But there is renewed interest in the automotive field in Japan. Fuel cells are replacing battery banks and diesel generators in office buildings as they can be installed in tight storage places with minimal maintenance and without the need for exhaust. Fuel cells allow continuous and pollution-free operation of forklifts in warehouses, whereas 40MW fuel cells generate clean electricity in remote locations.

Fuel cells may one day taxi airplanes with electric wheel hub motors. This would lower pollution and save up to 4 percent fuel by not running the jet engines. Water produced from the fuel cell while charging the batteries could serve as on-board drinking water; regenerative braking could further assist in charging the batteries and supercapacitors for fast charge acceptance. The ultimate dream is propelling airplanes and vehicles with the clean fuel cell.

Flow Battery

A flow battery is an electrical storage device that is a cross between a conventional battery and a fuel cell. Liquid electrolyte of metallic salts is pumped through a core that consists of a positive and negative electrode, separated by a membrane. The ion exchange that occurs between the cathode and anode generates electricity.

Most commercial flow batteries use acid sulfur with vanadium salt as electrolyte; the electrodes are made of graphite bipolar plates. Vanadium is one of few available active materials that keeps corrosion under control. Flow batteries have been tried that contain precious metal such as platinum, which is also used in fuels cells. Research is continuing to find materials that are low cost and readily available.

Activated by pumps, flow batteries perform best at a size above 20kWh. They are said to deliver more than 10,000 full cycles and are good for about 20 years. Each cell produces 1.15–1.55 volts; they are connected in series to achieve the desired voltage levels. The battery has a specific energy of about 40Wh/kg, which resembles lead acid. Similar to the fuel cell, the power density and ramp-up speed is moderate. This makes the battery best suited for bulk energy storage; less for electric powertrains and load leveling that requires quick action.

The electrolyte is stored in tanks. To increase the energy density, the tank sizes can be doubled using ready-made storage tanks at an estimated cost increase of only 50 percent compared to a new system. When replacing the battery, the electrolyte can be reused, further saving cost. Problem areas are the membranes that tend to corrode and are expensive; additives are said to solve this issue. Figure 2-42 illustrates the battery concept.

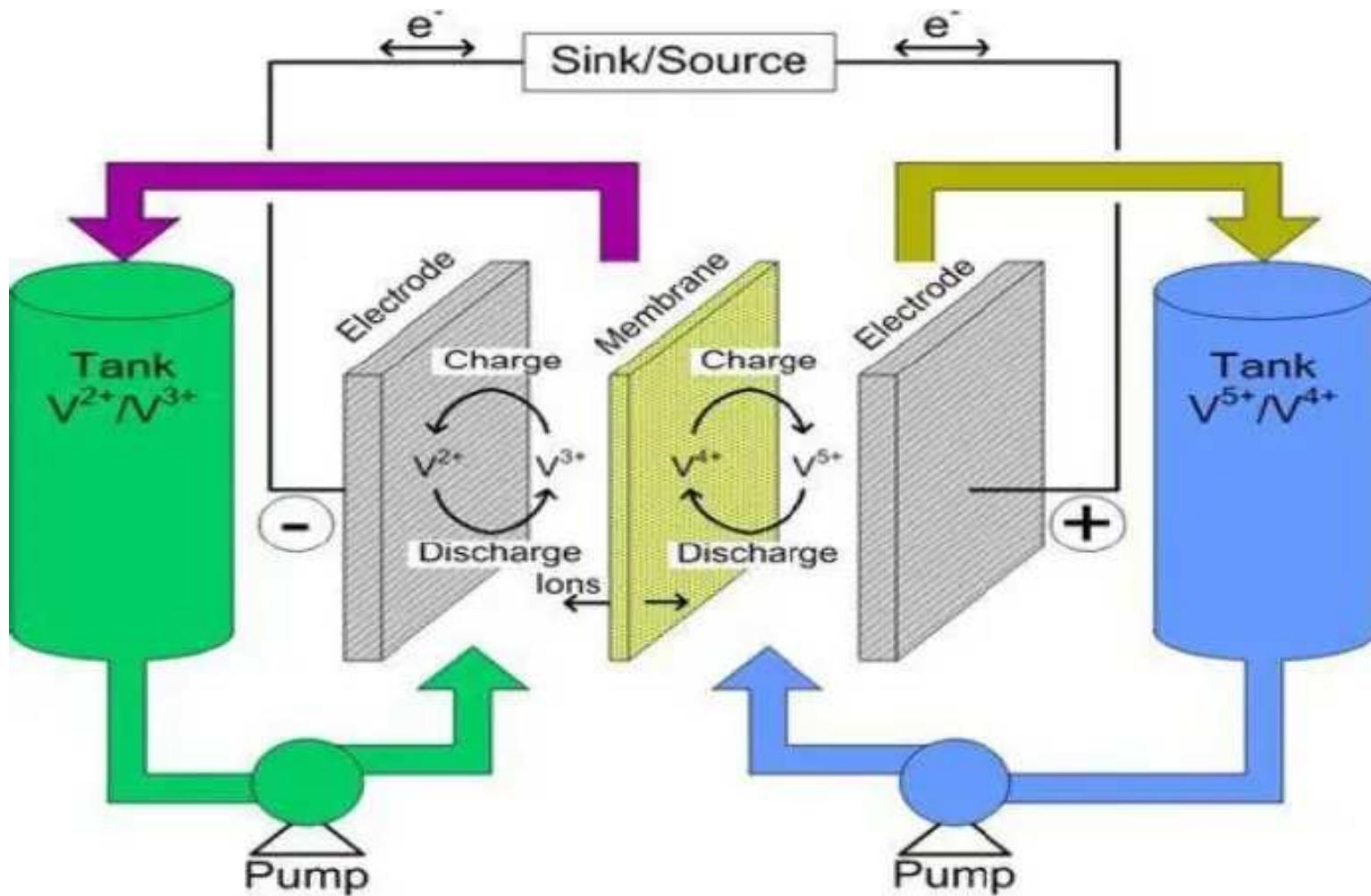


Figure 2-42: Flow battery.

Electrolyte is stored in tanks and pumped through the core to generate electricity; charging is the process in reverse. The volume of electrolyte governs battery capacity.

Vanadium is the 23rd element on the periodic table and is mined in China, Russia and South Africa. Sun-backed central Nevada may soon become a contributor in the form of heavily oxidized crumbled rock. Currently, 90 percent of lower grade vanadium is used as an additive to strengthen steel. Battery scientists, mining companies and politicians are excited about vanadium becoming a strategic metal for “green energy.” As of now, the cost of the flow battery is similar to that of lithium-ion at about \$500/kWh; a future cost of US\$250/kWh seems feasible.

For a more precise cost estimation, the flow battery is divided into *power cost* and *energy cost*. The power cost can go above \$1,500/kW and consists of stacks, pumps, pipes and power electronics. The energy cost consisting of tanks and electrolyte comes in at a bit more than \$300/kWh.

since 1996. Some of the biggest current installations boast a capability of several megawatts and a flow battery for frequency regulation is being installed in Japan that will deliver a whooping 60MWh.

There is a move towards cost and size reduction. Rather than building a monster battery resembling a chemical plant, newer systems come in container-sizes of typically 250kWh that can be stacked. Modern flow batteries are also becoming common in Europe.

The first patent for a titanium chloride flow battery was granted in July 1954. The present day vanadium redox battery was patented in 1986 by the University of New South Wales in Australia. The term “redox” comes from “electron transfer” of *reduction* and *oxidation*.

Sodium-sulfur

Sodium batteries, also known as molten salt or thermal batteries, come in primary and secondary versions. The battery uses molten salts as an electrolyte and gains conductivity by heating the stack to a temperature of 400–700°C (752–1,292°F). Newer designs run at a lower 245–350°C (473–662°F) temperature.

Conceived by the Germans during World War II and used in their V-2 rockets, the electrolyte of the molten salt battery is inactive when cold and has a long storage of more than 50 years in that state. Once activated with a heat source, the battery can provide a high power burst for a fraction of a second or deliver energy over several hours. High power is made possible by the good ionic conductivity of the molten salt. Primary sodium batteries are almost exclusively used for the military as a “one-shot” engagement in guided missiles, but the interest lies in the rechargeable version.

The rechargeable sodium-sulfur (NaS) gained worldwide attention during the 1970s and 1980s, but short service life and high cost dampened the enthusiasm. The *sodium-nickel-chloride* battery, also known as ZEBRA, came to the rescue, and today this battery is successfully being deployed in many applications. (ZEBRA stands for Zeolite Battery Research Africa Project.)

ZEBRA has a nominal cell voltage of 2.58 volts and a specific energy of 90–120Wh/kg, a level comparable with Li-manganese and Li-phosphate. The service life is about 8 years and delivers about 3,000 cycles. It can be fast charged, is non-toxic and the raw materials are abundant and low-cost. ZEBRA batteries come in sizes of 10kWh or higher; typical applications are forklifts, railways, ships, submarines and electric cars.

The Think City, an electric car, offered purchasers the choice of a ZEBRA or a Li-ion battery. ZEBRA had advantages over regular batteries when operating in a hot climate and when the battery is in continuous use, such as in taxis and delivery vans. A growing market for sodium-based batteries is load leveling, also known as grid storage.

The ZEBRA battery must be heated to 270–350°C (518–662°F), a temperature that is lower than the original sodium-sulfur battery. Even with special insulation that minimizes heat loss, heating consumes 14 percent of the battery's energy per day. Since the energy to keep the battery hot is taken from the battery, the resulting parasitic load amounts to 18 percent. This can be compared with the high self-discharge of a battery. A cool down takes 3 to 4 days; depending on SoC, reheating is about 2 days.

Common failures are electrical shorts due to corrosion of the insulators, which then become conductive, as well as growth of dendrites, which increases self-discharge. ZEBRA batteries are safer than sodium-sulfur, and an electrical short does not cause a complete failure of the battery.

Zinc-air (Primary & Secondary)

Zinc-air batteries generate electrical power by an oxidation process of zinc and oxygen from the air. The cell can produce 1.65V; however, cells with 1.4V and lower voltages achieve a longer lifetime. To activate the battery, the user removes a sealing tab that enables airflow. The battery reaches full operating voltage within 5 seconds. Airflow can control the rate of the reaction somewhat and once turned on, the battery cannot be reverted back to standby mode.

Adding a tape to stop the airflow only slows the chemical activity and the battery

will soon dry out.

The Zinc-air battery shares similarities with the fuel cell by using oxygen from the air to fuel the positive electrode. It is considered a primary battery, and recharging versions for high-power applications have been tried. Recharging occurs by replacing the spent zinc electrodes, which can be in the form of a zinc electrolyte paste. Other zinc-air batteries use zinc pellets.

At 300–400Wh/kg, zinc-air has a high specific energy but the specific power is low. Manufacturing cost is low and in a sealed state, zinc-air has a 2 percent self-discharge per year. The battery is sensitive to hot and cold temperatures and high humidity. Pollution also affects performance; high carbon dioxide content reduces the performance by increasing the internal resistance. Typical applications are hearing aids while large systems operate remote railway signaling and safety lamps at construction sites.

Silver-zinc (Primary & Secondary)

The small silver-based batteries in button cells are typically called *silver-oxide* and are non-rechargeable; the higher capacity rechargeable versions are referred to as *silver-zinc*. Both have an open circuit voltage of 1.60 volts. Because of the high cost of silver, these batteries come in either very small sizes where the amount of silver does not contribute significantly to the overall product cost, or

they are available in larger sizes for critical applications where the superior performance outweighs any cost considerations.

The primary cells are used for watches, hearing aids and memory backup; the larger rechargeable version is found in submarines, missiles and aerospace applications. Silver-zinc also powers TV cameras needing extra runtime. High cost and short service life locked the silver-zinc out of the commercial market, but it is on the verge of a rebirth with improvements.

The primary cause of failure in the original design was the decaying of the zinc electrode and separator. Cycling developed zinc dendrites that pierced through the separator, causing electrical shorts. In addition, the separator

through the separator, causing electrical shorts. In addition, the separator

degraded by sitting in the potassium hydroxide electrolyte. This limited the calendar life to about 2 years.

Improvements in the zinc electrode and separator promise a longer service life and a 40 percent higher specific energy than Li-ion. Silver-zinc is safe, has no toxic metals and can be recycled, but the use of silver makes the battery expensive to manufacture.

Reusable Alkaline

The reusable alkaline served as an alternative to disposable batteries. Although fabrication costs were said to be similar to regular alkaline, the consumer did not accept the product.

Recharging alkaline batteries is not new. Ordinary alkaline batteries have been recharged in households for many years. Recharging is most effective if alkaline is discharged to less than 50 percent before recharging. The number of recharges depends on the depth of discharge and is limited to just a few cycles. Battery makers do not endorse this practice for safety reasons; charging ordinary alkaline batteries may generate hydrogen gas that can lead to an explosion.

The reusable alkaline overcomes some of these deficiencies, but a limited cycle count and low capacity on repeat charge are major drawbacks. Longevity is also in direct relationship to the depth of discharge. At a 50 percent depth of discharge, the battery may deliver 50 cycles, but most users run a battery empty before recharging and the manufacturer, including the inventor Karl Kordesch, overestimated the eagerness of the user wanting to recharge early. An additional limitation is its low load current of 400mA, which is only sufficient for flashlights and personal entertainment devices. NiMH in AA and AAA cells has mostly replaced the reusable alkaline.

Future Batteries

Experimental batteries live mostly in sheltered laboratories and communicate to the outside world with promising reports often to entice investors. Some designs

the outside world with promising reports, often to entice investors. Some designs

show unrealistic results with anticipated release dates that move with time. Most concepts disappear from the battery scene and die gracefully in the lab without anyone hearing of their passing.

Few other products have similar stringent requirements as the battery, and the complexity puzzles venture capitalists who did well during the dot-com era and expect similar generous returns of their investment in only 3 years; battery development typically takes 10 years. Most venture capitalists don't have the patience to wait and they pull back the money, leaving the developer in deep water. Raising capital is time consuming and many startups devote as much time and energy to this task as to doing research.

Most experimental batteries in the lithium family have one thing in common; they use a metallic lithium anode to achieve a higher specific energy than what is possible with the oxidized cathode in lithium-ion, the battery that is in common use today.

Moli Energy was first to mass-produce a rechargeable Li-metal battery in the 1980s, but it posed a serious safety risk as the growth of lithium dendrites caused electric shorts leading to thermal runaway conditions. The local fire department knew exactly where to go on a fire alarm at the Moli plant; it was the battery warehouse. After a venting event injured a battery user, all lithium-metal packs were recalled in 1989. NEC and Tadiran tried to improve the design with limited success. Very few companies make rechargeable lithium-metal batteries, and most offer the primary versions only. Research continues and a possible solution with new materials as part of the *solid-state lithium* could be on hand. This design is described further in this section.

Researchers have also developed an anode structure for Li-ion batteries that is based on silicon-carbon nanocomposite materials. A silicon anode could theoretically store 10 times the energy of a graphite anode, but expansions and shrinkage during charge and discharge make the system unstable. Adding

graphite to the anode is said to achieve a theoretical capacity that is five times that of regular Li-ion with stable performance, however, the cycle life would be

and original Li-ion will have performance, however, and cycle life would be

limited due to structural problems when inserting and extracting lithium-ion at high volume.

Meeting the eight basic requirements of the *octagon battery* (page 29) is a challenge. Commercialization appears to dwell on a moving target that is always a decade ahead, but scientists are not giving up. Here are some of the most promising experimental batteries.

Lithium-air (Li-air)

Lithium-air provides an exciting new frontier because this battery promises to store far more energy than is possible with current lithium-ion technologies. Scientists borrow the idea from zinc-air and the fuel cell in making the battery “breathe” air. The battery uses a catalytic air cathode that supplies oxygen, an electrolyte and a lithium anode.

The theoretical specific energy of lithium-air is 13kWh/kg. Aluminum-air is also being tried, and it is a bit lower at 8kWh/kg. If these energies could indeed be delivered, metal-air, as the battery is also known, would be on par with gasoline at roughly 13kWh/kg. But even if the end product were only one-quarter of the theoretical energy density, the electric motor with its better than 90 percent efficiency would make up for its lower capacity against the ICE with a thermal efficiency of only 25–30 percent.

Li-air was proposed in the 1970s and gained renewed interest in the late 2000s, in part because of advancements in material science and the endeavor to find a better battery for the electric powertrain. Depending on the materials used, lithium-air produces voltages of between 1.7 and 3.2V/cell. IBM, MIT, the University of California and other research centers are developing the technology.

As with other air-breathing batteries, the specific power may be low, especially at cold temperatures. Air purity is also said to be a challenge as the air we breathe in our cities is not clean enough for lithium-air and would need to be filtered. For all we know, the battery may end up with compressors, pumps and

intered. For all we know, the battery may end up with compressors, pumps and

filters resembling a fuel cell, consuming 30 percent of its produced energy for auxiliary support to stay alive.

Another problem is the sudden death syndrome. Lithium and oxygen form lithium peroxide films that produce a barrier, which prevents electron movement and results in an abrupt reduction in the battery's storage capacity. Scientists are experimenting with additives to prevent the film formation. The cycle life will also need to improve; lab tests currently produce only 50 cycles.

Lithium-metal (Li-metal)

After several failed attempts to commercialize rechargeable lithium-metal batteries, research and limited manufacturing of this battery continues. In 2010, a trial lithium-metal with a capacity of 300Wh/kg was installed in an experimental electric vehicle. DBM Energy, the German manufacturer of this battery, claims 2,500 cycles, short charge times and competitive pricing if the battery were mass-produced.

An Audi A2 with these batteries drove over 450km (284mi) from Munich to Berlin on a single charge. There is a rumor that the car destroyed itself by a fire while on a laboratory test. Although the lithium-metal batteries passed the stringent approval tests, long-term safety remains an issue because metal filaments can form that might cause an electric short.

At 300Wh/kg, lithium-metal has one of the highest specific energies of lithium-based rechargeable batteries. NCA in the Tesla S 85 comes in at 250Wh/kg, LMO in the BMW i3 has 120Wh/kg and a similar chemistry in the Nissan Leaf has 80–96Wh/kg. The BMW i3 and Leaf batteries are made for high durability; Tesla achieves this by over-sizing.

Solid-state Lithium

The current Li-ion uses a graphite anode and this reduces the specific energy. Solid-state technology replaces graphite with pure lithium and substitutes the liquid electrolyte soaked in a porous separator with a solid polymer or a ceramic

separator. This resembles the 1970 lithium-polymer that was discontinued due to safety and performance reasons.

The solid-state battery shares similarity with lithium-metal and scientists are trying to overcome the problem of metallic filament formation with the use of dry polymer and ceramic separators. Additional challenges are achieving sufficient conductivity at cool temperatures and the need to improve the cycle count. Solid-state prototypes are said to only reach 100 cycles.

Solid-state batteries promise to store twice the energy compared to regular Li-ion, but the loading capabilities might be low, making them less suited for electric powertrains and similar applications requiring high currents. Targeted applications are load leveling for renewable energy sources as well as EVs by cashing in on the short charge times that this battery allows. Research laboratories, including Bosch, predict that the solid-state battery might become commercially available by 2020 and be implemented in cars in 2025.

Lithium-sulfur (Li-S)

By virtue of the low atomic weight of lithium and the moderate weight of sulfur, lithium-sulfur batteries offer a very high specific energy of 550Wh/kg, about three times that of Li-ion. Li-S also has a respectable specific power of 2,500W/kg. During discharge, lithium dissolves from the anode surface and

reverses itself when charging by plating itself back onto the anode. Li-S has a cell voltage of 2.10V, offers good cold temperature discharge characteristics and can be recharged at -60°C (-76°F). The battery is environmentally friendly; sulfur, the main ingredient, is abundantly available and inexpensive. A price of US\$250 per kWh is said to be possible.

A typical Li-ion has a graphite anode that hosts lithium-ions much like a hotel books guests. On discharge, the anode releases the ions to the cathode, replicating guests checking out in the morning. In Li-S, graphite is replaced by lithium metal, a catalyst that provides double duty as electrode and supplier of lithium ions. The Li-S battery gets rid of “dead weight” by replacing the metal

oxide cathode used in a Li-ion with cheaper and lighter sulfur. Sulfur has the

added advantage of double-booking lithium atoms, something Li-ion cannot do.

A challenge with lithium-sulfur is the limited cycle life of only 40–50 charges/discharges as sulfur is lost during cycling by shuttling away from the cathode and reacting with the lithium anode. Other problems are poor conductivity, a degradation of the sulfur cathode with time and poor stability at higher temperatures. Since 2007, Stanford engineers have experimented with nanowire. Trials with graphene are also being done with promising results.

Sodium-ion (Na-ion)

Sodium-ion represents a possible lower-cost alternative to Li-ion as sodium is inexpensive and readily available. Put aside in the late 1980s in favor of lithium, Na-ion has the advantage that it can be completely discharged without encountering stresses that are common with other battery systems. The battery can also be shipped without having to adhere to Dangerous Goods Regulations. Some cells have 3.6V, and the specific energy is about 90Wh/kg with a cost per kWh that is similar to the lead acid battery. Further development will be needed to improve the cycle count and solve the large volumetric expansion when the battery is fully charged.

Chapter 3 | Packaging and Safety

A Look at Old and New Battery Formats

Early batteries of the 1700s and 1800s developed in Europe were mostly encased in glass jars. As batteries grew in size, jars shifted to sealed wooden containers and composite materials. In the 1890s, battery manufacturing spread from Europe to the United States and in 1896 the National Carbon Company successfully produced a standard cell for widespread consumer use. It was the zinc-carbon *Columbia Dry Cell Battery* producing 1.5 volts and measuring 6 inches in length.

With the move to portability, sealed cylindrical cells emerged that led to standard sizes. The International Electrochemical Commission (IEC), a non-governmental standards organization founded in 1906, developed standards for most rechargeable batteries. In around 1917, the National Institute of Standards and Technology formalized the alphabet nomenclature that is still used today.

Table 3-1 summarizes these historic and current battery sizes.

Standardization included primary cells, mostly in zinc-carbon; alkaline emerged only in the early 1960s. With the growing popularity of the sealed nickel-cadmium in the 1950s and 1960s, new sizes appeared, many of which were derived from the “A” and “C” sizes. Beginning in the 1990s, makers of Li-ion departed from conventional sizes and invented their own standards.

A successful standard is the 18650 cylindrical cell. Developed in the early 1990s for lithium-ion, these cells are used in laptops, electric bicycles and even electric vehicles (Tesla). The first two digits of 18650 designate the diameter in millimeters; the next three digits are the length in tenths of millimeters. The

millimeters, the next three digits are the length in tenths of millimeters. The

18650 cell is 18mm in diameter and 65.0mm in length.

Other sizes are identified with a similar numbering scheme. For example, a prismatic cell carries the number 564656P. It is 5.6mm thick, 46mm wide and 56mm long. P stands for prismatic. Because of the large variety of chemistries and their diversity within, battery cells do not show the chemistry.

Looking at the batteries in mobile phones and laptops, one sees a departure from established standards. This is due in part to the manufacturers' inability to agree on a standard, meaning that most consumer devices come with custom-made cells or battery packs. Compact design and market demand are swaying manufacturers to go their own way. High volume with planned obsolescence allows the production of unique sizes in consumer products.

In the early days, a battery was perceived "big" by nature, and this is reflected in the sizing convention. While the "F" nomenclature may have been seen as mid-sized in the late 1800s, our forefathers did not anticipate that a battery resembling a credit card could power computers, phones and cameras. Running out of letters towards the smaller sizes led to the awkward numbering of AA, AAA and AAAA.

Size	Dimensions	History
F cell	33 x 91 mm	Introduced in 1896 for lanterns; later used for radios; only available in nickel-cadmium today.
E cell	N/A	Introduced ca. 1905 to power box lanterns and hobby applications. Discontinued ca. 1980.
D cell	34.2 x 61.5mm	Introduced in 1898 for flashlights and radios; still current.
C cell	25.5 x 50mm	Introduced ca. 1900 to attain smaller form factor
Sub-C	22.2 x 42.9mm 16.1mL	Cordless tool battery. Other sizes are 1/2, 4/5 and 5/4 sub-C lengths. Mostly NiCd.
B cell	20.1 x 56.8mm	Introduced in 1900 for portable lighting, including bicycle lights in Europe; discontinued in North America in 2001.
A cell	17 x 50mm	Only available as a NiCd or NiMH cell; also available in 2/3 and 4/5 size. Popular in old laptops and hobby batteries.
AA cell	14.5 x 50mm 8.1mL	Introduced in 1907 as penlight battery for pocket lights and spy tool in WWI; added to ANSI standard in 1947.
AAA cell	10.5 x 44.5mm	Developed in 1954 to reduce size for Kodak and Polaroid cameras. Added to ANSI standard in 1959.
AAAA cell	8.3 x 42.5mm	Offshoot of 9V, since 1990s; used for laser pointers, LED penlights, computer styli, headphone amplifiers.
4.5V battery	67 x 62 x 22mm	Three cells form a flat pack; short terminal strip is positive, long strip is negative; common in Europe, Russia.
9V battery	48.5 x 26.5 x 17.5mm	Introduced in 1956 for transistor radios; contains six prismatic or AAAA cells. Added to ANSI standard in 1959.
18650	18 x 65mm 16.5mL	Developed in the mid-1990s for lithium-ion; commonly used in laptops, e-bikes, including Tesla EV cars.
26650	26 x 65mm 34.5mL	Larger Li-ion. Some measure 26x70mm sold as 26700. Common chemistry is LiFeO ₄ for UPS, hobby, automotive.
14500	14 x 50mm	Li-ion, similar size to AA. (Observe voltage incompatibility: NiCd/NiMH = 1.2V, alkaline = 1.5V, Li-ion = 3.6V).

Table 3-1: Common old and new battery norms.

Since the introduction of the 9V battery in 1956, no new formats have emerged. Meanwhile portable devices lowered the operating voltages to between 3V and 5V. Switching six cells in series (6S) to attain 9V is expensive to

manufacture, and a 3.6V alternative would serve better. This imaginary new

pack would have a coding system to prevent charging primaries and select the correct charge algorithm for secondary chemistries.

Starter batteries for vehicles also follow battery norms that are based on the North American BCI, the European DIN and the Japanese JIS standards. These batteries are similar in footprint to allow swapping. Deep-cycle and stationary batteries follow no standardized norms and the replacement packs must be sourced from the original maker. The attempt to standardize electric vehicle batteries may not work and might follow the failed attempt to standardize laptop batteries in the 1990s.

Cylindrical Cell

The cylindrical cell continues to be one of the most widely used packaging styles for primary and secondary batteries. The advantages are ease of manufacture and good mechanical stability. The tubular cylinder can withstand high internal pressures without deforming.

Most lithium and nickel-based cylindrical cells include a *positive thermal coefficient (PTC)* switch. When exposed to excessive current, the normally conductive polymer heats up and becomes resistive, stopping current flow and acting as short circuit protection. Once the short is removed, the PTC cools down and returns to the conductive state.

Most cylindrical cells also feature a pressure relief mechanism, and the simplest design utilizes a membrane seal that ruptures under high pressure. Leakage and dry-out may occur after the membrane breaks. Re-sealable vents with a spring-loaded valve are the preferred design. Some Li-ion cells connect the pressure relief valve to an electrical fuse that permanently opens the cell if an unsafe pressure builds up. Figure 3-2 shows a cross section of a cylindrical cell.

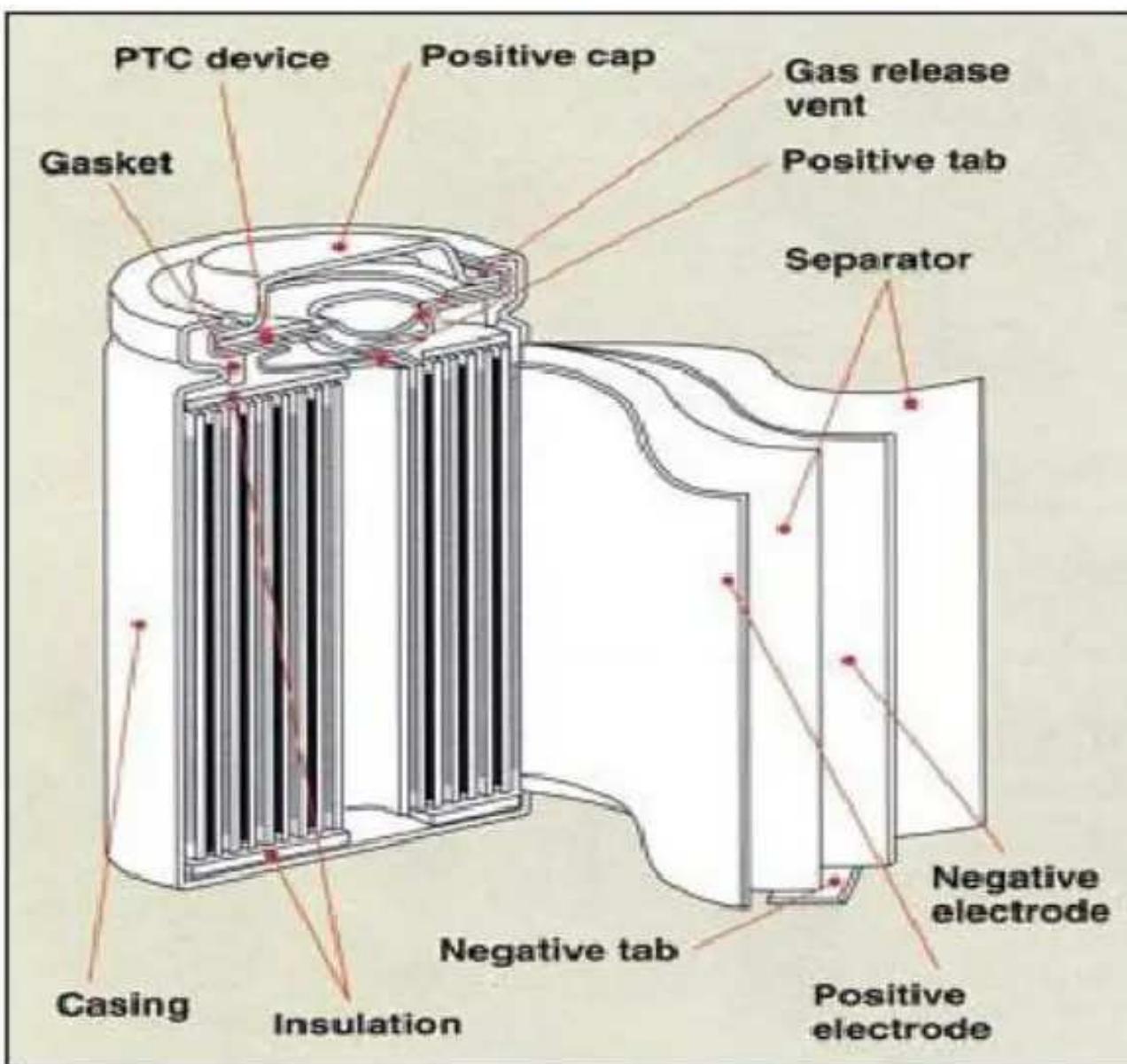


Figure 3-2: Cross section of a lithium-ion cylindrical cell.

The cylindrical cell design has good cycling ability, offers a long calendar life and is economical, but it is heavy and has low packaging density due to space cavities.

Source: Sanyo

Typical applications for the cylindrical cell are power tools, medical instruments, laptops and e-bikes. To allow variations within a given size, manufacturers use partial cell lengths, such as half and three-quarter formats, and nickel-cadmium provides the largest variety of cell choices. Some spilled over to nickel-metal-hydride but not to lithium-ion as this chemistry established its own formats. The 18650s illustrated in Figure 3-3 remains one of the most popular cell packages. Typical applications for the 18650 Li-ion are power tools, medical devices, laptops and e-bikes.



Figure 3-3: Popular 18650 lithium-ion cell.

The metallic cylinder measures 18mm in diameter and 65mm in length. The larger 26650 cell measures 26mm in diameter.

Courtesy of Cadex

In 2013, 2.55 billion 18650 cells were produced. Early Energy Cells had 2.2Ah; this was replaced with the 2.8Ah cell. The new cells are now 3.1Ah with an increase to 3.4Ah by 2017. Cell manufacturers are preparing for the 3.9Ah 18650.

The 18650 could well be the most optimized cell; it offers one of the lowest costs per Wh and has good reliability records. As consumers move to the flat designs in smart phones and tablets, the demand for the 18650 is fading and Figure 3-4 shows the over-supply that is being corrected thanks to the demand of the Tesla electric vehicles that also uses this cell format for now.

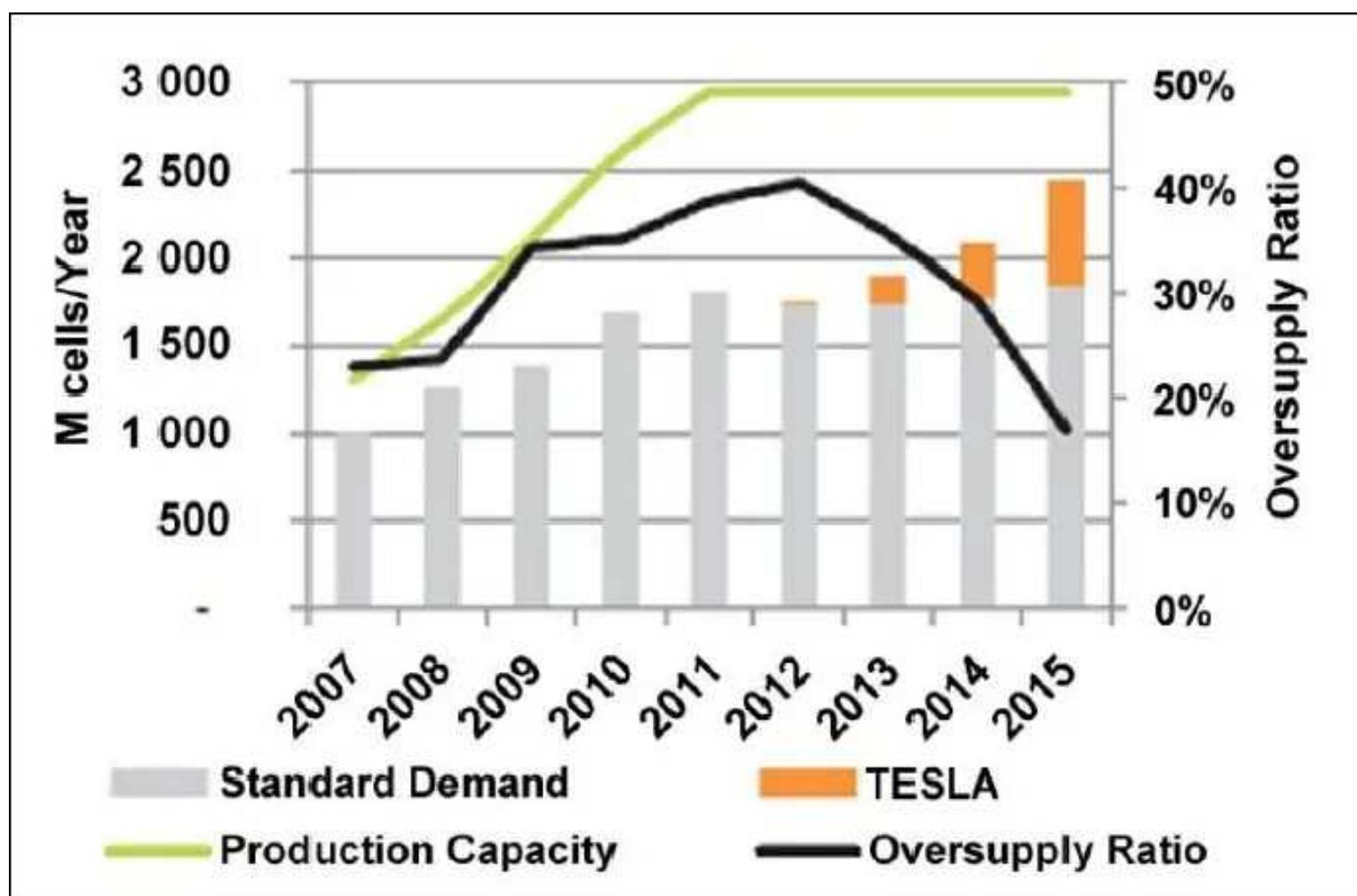


Figure 3-4: Demand and supply of the 18650.

The demand for the 18650 would have peaked in 2011 had it not been for Tesla. The switch to a flat-design in consumer products and larger format for the electric powertrain will eventually saturate the 18650.

Source: Avicenne Energy

The larger 26650 cell with a diameter of 26mm does not enjoy the same popularity as the 18650. The 26650 is commonly used in load-leveling systems. A thicker cell is said to be harder to build than a thinner one. Making the cell longer is preferred.

Some lead acid systems also borrow the cylindrical design. Known as the *Hawker Cyclone*, this cell offers improved cell stability, higher discharge currents and better temperature stability compared to the conventional prismatic design. The Hawker Cyclone has its own format.

Even though the cylindrical cell does not fully utilize the space by creating air cavities on side-by-side placement, the 18650 has a higher energy density than a prismatic/pouch Li-ion cell. The 3Ah 18650 delivers 248Ah/kg whereas a

than a prismatic/ pouch Li Ion cell. The Sanyo 18650 delivers 240Ah/kg, whereas a

modern pouch cell has about 140Ah/kg. The higher energy density of the cylindrical cell compensates for its less ideal stacking abilities and the empty space can always be used for cooling to improve thermal management.

Cell disintegration cannot always be prevented but propagation can. Cylindrical cells are often spaced apart to stop propagation should one cell take off. Spacing also helps in the thermal management. In addition, a cylindrical design does not change size. In comparison, a 5mm prismatic cell can expand to 8mm with use and allowances must be made.

Button Cell

The button cell, also known as coin cell, enabled compact design in portable devices of the 1980s. Higher voltages were achieved by stacking the cells into a tube. Cordless telephones, medical devices and security wands at airports used these batteries.

Although small and inexpensive to build, the stacked button cell fell out of favor and gave way to more conventional battery formats. A drawback of the button cell is swelling if charged too rapidly. Button cells have no safety vent and can only be charged at a 10- to 16-hour charge; however, newer designs claim rapid charge capability.

Most button cells are non-rechargeable and are found in medical implants, watches, hearing aids, car keys and memory backup. Figure 3-5 shows the button cells with a cross section.

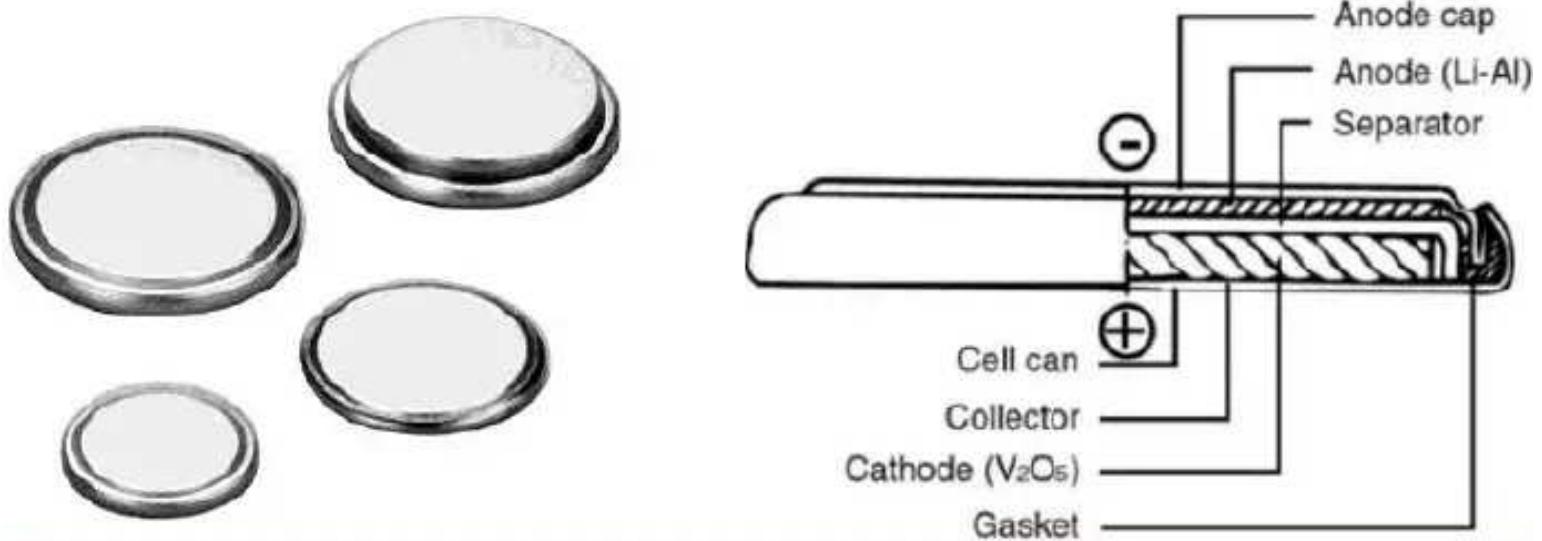


Figure 3-5: Button or coin cells.

Provides small size, most are primary for single-cell use.

Source: Sanyo and Panasonic

CAUTION Keep button cells to out of reach of children. Swallowing a cell can cause serious health problems. See "Health Concerns with Batteries" on page 198.

Prismatic Cell

Introduced in the early 1990s, the modern prismatic cell satisfies the demand for thinner sizes. Wrapped in elegant packages resembling a box of chewing gum or a small chocolate bar, prismatic cells make optimal use of space by using the layered approach. Other designs are wound and flattened into a pseudo-prismatic jelly roll. These cells are predominantly found in mobile phones, tablets and low-profile laptops ranging from 800mAh to 4,000mAh. No universal format exists and each manufacturer designs its own.

Prismatic cells are also available in large formats. Packaged in welded aluminum housings, the cells deliver capacities of 20–50Ah and are primarily used for electric powertrains in hybrid and electric vehicles. Figure 3-6 shows the prismatic cell.

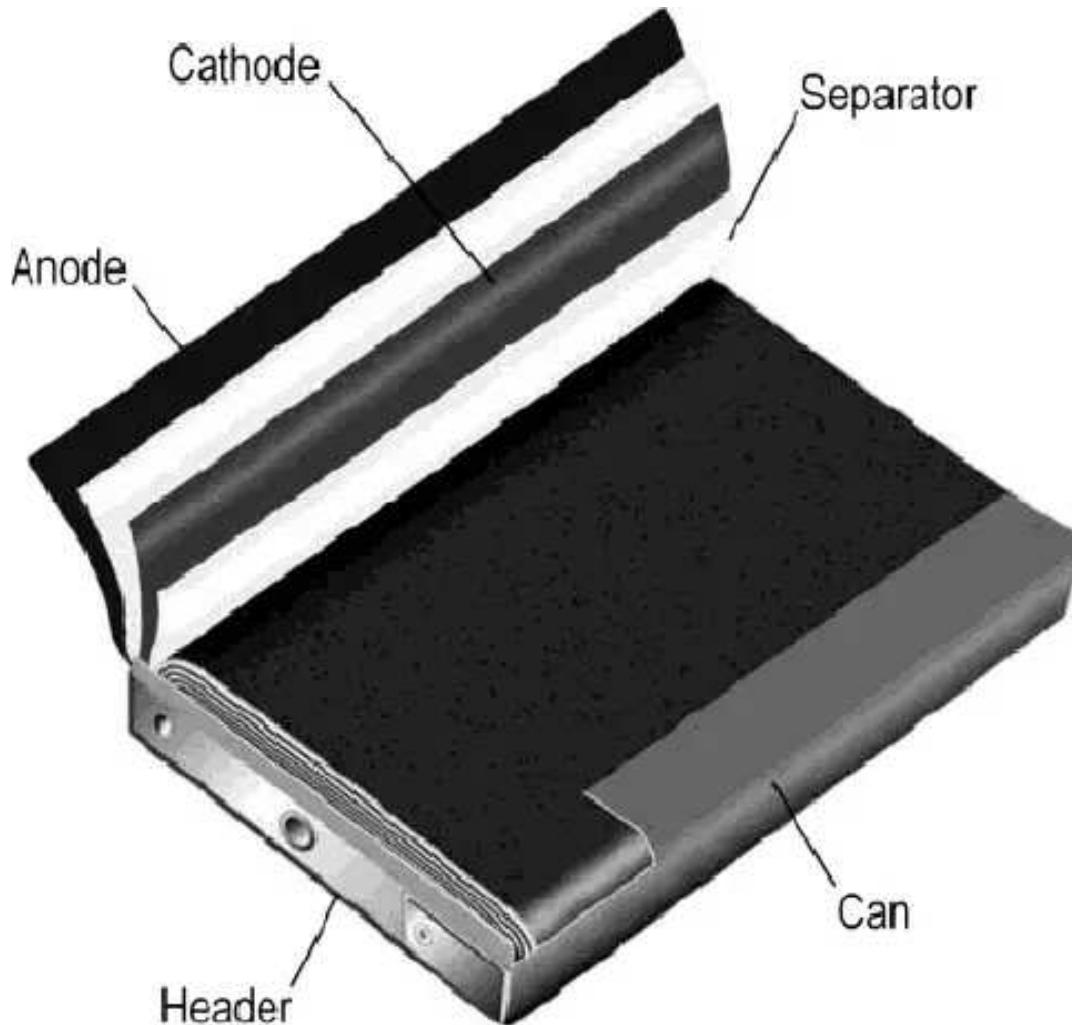


Figure 3-6: Cross section of a prismatic cell.

The prismatic cell improves space utilization and allows flexible design but it can be more expensive to manufacture, less efficient in thermal management and have a shorter cycle life than the cylindrical design. Allow for some swelling.

Source: Polystor Energy Corporation

The prismatic cell requires a firm enclosure to achieve compression. Some swelling due to gas buildup is normal, and growth allowance must be made; a 5mm (0.2") cell can grow to 8mm (0.3") after 500 cycles. Discontinue using the battery if the distortion presses against the battery compartment. Bulging batteries can damage equipment and compromise safety.

Pouch Cell

In 1995, the pouch cell surprised the battery world with a radical new design. Rather than using a metallic cylinder and glass-to-metal electrical feed-through, conductive foil-tabs were welded to the electrodes and brought to the outside in

a fully sealed way. Figure 3-7 shows a pouch cell.

The pouch cell makes most efficient use of space and achieves 90–95 percent packaging efficiency, the highest among battery packs. Eliminating the metal enclosure reduces weight, but the cell needs some support and allowance to expand in the battery compartment. The pouch packs are used in consumer, military and automotive. No standardized pouch cells exist; each manufacturer designs its own.



Figure 3-7: The pouch cell.

The pouch cell offers a simple, flexible and lightweight solution to battery design. Some stack pressure is recommended but allowance for swelling must be made. The pouch cells can deliver high load currents but it performs best under light loading conditions and with moderate charging.

Source: A123

Pouch packs are commonly Li-polymer. Small cells are popular for portable applications requiring high load currents, such as drones and hobby gadgets. The larger cells in the 40Ah range serve in energy storage systems (ESS) because fewer cells simplify the battery design.

Although easily stackable, provision must be made for swelling. While

smaller pouch packs can grow 8–10 percent over 500 cycles, large cells may

expand to that size in 5,000 cycles. It is best not to stack pouch cells on top of each other but to lay them flat, side by side or allow extra space in between them. Avoid sharp edges that can stress the pouch cells as they expand.

Extreme swelling is a concern. Users of pouch packs have reported up to 3 percent swelling incidents on a poor batch run. The pressure created can crack the battery cover and, in some cases, break the display and electronic circuit boards. Discontinue using an inflated battery and do not puncture the bloating cell in close proximity to heat or fire. The escaping gases can ignite. Figure 3-8 shows a swollen pouch cell.



Figure 3-8: Swollen pouch cell.

Swelling can occur due to gassing. Improvements are being made with newer designs. Large pouch cells designs experience less swelling.

Courtesy of Cadex

Pouch cells are manufactured by adding a temporary “gasbag” on the side. During the first charge, gases escape into the gasbag, the gasbag is cut off and the pack is resealed as part of the finishing process. Subsequent charges should no longer produce gases. Ballooning most often hints to a flawed batch; however, some growth with cycling is normal.

however, some growth with cycling is normal.

The technology has matured and prismatic and pouch cells have the potential for greater capacity than the cylindrical format. Large flat packs serve electric powertrains and Energy Storage System (ESS) with good results. The cost per kWh in the prismatic/pouch cell is still higher than with the 18650 cell, but this is changing. Figure 3-9 compares the price of the cylindrical, prismatic and pouch cells, also known as laminated. Flat-cell designs are getting price competitive and battery experts predict a shift towards these cell formats, especially if the same performance criteria of the cylindrical cell can be met.

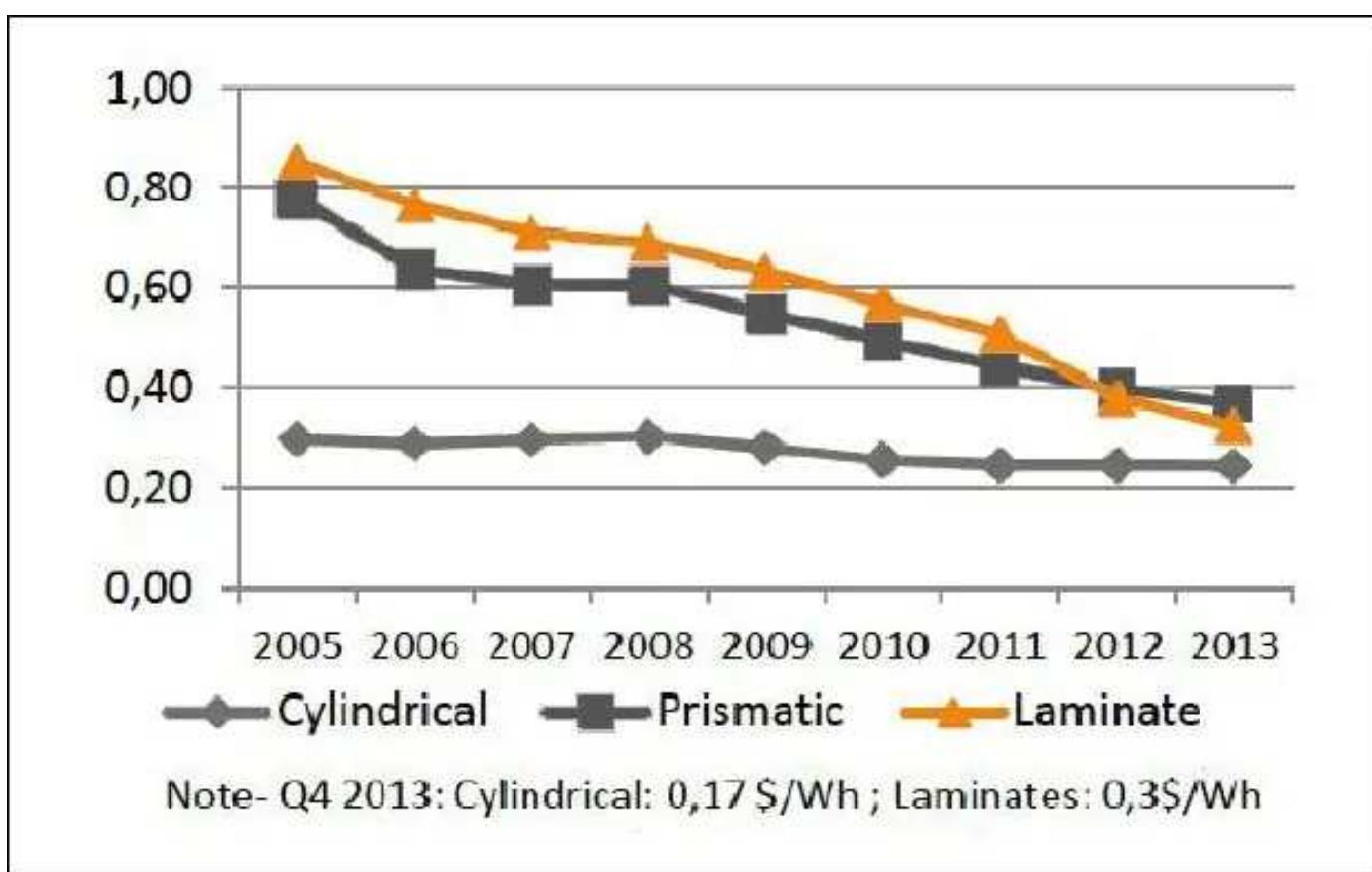


Figure 3-9: Price of Li-ion (\$US/Wh).

Historically, manufacturing costs of prismatic and pouch formats (lamine) were higher, but they are converging with cellular design. Pricing involves the manufacturing of the bare cells only.

Source: Avicenne Energy

Summary

With the pouch cell, the manufacturer is attempting to simplify cell manufacturing by replicating the packaging of food. Each format has pros and cons as summarized below.

cells as summarized below.

- **Cylindrical cell** has high specific energy, good mechanical stability and

lends itself to automated manufacturing. Cell design allows added safety features that are not possible with other formats; it cycles well, offers a long calendar life and is low cost, but it has less than ideal packaging density. The cylindrical cell is commonly used for portable applications.

- **Prismatic cell** is encased in aluminum or steel for stability. Jelly-rolled or stacked, the cell is space-efficient but can be costlier to manufacture than the cylindrical cell. The modern prismatic cell is used in the electric powertrain and energy storage systems.
- **Pouch cell** uses laminated architecture in a bag. It is light and cost-effective but exposure to humidity and high temperature can shorten life. Light stack pressure adds to longevity by preventing delamination. Swelling of 8–10 percent over 500 cycles must be considered with some cell designs. Large cells work best with light loading and moderate charge times. The pouch cell is growing in popularity and serves similar applications to the prismatic cell.

Series and Parallel Connection

Batteries achieve the desired operating voltage by connecting several cells in series; each cell adds its voltage potential to derive at the total terminal voltage. Parallel connection attains higher capacity by adding up the total ampere-hour (Ah).

Some packs may consist of a combination of series and parallel connections. Laptop batteries commonly have four 3.6V Li-ion cells in series to achieve a nominal voltage of 14.4V and two in parallel to boost the capacity from 2,400mAh to 4,800mAh. Such a configuration is called 4S2P, meaning four cells in series and two in parallel. Insulating foil between the cells prevents the conductive metallic skin from causing an electrical short.

Most battery chemistries lend themselves to series and parallel connection. It is important to use the same battery type with equal voltage and capacity (Ah) and never to mix different makes and sizes. A weaker cell would cause an imbalance. This is especially critical in a series configuration because a battery is only as strong as the weakest link in the chain. An analogy is a chain in which

is only as strong as the weakest link in the chain. An analogy is a chain in which the links represent the cells of a battery connected in series. (Figure 3-10).



Figure 3-10: Comparing a battery with a chain.

Chain links represent cells in series to increase voltage, doubling a link denotes parallel connection to boost current loading.

A weak cell may not fail immediately but will get exhausted more quickly than the strong ones when on a load. On charge, the low cell fills up before the strong ones because there is less to fill and it remains in over-charge longer than the others. On discharge, the weak cell empties first and gets hammered by the stronger brothers. Cells in multi-packs must be matched, especially when used under heavy loads (See “Cell Matching and Balancing” on page 231.)

Single Cell Applications

The single-cell configuration is the simplest battery pack; the cell does not need matching and the protection circuit on a small Li-ion cell can be kept simple. Typical examples are mobile phones and tablets with one 3.60V Li-ion cell. Other uses of a single cell are wall clocks, which typically use a 1.5V alkaline cell, wristwatches and memory backup, most of which are very low power applications.

The nominal cell voltage for a nickel-based battery is 1.2V, alkaline is 1.5V, silver-oxide is 1.6V and lead acid is 2.0V. Primary lithium batteries range between 3.0V and 3.9V. Li-ion is 3.6V; Li-phosphate is 3.2V and Li-titanate is 2.4V.

Li-manganese and other lithium-based systems often use cell voltages of 3.7V and higher. This has less to do with chemistry than promoting a higher watt-hour (Wh), which is made possible with a higher voltage. The argument goes that a low internal cell resistance keeps the voltage high under load. For operational purposes these cells go as 3.6V candidates.

operational purposes these cells go as 3.6 V candidates.

Series Connection

Portable equipment needing higher voltages use battery packs with two or more cells connected in series. Figure 3-11 shows a battery pack with four 3.6V Li-ion cells in series, also known as 4S, to produce 14.4V nominal. In comparison, a six-cell lead acid string with 2V/cell will generate 12V, and four alkaline with 1.5V/cell will give 6V.



Figure 3-11: Series connection of four cells (4S). Adding cells in a string increases the voltage; the capacity remains the same.

If you need an odd voltage of, say, 9.50 volts, connect five lead acid, eight NiMH or NiCd, or three Li-ion in series. The end battery voltage does not need to be exact as long as it is higher than what the device specifies. A 12V supply might work in lieu of 9.50V. Most battery-operated devices can tolerate some over-voltage; the end-of-discharge voltage must be respected, however.

High voltage batteries keep the conductor size small. Cordless power tools run on 12V and 18V batteries; high-end models use 24V and 36V. Most e-bikes come with 36V Li-ion, some are 48V. The car industry wanted to increase the starter battery from 12V (14V) to 36V, better known as 42V, by placing 18 lead acid cells in series. Logistics of changing the electrical components and arcing problems on mechanical switches derailed the move.

Some mild hybrid cars run on 48V Li-ion and use DC-DC conversion to 12V for the electrical system. Starting the engine is often done by a separate 12V lead acid battery. Early hybrid cars ran on a 148V battery; electric vehicles are typical 450–500V. Such a battery needs more than 100 Li-ion cells connected in series.

High-voltage batteries require careful cell matching, especially when drawing heavy loads or when operating at cold temperatures. With multiple cells

drawing heavy loads or when operating at cold temperatures. With multiple cells connected in a string, the possibility of one cell failing is real and this would

cause a failure. To prevent this from happening, a solid state switch in some large packs bypasses the failing cell to allow continued current flow, albeit at a lower string voltage.

Cell matching is a challenge when replacing a faulty cell in an aging pack. A new cell has a higher capacity than the others, causing an imbalance. Welded construction adds to the complexity of the repair, and this is why battery packs are commonly replaced as a unit.

High-voltage batteries in electric vehicles, in which a full replacement would be prohibitive, divide the pack into modules, each consisting of a specific number of cells. If one cell fails, only the affected module is replaced. A slight imbalance might occur if the new module is fitted with new cells. (See “How to Repair a Battery Pack” on page 290.)

Cell 3 in Figure 3-12 produces only 2.8V instead of the full nominal 3.6V. With depressed operating voltage, this battery reaches the end-of-discharge point sooner than a normal pack. The voltage collapses and the device turns off with a “Low Battery” message.



Figure 3-12: Series connection with a faulty cell. Faulty cell 3 lowers the voltage and cuts the equipment off prematurely.

Batteries in drones and remote controls for hobbyist requiring high load current often exhibit an unexpected voltage drop if one cell in a string is weak. Drawing maximum current stresses frail cells, leading to a possible crash. Reading the voltage after a charge does not identify this anomaly; examining the cell-balance or checking the capacity with a battery analyzer will.

Parallel Connection

Parallel Connection

If higher currents are needed and larger cells are not available or do not fit the

design constraint, one or more cells can be connected in parallel. Most battery chemistries allow parallel configurations with little side effect. Figure 3-13 illustrates four cells connected in parallel in a P4 arrangement. The nominal voltage of the illustrated pack remains at 3.60V, but the capacity (Ah) and runtime are increased fourfold.

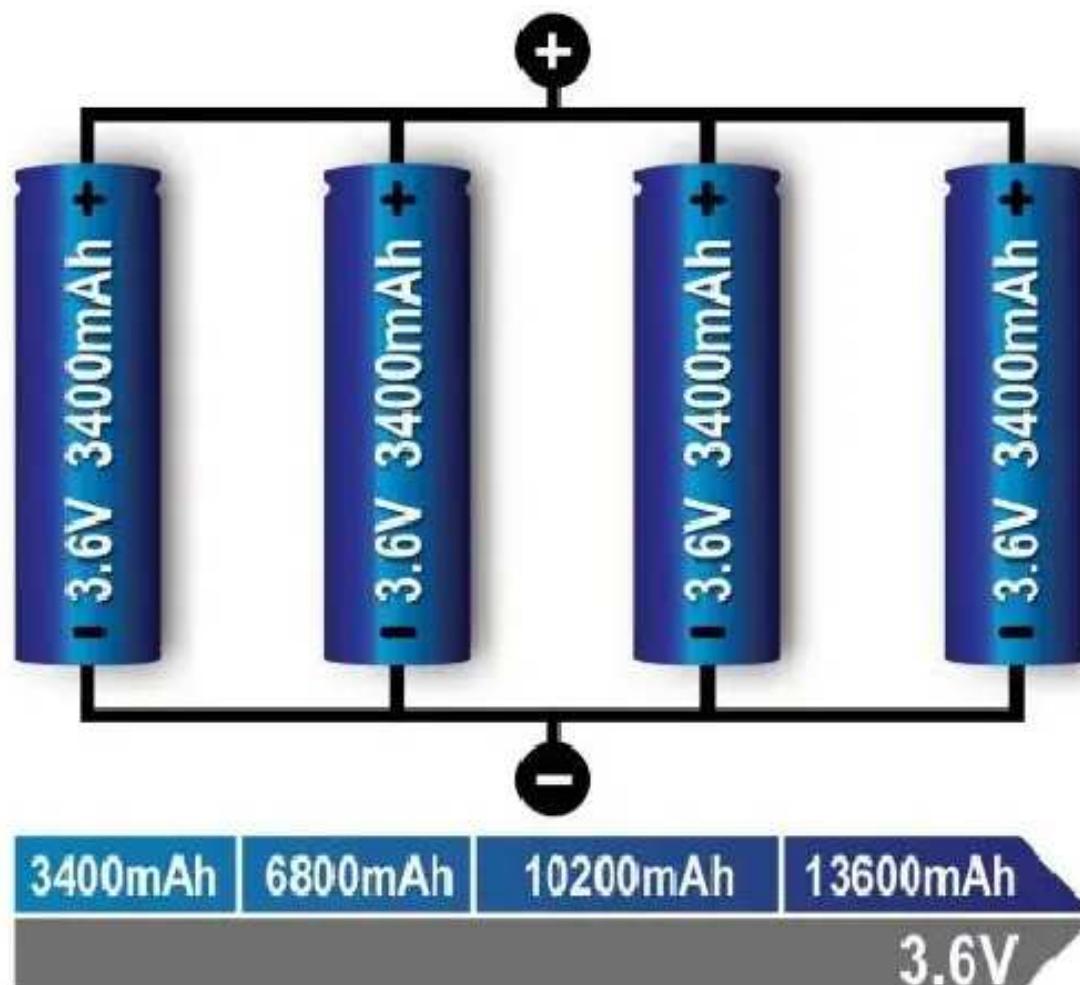


Figure 3-13: Parallel connection of four cells (4P).

With parallel cells, capacity in Ah and runtime increases while the voltage stays the same.

Courtesy of Cadex

A cell that develops high resistance or opens is less critical in a parallel circuit than in a series configuration, but a failing cell will reduce the total load capability. It's like an engine only firing on three cylinders instead of on all four. An electrical short, on the other hand, is more serious as the faulty cell drains energy from the other cells, causing a fire hazard. Most so-called electrical shorts are mild and manifest themselves as elevated self-discharge.

shorts are mild and manifest themselves as elevated self-discharge.

A total short can occur through reverse polarization or dendrite growth.

Large packs often include a fuse that disconnects the failing cell from the parallel circuit if it shorts. Figure 3-14 illustrates a parallel configuration with one faulty cell.

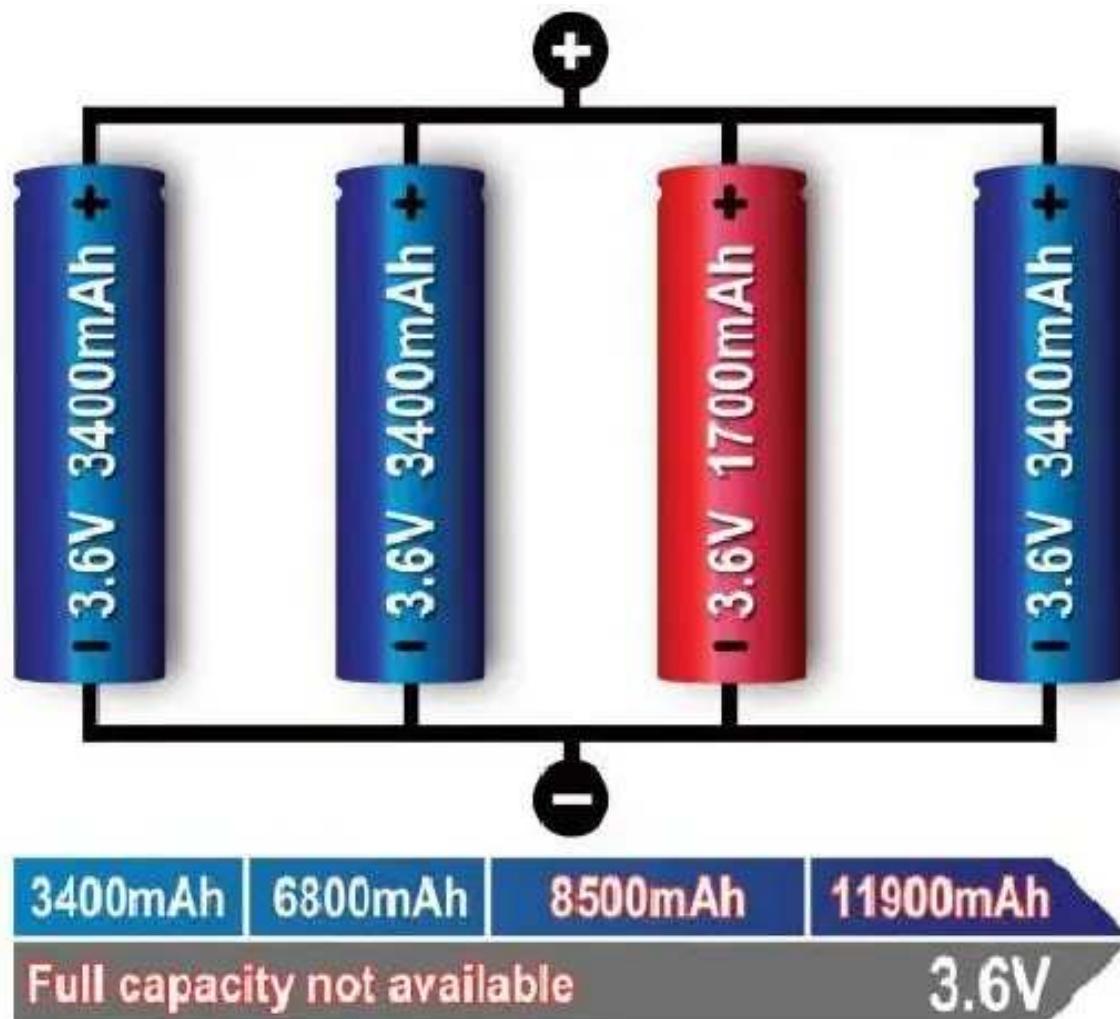


Figure 3-14: Parallel connection with one faulty cell.

A weak cell will not affect the voltage but provide a low runtime due to reduced capacity. A shorted cell could cause excessive heat and become a fire hazard. A fuse prevents on larger packs a high current rush by isolating the cell.

Courtesy of Cadex

Series/parallel Connection

The series/parallel configuration shown in Figure 3-15 enables design flexibility while achieving the desired voltage and current ratings with a standard cell size. The total power is the product of voltage-times-current; four 3.6V cells multiplied by 3,400mAh produce 12.24Wh. Four 18650 Energy Cells of 3,400mAh each can be connected in series and parallel as shown to get 7.2V and

3,400mAh each can be connected in series and parallel as shown to get 7.2V and 12.24Wh. The slim cell allows flexible pack design but a protection circuit is

needed.

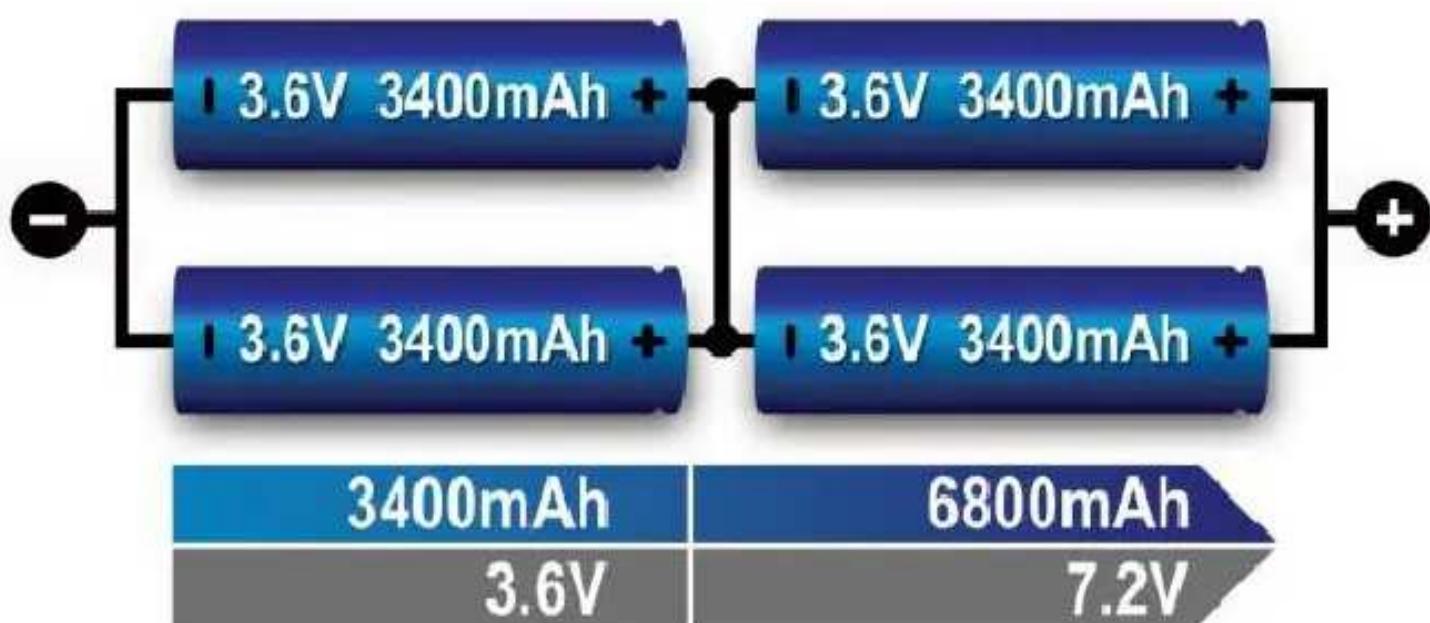


Figure 3-15: Series/parallel connection of four cells (2S2P).

This configuration provides maximum design flexibility. Paralleling the cells helps in voltage management.
Courtesy of Cadex

Li-ion lends itself well to series/parallel configurations but the cells need monitoring to stay within voltage and current limits. Integrated circuits (ICs) for various cell combinations are available to supervise up to 13 Li-ion cells. Larger packs need custom circuits, and this also applies to the Tesla Model 85 that devours over 7,000 18650 cells to make up the 90kWh pack.

Simple Guidelines for Using Household Primary Batteries

- Keep the battery contacts clean. A four-cell configuration has eight contacts and each contact adds resistance (cell to holder and holder to next cell).
- Never mix batteries; replace all cells when weak. The overall performance is only as good as the weakest link in the chain.
- Observe polarity. A reversed cell subtracts rather than adds to the cell voltage.
- Remove batteries from the equipment when no longer in use to prevent

Remove batteries from the equipment when no longer in use to prevent leakage and corrosion. This is especially important with zinc-carbon

primary cells.

- Do not store loose cells in a metal box. Place individual cells in small plastic bags to prevent an electrical short. Do not carry loose cells in your pockets.
- Keep batteries away from small children. In addition to being a choking hazard, the current-flow of the battery can ulcerate the stomach wall if swallowed. The battery can also rupture and cause poisoning. (See “Health Concerns with Batteries” on page 198.)
- Do not recharge non-rechargeable batteries; hydrogen buildup can lead to an explosion. Perform experimental charging only under supervision.

Simple Guidelines for Using Secondary Batteries

- Observe polarity when charging a secondary cell. Reversed polarity can cause an electrical short, leading to a hazardous condition.
- Remove fully charged batteries from the charger. A consumer charger may not apply the correct trickle charge when fully charged and the cell can overheat.
- Charge only at room temperature.

Confusion with Voltages

A battery is an electrochemical device that produces a voltage potential when placing metals of different affinities into an acid solution (electrolyte). The *open circuit voltage (OCV)* that develops as part of an electrochemical reaction varies with the metals and electrolyte used.

Applying a charge or discharge places the battery into the *closed circuit voltage (CCV)* condition. Charging raises the voltage and discharging lowers it, simulating a rubber band effect. The voltage behavior under a load and charge is governed by the current flow and the internal battery resistance. A low resistance produces low fluctuation under load or charge; a high resistance causes the voltage to swing excessively. Charging and discharging agitates the battery; full

voltage to swing excessively. Charging and discharging agitates the battery, full voltage stabilization takes up to 24 hours. Temperature also plays a role; a cold

temperature lowers the voltage and heat raises it.

Manufacturers rate a battery by assigning a nominal voltage, and with a few exceptions, these voltages follow an agreed convention. Here are the nominal voltages of the most common batteries in brief.

Lead Acid

The nominal voltage of lead acid is 2 volts per cell, however when measuring the open circuit voltage, the OCV of a charged and rested battery should be 2.1V/cell. Keeping lead acid much below 2.1V/cell will cause the buildup of sulfation. While on float charge, lead acid measures about 2.25V/cell, higher during normal charge.

Nickel-based

In consumer applications, NiCd and NiMH are rated at 1.20V/cell; industrial, aviation and military batteries may adhere to the original 1.25V rating. There is no difference between the 1.20V and 1.25V cell; the marking is simply preference.

Lithium-ion

The nominal voltage of lithium-ion is 3.60V/cell. Some cell manufacturers mark their Li-ion as 3.70V/cell or higher. This offers a marketing advantage because the higher voltage boosts the watt-hours on paper (voltage times current equals watts). The 3.70V/cell rating also creates unfamiliar references of 11.1V and 14.8V when connecting three and four cells in series rather than the more familiar 10.80V and 14.40V respectively. Equipment manufacturers adhere to the nominal cell voltage of 3.60V for most Li-ion systems as a power source.

How did this higher voltage creep in? The cell manufacturer plots the voltage of a fully charged cell that measures 4.20V, discharges it at 0.5C to 3.0V and takes the mid-way point. For Li-cobalt the mid-way point is about 3.60V. The same scan done on Li-manganese with a lower internal resistance gives an average voltage of about 3.70V. It should be noted that the higher voltage is arbitrary and does not affect the operation of portable devices or the setting of

arbitrary and does not affect the operation of portable devices or the setting of chargers.

The phosphate-based lithium-ion has a nominal cell voltage of 3.20 and 3.30V; lithium-titanate is 2.40V. This voltage differences make these chemistries incompatible with regular Li-ion in terms of cell count and charging algorithm.

Protection Circuits

Batteries can release high energies and the safety requirements for nickel- and lithium-based batteries and cells for portable applications are harmonized under IEC 62133. The standard came into effect in 2012 to reduce the global risk in transporting, storing and operating batteries.

The most basic safety device in a battery is a fuse that opens on high current. Some fuses open permanently and render the battery useless; others are more forgiving and reset. The *positive thermal coefficient (PTC)* is such a resettable device that creates high resistance on excess current and reverts back to the low ON position when the condition normalizes.

Further layers of safeguards are solid-state switches that measure the current and voltage and disconnect the circuit if the values are too high. The protection circuits of Li-ion work on this on/off basis. All switching devices have a residual resistance, which causes a slight increase in overall battery resistance and a subsequent voltage drop.

Intrinsically Safe Batteries

Safety is vitally important when using electronic devices in hazardous areas. Intrinsic safety (IS) ensures harmless operation in areas where an electric spark could ignite flammable gas or dust. Hazardous areas include oil refineries, chemical plants, grain elevators and textile mills.

All electronic devices entering a hazardous area must be intrinsically safe. This includes two-way radios, mobile phones, laptops, cameras, flashlights, gas detectors, test devices and medical instruments, even when powered with primary AAA and AA cells. Intrinsically safe devices and batteries contain

primary AA and AAA cells. Inherently safe devices and batteries contain protection circuits that prevent excessive currents that could lead to high heat,

sparks and explosion. The hazard levels are subdivided into these four disciplines:

1. Types of Hazardous Materials present

- | | |
|-----------|---------------------------------------------------------------------------------|
| Class I | Flammable gases, vapors or liquids in petroleum refineries, utility gas plants |
| Class II | Combustible dust in grain elevators, coal preparations plants |
| Class III | Ignitable fibers and flyings in textile mills, wood processing creating sawdust |

2. Likelihood of Hazardous Materials present

Division I Hazardous materials can exist in ignitable concentrations

Division II Hazardous materials will not likely exist in ignitable concentrations

3. Potency of Hazardous Material (Groups from A to G)

A hazardous material is given a designation of: Acetylene (A), hydrogen (B), ethylene (C), propane, gasoline, etc. (D), metal dust (E), coal dust (F) and grain dust (G).

4. Temperature Codes (from T1 to T6)

The explosion danger of gases or combustible dust is affected by surface temperature. T1 is a hot 450°C (842°F); T6 is a moderate 85°C (185°F). All other temperatures fall in between.

Intrinsic safety requirements vary from country to country. North America has the Factory Mutual Research Corporation, Underwriters Laboratories (UL) and Canadian Standards Association (CSA); Europe has the ATEX directive; while other countries follow the IECEx standards. Many countries recognize the harmonized IEC 60079.

Safety Concerns with Li-ion

Safety of lithium-based batteries has attracted much media and legal attention.

Any energy storage device carries a risk, as demonstrated in the 1800s when

steam engines exploded and people got hurt. Carrying highly flammable

steam engines exploded and people got hurt. Carrying highly flammable gasoline in cars was a hot topic in the early 1900s. All batteries carry a safety

risk, and battery makers are obligated to meet safety requirements; less reputable firms are known to make shortcuts and it's "buyer be beware!"

Lithium-ion is safe but with millions of consumers using batteries, failures are bound to happen. In 2006, a one-in-200,000 breakdown triggered a recall of almost six million lithium-ion packs. Sony, the maker of the lithium-ion cells in question, points out that on rare occasions microscopic metal particles may come into contact with other parts of the battery cell, leading to a short circuit within the cell.

Battery manufacturers strive to minimize the presence of such particles; however, complex assembly techniques make the elimination of all metallic dust a challenge. Cells with ultra-thin separators of 24 μm or less (24-thousandth of an mm) are more susceptible to impurities than the older designs with lower Ah ratings. Whereas the 1,350mAh cell in the 18650 package could tolerate a nail penetration test, the high-density 3,400mAh becomes a bomb when performing the same test. New safety standards direct how batteries are used, and the UL1642 Underwriters Laboratories (UL) test no longer mandates nail penetration for safety acceptance of lithium-based batteries.

Li-ion using conventional metal oxides is nearing its theoretical limit on specific energy. Rather than optimizing capacity, battery makers are improving manufacturing methods to enhance safety and increase calendar life. The real problem lies when on rare occasions an electrical short develops inside the cell. The external protection peripherals are ineffective to stop a thermal runaway once in progress. The batteries recalled in 2006 had passed the UL safety requirements — yet they failed under normal use with appropriate protection circuits.

There are two basic types of battery failures. One occurs at a predictable interval-per-million and is connected with a design flaw involving the electrode, separator, electrolyte or processes. These defects often involve a recall to correct a discovered flaw. The more difficult failures are random events that do not point

a discovered flaw. The more difficult failures are random events that do not point to a design flaw. It may be a stress event like charging at sub-freezing

temperature, vibration, or a fluke incident that is comparable to being hit by a meteor.

Let's examine the inner workings of the cell more closely. A mild short will only cause elevated self-discharge and the heat buildup is minimal because the discharging power is very low. If enough microscopic metallic particles converge on one spot, a sizable current begins to flow between the electrodes of the cell, and the spot heats up and weakens. As a small water leak in a faulty hydro dam can develop into a torrent and take a structure down, so too can heat buildup damage the insulation layer in a cell and cause an electrical short. The temperature can quickly reach 500°C (932°F), at which point the cell catches fire or explodes. This thermal runaway that occurs is known as "venting with flame." "Rapid disassembly" is the preferred term by the battery industry.

Uneven separators can also trigger cell failure. Poor conductivity due to dry areas increases the resistance, which can generate local heat spots that weaken the integrity of the separator. Heat is always an enemy of the battery.

What to Do when a Battery Overheats

If a Li-ion battery overheats, hisses or bulges, immediately move the device away from flammable materials and place it on a non-combustible surface. If at all possible, remove the battery and put it outdoors to burn out.

A small Li-ion fire can be handled like any other combustible fire. For best result use a foam extinguisher, CO₂, ABC dry chemical, powdered graphite, copper powder or soda (sodium carbonate). If the fire occurs in an airplane cabin, the FAA instructs flight attendants to use water or soda pop. Water-based products are most readily available and are appropriate since Li-ion contains very little lithium metal that reacts with water. Water also cools the adjacent area and prevents the fire from spreading. Research laboratories and factories also use water to extinguish Li-ion battery fires. Halon is also used as fire suppressant, but this agent may not be sufficient to extinguish a large Li-ion fire in the cargo

day or an aircraft.

A large Li-ion fire, such as in an EV, may need to burn out as water is

ineffective. Water with copper material can be used, but this may not be available and is costly for fire halls.

When encountering a fire with a lithium-metal battery, only use a Class D fire extinguisher. Lithium-metal contains plenty of lithium that reacts with water and makes the fire worse. As the number of EVs grows, so must the methods to extinguish such fires.

CAUTION Do not use a Class D fire extinguisher to put out other types of fires; make certain regular extinguishers are also available. With all battery fires, allow ample ventilation while the battery burns itself out.

During a thermal runaway, the high heat of the failing cell inside a battery pack may propagate to the next cells, causing them to become thermally unstable also. A chain reaction can occur in which each cell disintegrates on its own timetable. A pack can thus be destroyed in a few seconds or over several hours as each cell is being consumed. To increase safety, packs should include dividers to protect the failing cell from spreading to the neighboring one. Figure 3-16 shows a laptop that was damaged by a faulty Li-ion battery.



Figure 3-16: Li-ion battery suspected to have destroyed the laptop.

The owner says the laptop popped, hissed, sizzled and began filling the room with smoke.

Source: Shmuel De-Leon

The gas released by a venting Li-ion cell is mainly carbon dioxide (CO_2).

Other gases that form through heating are vaporized electrolyte consisting of ethylene and/or propylene. Burning gases also include combustion products of organic solvents.

While lithium-based batteries are heavily scrutinized for safety, nickel- and lead-based batteries also cause fires and are being recalled. The reasons are faulty separators resulting from aging, rough handling, excessive vibration and high-temperature. Lithium-ion batteries have become very safe and heat-related failures occur rarely when used correctly.

Simple Guidelines for Using Lithium-ion Batteries

- Lithium-ion batteries contain little lithium metal and in case of a fire they can be doused with water. Only lithium-metal batteries require a Class D fire extinguisher.
- Water interacts with lithium. If a Class D extinguisher is not available to douse a lithium-metal fire, only pour water to prevent the fire from spreading.
- For best results when dousing a Li-ion fire, use a foam extinguisher, CO_2 , ABC dry chemical, powdered graphite, copper powder or soda (sodium carbonate) as you would extinguish other combustible fires. Reserve the Class D extinguishers for lithium-metal fires only.
- If the fire of a burning lithium-ion battery cannot be extinguished, allow the pack to burn in a controlled and safe way.
- Be aware of cell propagation as each cell might be consumed on its own time-table when hot. Place a seemingly burned-out pack outside for a time.

Making Lithium-ion Safe

Battery packs using Li-ion require a mandatory protection circuit to assure safety

under (almost) all circumstances. Governed by IEC 62133, the safety of Li-ion cell or packs begins by including some or all of the following safeguards.

1. Built-in PTC (positive temperature coefficient) protects against current surges.
2. CID (circuit interrupt device) opens the circuit at a cell pressure of 1,000kPa (145psi)
3. Safety vent releases gases on excessive pressure buildup at 3,000kPa (450psi).
4. Separator inhibits ion-flow by melting process when exceeding a certain temperature threshold. (See “Battery Separator” on page 114.)

In addition to internal cell safeguards, an external electronic protection

circuit prevents any cell from exceeding 4.30V on charge. In addition, a fuse cuts the current if the skin temperature of any cell approaches 90°C (194°F). To prevent the battery from over-discharging, a control circuit cuts off the current path at about 2.20V/cell.

Each cell in a string needs independent voltage monitoring. The higher the cell count, the more complex the protection circuit becomes. Four cells in series had been the practical limit for consumer applications. Today, off-the-shelf chips also accommodate 5–7, 7–10 and 13 cells in series. For specialty applications, such as the hybrid or electric vehicle delivering several hundred volts, specialty protection circuits are made. Monitoring two or more cells in parallel to get higher current is less critical than controlling the voltage in a string configuration.

Protection circuits can only shield abuse from the outside, such as an electrical short or faulty charger. If, however, a defect occurs within the cell, such as a contamination of microscopic metal particles, the external protection circuit has little effect and cannot arrest the reaction. Reinforced and self-healing separators are being developed for cells used in electric powertrains, but this

makes the batteries large and expensive.

Li-ion commonly discharges to 3.0V/cell. The lowest permitted “low-

voltage” power cutoff is 2.5V/cell. It is not advised to keep the battery at that level as self-discharge could bring the cell to its cutoff voltage, causing the battery to go into sleep mode. Most chargers ignore Li-ion packs that have gone to sleep and a charge is no longer possible. (See “How to Awaken an Over-discharged Li-ion” on page 253.)

In the ON position, the internal protection circuit has a resistance of 50–100mOhm, lower on power packs. The circuit typically consists of two switches connected in series; one is responsible for the high cutoff, and the other for the low cutoff. Larger packs need a more careful design than a smaller battery, and single cell packs for mobile phones and tablets get away with a voltage and current limit in addition to some intrinsic cell protection.

Some low-cost consumer chargers may rely solely on the battery’s protection circuit to terminate the charge. Redundancy is paramount for safety, and unknowingly to the buyer, low-cost consumer chargers may be offered that do not have properly functioning charge algorithms. This could be a vehicular charger for a mobile phone or an e-cigarette.

A further concern arises if static electricity has destroyed the battery’s protection circuit. A shorted solid-state switch is permanently fused in the ON position without the user knowing. A battery with a faulty protection circuit functions normally but it fails to provide protection. The cell voltage could rise above a safe level and overcharge the battery. Heat buildup and bulging are early signs of malfunction, but some batteries explode without warning.

Low prices make products from Asia attractive, but safety standards may not be equal to those in branded products. A wise shopper spends a little more money and buys recognized brands. (See “Aftermarket Batteries” on page 259.)

Manufacturers of lithium-ion batteries do not mention the word “explosion” but refer to “venting with flame” or “rapid disassembly.” Although seen as a slower and more controlled process than explosion, venting with flame or rapid disassembly can lead to ignition and fire in an uncontrolled environment.

disassembly can nevertheless be violent and inflict injury to those in close proximity.

Building a Lithium-ion Pack

Building a Li-ion battery pack begins by satisfying voltage and runtime requirements, and then taking loading, environmental, size and weight limitations into account. Portable designs for consumer products want a slim profile and the choice is a prismatic or pouch cell. If space allows, a cylindrical cell such as the 18650 often provides the lowest cost and best performance in terms of specific energy, safety and durability.

Most battery packs for medical devices, power tools, e-bikes and even powertrains for electric cars (EV) are based on the 18650. This appears impractical but the small cell works well because it is one of the most mature Li-ion formats available, is produced in high volume and enjoys a low cost per Wh.

The cylindrical cell is not ideal as it leaves empty spaces in a multi-cell configuration. This disadvantage turns into an advantage when considering flexibility and cooling. The Tesla S 85 EV uses over 7,000 cells, switched in parallel to boost the current and in series to increase the voltage. Should one cell in series open, the total power loss is minimal; if one in parallel shorts, fuse protection removes this cell from the circuit. Failing cells can thus be eliminated without bringing the battery down.

EV manufacturers are not united on the choice of cell, but there is a trend towards larger formats to reduce supportive electronics that adds 20–25 percent to the finished pack. With a larger cell, however, the electronic components get dearer because of higher current handling. According to 2015 reports, the Tesla S 85 has the lowest cost per kWh using the 18650. Other EVs have larger prismatic cells at higher kWh costs. Table 3-17 compares the kWh cost.

Make and model	Cell type	Cost per kWh (est.)	Specific energy
Tesla S 85, 90kWh (2015)*	18650	\$260/kWh	250Wh/kg
Tesla, 48kWh Gen III	18650	\$260/kWh	250Wh/kg
Best practices DoE/AABC)	pouch/prismatic	\$350/kWh	150–180Wh/kg
Nissan Leaf, 30kWh (2016)*	pouch/prismatic	\$455/kWh	80–96Wh/kg
BMW i3	pouch/prismatic	N/A	120Wh/kg

Table 3-17: Price comparison of EV batteries. Mass production allows a low price using the 18650 cell.

* In 2015/16 Tesla S 85 increased the battery from 85kWh to 90kWh; Nissan Leaf from 25kWh to 30kWh.

Batteries should be designed to permit failure without a catastrophic event. All energy sources will fail eventually and the battery is no exception. After an unwanted event, the FAA mandated to place the Li-ion ship-battery of the Boeing Dreamliner 787 into a metal container with venting to the outside. Tesla reinforced the EV battery by adding a heavy-gauge steel plate on the bottom that provides extra protection against projectiles from the road.

Large batteries for power applications are cooled. Some use a rod system to bring the heat to the outside, others deploy forced air or use liquid cooling. Liquid cooling is superior and although more expensive, EV batteries gravitate towards this form of cooling.

Meeting Safety Approvals

Reputable battery manufacturers do not supply Li-ion cells to uncertified battery assemblers. This precaution is understandable, considering that Li-ion cells could be charged and discharged beyond safe limits with inadequate protection circuits.

Authorizing a battery pack for the commercial market and for air transport can cost \$10,000 to \$20,000. Such a high price is troubling, knowing that cell manufacturers discontinue older cells in favor of higher capacity replacements. A pack with the new cell, even if specified as a direct replacement, requires new

certifications.

The common question asked is, “Why are additional tests needed when the

cells are already approved?” The simple answer is that cell approvals cannot be transferred to the pack because regulatory authorities place the safety confirmation on a finished product and not the components. The completed battery must be tested and registered to assure correct assembly and compliance with safety standards.

As part of the test requirements, the finished battery must undergo electrical and mechanical assessment to meet the Recommendations on the Transport of Dangerous Goods on lithium-ion batteries for air shipment, rules set by the United Nations (UN). The UN Transportation Testing (UN/DOT 38.3) works in conjunction with the Federal Aviation Administration (FAA), the US Department of Transport (US DOT) and the International Air Transport Association (IATA)^{*}. The certification applies to primary and secondary lithium-based cells. The UN 38.3 test includes:

T1 – Altitude Simulation (Primary and Secondary Cells and Batteries)

T2 – Thermal Test (Primary and Secondary Cells and Batteries)

T3 – Vibration (Primary and Secondary Cells and Batteries)

T4 – Shock (Primary and Secondary Cells and Batteries)

T5 – External Short Circuit (Primary and Secondary Cells and Batteries)

T6 – Impact (Primary and Secondary Cells)

T7 – Overcharge (Secondary Batteries)

T8 – Forced Discharge (Primary and Secondary Cells)

The test batteries must pass the tests without causing harm, but the packs do not need to function thereafter. The test is strictly for safety and not consumer endurance. The authorized laboratory needs 24 battery samples consisting of 12 new packs and 12 specimens that have been cycled 50 times. IATA wants to ensure that the batteries in question are airworthy and have field integrity; cycling the packs 50 times before the test satisfies this requirement.

The high certification cost discourages small manufacturers from using Li-

ion for low-volume products and entrepreneurs may choose nickel-based systems instead. These batteries do not need to be tested to the level of lithium-

based products for air transport. While reputable companies follow the instructions, rules are being broken and the penalties are stiff.

Simple Guidelines for Using Lithium-ion Batteries

- Exercise caution when handling and testing lithium-ion batteries.
- Do not short circuit, overcharge, crush, drop, mutilate, penetrate with foreign objects, apply reverse polarity, expose to high temperature or disassemble packs and cells.
- Use only lithium-ion batteries with a designated protection circuit and approved charger.
- Discontinue using a battery and/or charger if the pack temperature rises more than 10°C (18°F) on a regular charge.
- The electrolyte is highly flammable and battery rupture can cause physical injury.

Battery Components

Speculators and mining companies often raise fear of pending shortages of raw materials to produce batteries. This may boost the shares momentarily, but concerns often evaporate with time. Materials that occasionally suffer shortages are lead, cobalt, lithium and graphite.

Lead can easily be recycled from spent lead acid batteries and lead prices have stabilized at time of writing. Nickel-cadmium batteries are also recycled, but the switch to Li-ion has lowered the demand for cadmium. Cobalt remains expensive and manufacturers of Li-ion try to minimize its use by substituting with nickel, manganese and aluminum.

There has been talk about a shortage of lithium, but the anticipated switch from gasoline to Li-ion as propulsion for personalized transportation has not yet occurred. Instead, quality graphite and rare earth material are said to be in

limited supply, but this is not creating a bottleneck or undue price escalation. Most raw materials needed to build batteries are in sufficient supply.

Battery Separator

The building blocks of a battery are the cathode and anode, and these two electrodes are isolated by a separator. The separator is moistened with electrolyte and forms a catalyst that promotes the movement of ions from cathode to anode on charge and in reverse on discharge. Ions are atoms that have lost or gained electrons and have become electrically charged. Although ions pass freely between the electrodes, the separator is an isolator with no electrical conductivity.

The small amount of current that may pass through the separator is self-discharge and this is present in all batteries to varying degrees. Self-discharge eventually depletes the charge of a battery during prolonged storage. Figure 3-18 illustrates the building block of a lithium-ion cell with the separator and ion flow between the electrodes.

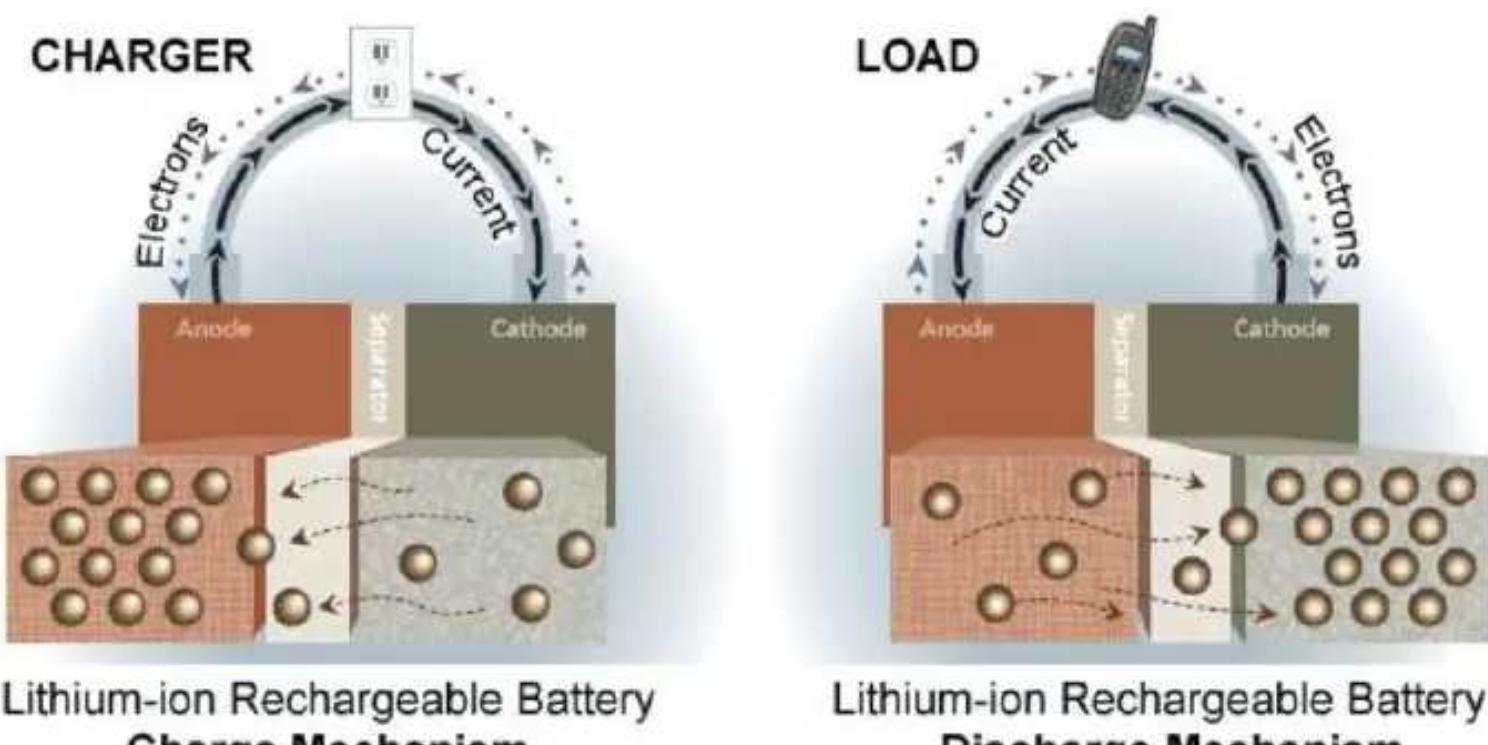


Figure 3-18. Ion flow through the separator of Li-ion.

Battery separators provide a barrier between the anode (negative) and the cathode (positive) while enabling the exchange of lithium ions from one side to the other.

Source: CELGARD, LLC

Early batteries were flooded, and this includes lead acid and nickel-

cadmium. With the development of the sealed nickel-cadmium in 1947 and the maintenance-free lead acid in the 1970s, the electrolyte is absorbed into a porous separator that is compressed against the electrodes to achieve chemical reaction.

The tightly wound or stacked separator/electrode arrangement forms a solid mechanical unit that offers similar performance to the flooded type but is smaller and can be installed in any orientation without leakage. The gases created during charge are absorbed and there is no water loss if venting can be prevented.

Early separators were made of rubber, glass fiber mat, cellulose and polyethylene plastic. Wood was the original choice but it deteriorated in the electrolyte. Nickel-based batteries use separators of porous polyolefin films, nylon or cellophane. The absorbed glass mat (AGM) in the sealed lead acid version uses a glass fiber mat as a separator that is soaked in sulfuric acid.

The earlier gelled lead acid developed in the 1970s converts the liquid electrolyte into a semi-stiff paste by mixing the sulfuric acid with a silica-gelling agent. Gel and AGM batteries have slight differences in performance; gel batteries are commonly used in UPS and AGM in starter and deep-cycle applications. (See “Lead-based Batteries” on page 46.)

Commercially available Li-ion cells use polyolefin as a separator. This material has excellent mechanical properties, good chemical stability and low-cost. A polyolefin is a class of polymer that is produced from olefin by polymerizing olefin ethylene. Ethylene comes from a petrochemical source; polyolefin is made from polyethylene, polypropylene or laminates of both materials.

The Li-ion separator must be permeable and the pore size ranges from 30 to 100nm. (Nm stands for nano-meter, which is one millionth of a millimeter or about 10 atoms thick.) The recommended porosity is 30–50 percent. This holds enough liquid electrolyte and enables the pores to close should the cell overheat.

Separator Serves as Fuse in Li-ion

On excessive heat, a shut-down occurs by closing the pores of the Li-ion separator through a melting process. The polyethylene (PE) separator melts

when the core reaches 130°C (266°F). This stops the transport of ions, effectively shutting the cell down. Without this provision, heat in the failing cell could rise to the thermal runaway threshold and vent with flame. This internal safety fuse also helps pass the stringent UN Transportation Testing for Lithium Batteries that includes altitude simulation, as well as thermal, vibration, shock, external short circuit, impact, overcharge and forced discharge tests.

Most batteries for mobile phones and tablets have a single polyethylene separator. Since ca. 2000, larger industrial batteries deploy a *trilayered separator* that provides enhanced fuse protection on thermal extremes and on multi-cell configurations. Figure 3-19 illustrates the PP/PE/PP trilayer separator consisting of polyethylene in the middle that is sandwiched by outer polypropylene (PP) layers. While the inner PE layer shuts down at 130°C by closing the pores, the outer PP layers stay solid and do not melt until reaching 155°C (311°F)

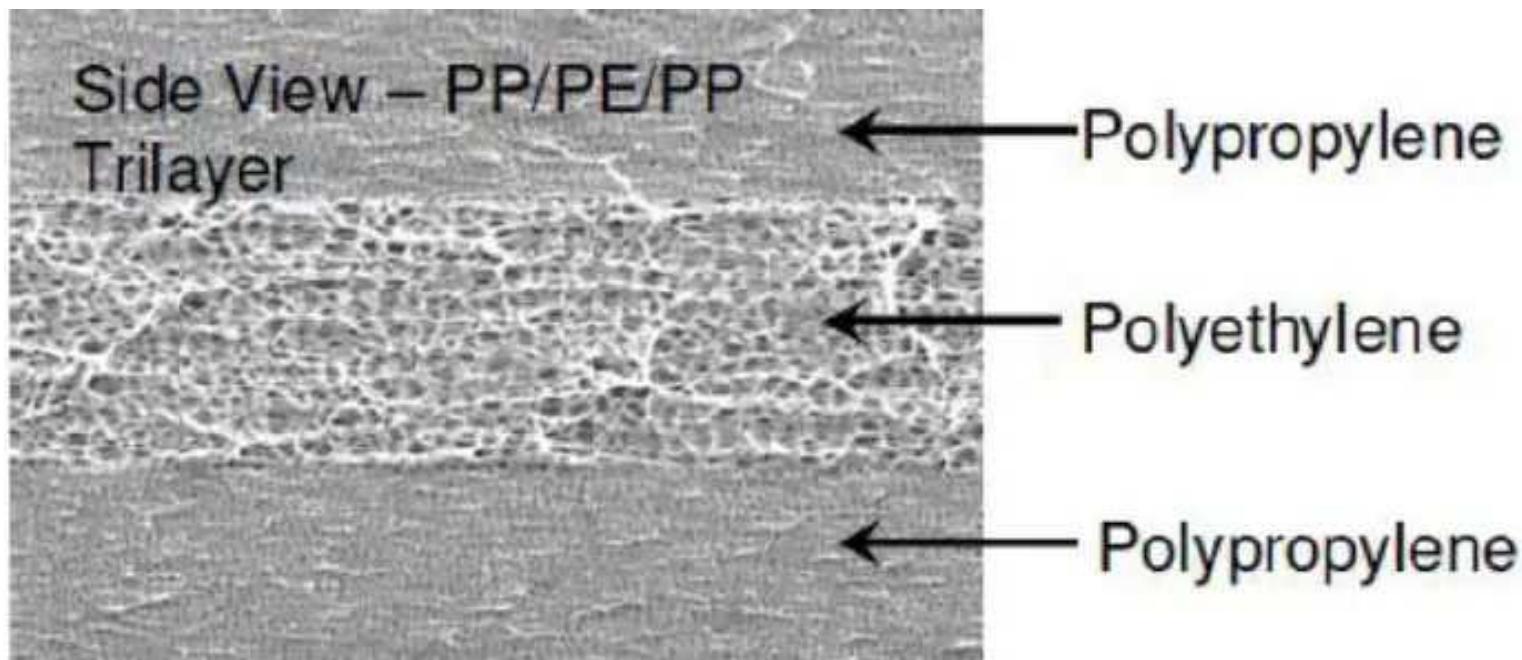


Figure 3-19: Side view of PP/PE/PP trilayer.

Combining separator material with different melting properties adds to safety. PE melts before PP to close the pores and stop current flow.

Source: Dalhousie, Handbook of Batteries

In ca. 2008, further improvements were made by adding a ceramic-coated

separator. Ceramic particles do not melt and this addition provides a further safety level. Ceramic coating is also used on lithium cobalt oxide (LCO) cells

that charge up to 4.40V/cell instead of the traditional 4.20V/cell. The ceramic coating works in tandem with the PE and PP layers and is placed next to the positive side to prevent electrical contact.

The separator should be as thin as possible so as to not add dead volume and still provide sufficient tensile strength to prevent stretching during the winding process and offer good stability throughout life. The pores must be uniformly spread on the sheet to ensure even distribution throughout the entire separator area. Furthermore, the separator must be compatible with the electrolyte and allow easy wetting. Dry areas can create hot spots through elevated resistance, leading to cell failure.

Separators are getting thinner. A thickness of 25.4 μm (1.0 mil) is common but some go down to 20 μm , 16 μm and now even 12 μm without significantly compromising the properties of the cell. (One micron, also known as μm , is one millionth of a meter.) The separator with electrolyte in modern Li-ion only makes up 3 percent of the cell content.

Ultrathin separators raise safety concerns. The massive Sony call-back comes to mind in which a one-in-200,000 cell-breakdown triggered an almost six million recall of Li-ion packs. On rare occasions, microscopic metal particles came into contact with other parts of the battery cell, which led to an electrical short circuit. The Sony cells in question had a separator thickness between 20 μm and 25 μm . (A micrometer (μm) is one-thousandths of a millimeter.)

Electrolyte

Electrolyte serves as catalyst to make a battery conductive by promoting the movement of ions from the cathode to the anode on charge and in reverse on discharge. Ions are electrically charged atoms that have lost or gained electrons. The electrolyte of a battery consists of soluble salts, acids or other bases in liquid, gelled and dry formats. Electrolyte also comes in a polymer, as used in

the solid-state battery, solid ceramic and molten salts, as in the sodium-sulfur battery.

Lead Acid

Lead acid uses *sulfuric acid*. When charging, the acid becomes denser as lead oxide (PbO_2) forms on the positive plate, and then turns to almost water when fully discharged. The specific gravity of the sulfuric acid is measured with a hydrometer. Lead acid batteries come in flooded and sealed formats also known as valve regulated lead acid (VRLA) or maintenance-free.

Sulfuric acid is colorless with a slight yellow tint, soluble in water and highly corrosive. Lead acid batteries come with different specific gravities (SG). Deep-cycle batteries use a dense electrolyte with an SG of up to 1.330 to achieve high specific energy, starter batteries contain an average SG of about 1.265 and stationary batteries come with a low SG of roughly 1.225 to moderate corrosion and promote longevity.

Sulfuric acid serves a wide range of applications and is also found in drain cleaners and various cleaning agents. It further serves in mineral processing, fertilizer manufacturing, oil refining, wastewater processing and chemical synthesis.

CAUTION Sulfuric acid can cause serious damage on skin contact and can lead to permanent blindness if splashed in eyes. Swallowing sulfuric acid causes irreversible damage.

Nickel-cadmium (NiCd)

The electrolyte in NiCd is an alkaline electrolyte (potassium hydroxide). Most NiCd batteries are cylindrical in which several layers of positive and negative materials are wound into a jelly-roll. The flooded version of NiCd is used as the ship-battery in commercial aircrafts and in UPS systems operating in hot and cold climates requiring frequent cycling. NiCd is more expensive than lead acid but lasts longer.

Nickel-metal-hydride (NiMH)

NiMH uses the same or similar electrolyte as NiCd, which is usually potassium

hydroxide. The NiMH electrodes are unique and consist of nickel, cobalt, manganese, aluminum and rare earth metals, which are also used in Li-ion.

NiMH is available in sealed versions only.

Potassium hydroxide is an inorganic compound with the formula KOH, commonly called caustic potash. The electrolyte is colorless and has many industrial applications, such as the ingredient in most soft and liquid soaps. KOH is harmful if indigested.

Lithium-ion (Li-ion)

Li-ion uses liquid, gel or dry polymer electrolyte. The liquid version is a solution of lithium salts with organic solvents similar to ethylene carbonate. Mixing the solutions with diverse carbonates provides higher conductivity and expands the temperature range. Other salts may be added to reduce gassing and improve high temperature cycling.

Li-ion with gelled electrolytes receives many additives to increase conductivity, so does the lithium-polymer battery. The true dry polymer only becomes conductive at elevated temperatures, and this battery is no longer in commercial use. Additives are also administered to achieve longevity and unique characteristics. The recipe is classified and each manufacturer has its own secret sauce. (See also “What Causes Li-ion to Age?” on page 249.)

The electrolyte should be stable, but this is not the case with Li-ion. A passivation film forms on the anode that is called solid electrolyte interface (SEI). This layer separates the anode from the cathode but allows ions to pass through much like a separator. In essence, the SEI layer must form to enable the battery to work. The film stabilizes the system and gives the Li-ion a long life but this causes a capacity reduction. *Electrolyte oxidation* also occurs on the cathode that permanently lowers the capacity. (See “How to Prime Batteries” on page 191.)

To prevent the films from becoming too restrictive, additives are mixed with the electrolyte that is consumed during the formation of the SEI layer. It would be difficult, if not impossible, to trace their presence when doing a

forensic evaluation. This keeps proprietary additives a trade secret, both their composition and the amount used.

A well-known additive is *vinylene carbonate* (VC). This chemical improves the cycle life of Li-ion, especially at higher temperatures, and keeps the internal resistance low with use and age. VC also maintains a stable SEI film on the anode with no adverse side effects of the electrolyte oxidation on the cathode (Aurbach et al). It is said that academic and research communities are lagging behind cell manufacturers in knowledge and choice of additives, hence the great secret. (See also “Additives and the Effects on Coulombic Efficiency” on page 256.)

Availability of Lithium

The demand for Li-ion batteries is increasing, and finding sufficient supply of lithium in raw material is gearing up mining industries for higher production. A compact EV battery (Nissan Leaf) uses about 4kg (9 lb) of lithium, and if every man, woman and teenager were to drive an electric car in the future, a lithium shortage could develop. Rumor of this happening has been spreading, perhaps prematurely.

About 70 percent of the world’s lithium comes from brine (salt lakes); the remainder is derived from hard rock. Research institutions are developing technology to draw lithium from seawater. China is the largest consumer of lithium, and hoarding is suspected. They believe that future cars will run on Li-ion and an unbridled supply of lithium is important to them.

In 2009, the total demand for lithium reached almost 92,000 metric tons, of which batteries consume 26 percent. Figure 3-20 illustrates typical uses of lithium, which include lubricants, glass, ceramics, pharmaceuticals and refrigeration.

Most of the known supply of lithium is in Bolivia, Argentina, Chile, Australia and China. The supply is ample and concerns of global shortages are speculative. To attain at one ton of lithium, Latin America uses 750 tons of brine,

the base material for lithium, and adds 24 months of preparation. Lithium can also be recycled an unlimited number of times, and it is said that 20 tons of spent Li-ion batteries yield one ton of lithium. This will help the supply, but recycling

can be more expensive than harvesting a new supply through mining.

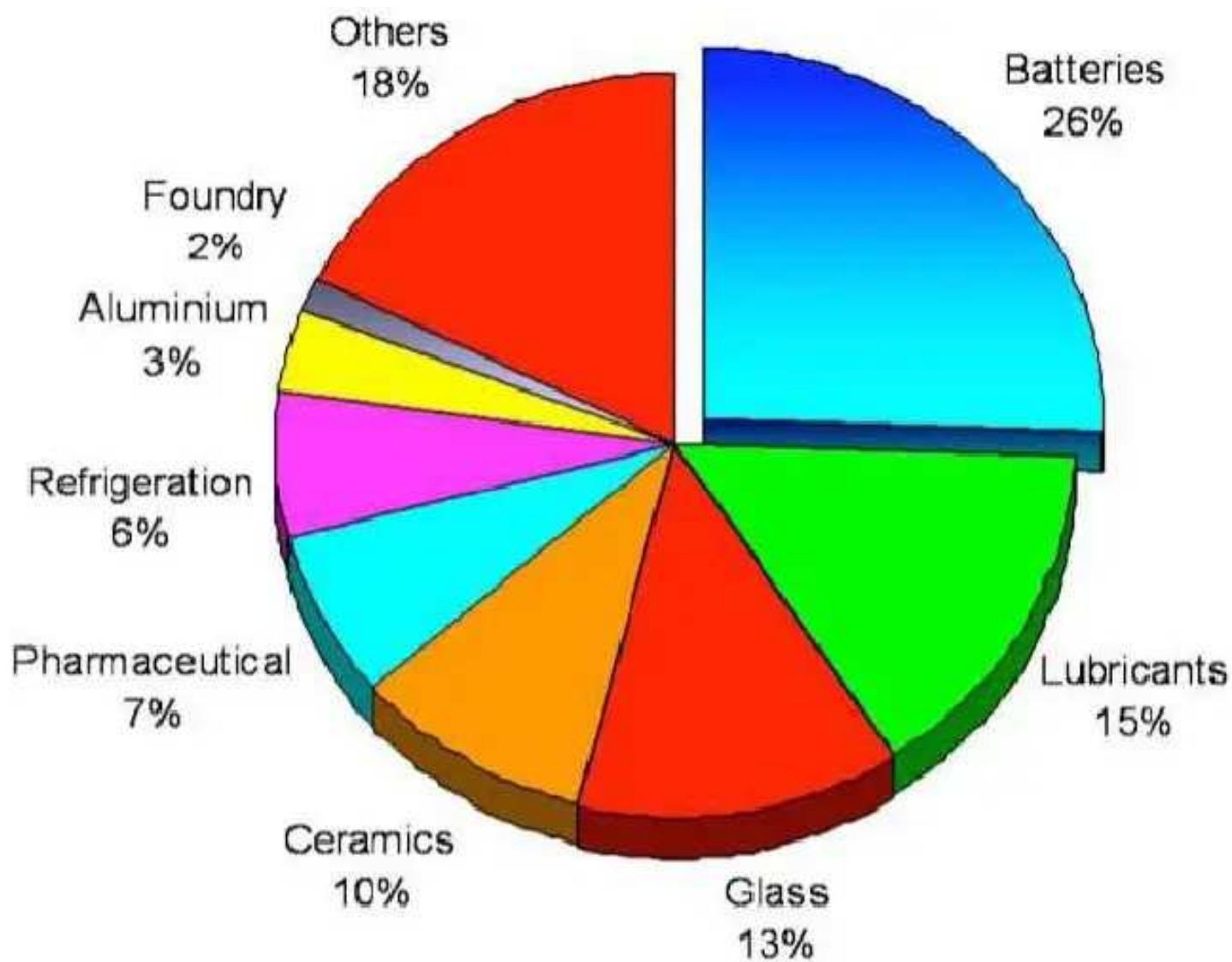


Figure 3-20: Lithium consumption (2008).

Batteries consume the largest share of lithium. With the advent of the electric vehicle, the demand could skyrocket but for now the world has enough proven lithium reserves.

Source: Talison Minerals

Lithium is named after the Greek word “lithos” meaning “stone.” The soft, silver-white metal belongs to the alkali metal group of chemical elements and is marked with the symbol Li. It is the lightest of all metals.

The lithium raw material in a Li-ion battery is only a fraction of one cent per watt, or less than 1 percent of the battery cost. A \$10,000 battery for a plug-in hybrid contains less than \$100 worth of lithium. Shortages when producing

millions of large batteries for vehicles and stationary applications could increase the price, but for now this is not the case.

Rather than worrying about a lack of lithium, there could be shortages of rare earth materials, should the EV replace the conventional car. One such material is the permanent magnet for electric motors. Permanent magnets make one of the most energy-efficient motors. China controls about 95 percent of the global market for rare earth metals and expects to use most of these resources for its own production. Export of rare earth materials is tightly controlled.

Graphite

In 2015, the media predicted heavy demand for graphite to satisfy the growth of Li-ion batteries used in electric vehicles. Speculation arose that graphite could be in short supply because a large EV battery requires about 25kg (55 lb) of graphite for the Li-ion anode. Although price and consumption has been lackluster, there are indications that the demand is tightening.

Producing anode-grade graphite with 99.99 percent purity is expensive and the process creates waste. The end-cost is not so much the material but the purification process. Recycling old Li-ion to retrieve graphite would not solve this because of the tedious purification process.

Carbon and graphite are related substances. Graphite is an allotrope of carbon, a structural modification that occurs by bonding the elements together in a different manner. Graphite is the most stable form of carbon. The diamond, a metastable allotrope of carbon known for its excellent physical qualities, is less stable than graphite; yet graphite is soft and malleable.

Graphite comes from the Greek word “graphein.” It is heat-resistant, electrically and thermally conductive, chemically passive (corrosion-resistant) and lighter than aluminum. Beside Li-ion anodes, high-grade graphite is also used in fuel cells, semiconductors, LEDs, solar cells and nuclear reactors.

A carbon fiber is a long, thin strand of about 5–10 μm in diameter, one-tenth the thickness of a human hair. The carbon atoms are bonded together in

microscopic crystals and are extremely strong. They are woven in a textile fashion and mixed with a polymer matrix, which is a hardened form of carbon

fiber that is as strong as steel but lighter. These materials are used in golf clubs and bicycle frames, as well as body parts for cars and airplanes to replace aluminum. The Boeing 787 and Airbus 350X make extensive use of carbon fiber. Graphite for batteries currently accounts to only 5 percent of the global demand.

Graphite comes in two forms: natural graphite from mines and synthetic graphite from petroleum coke. Both types are used for Li-ion anode material with 55 percent gravitating towards synthetic and the balance to natural graphite.

Manufacturers preferred synthetic graphite because of its superior consistency and purity to natural graphite. This is changing and with modern chemical purification processes and thermal treatment, natural graphite achieves a purity of 99.9 percent compared to 99.0 percent for the synthetic equivalent.

Purified natural flake graphite has a higher crystalline structure and offers better electrical and thermal conductivity than synthetic material. Switching to natural graphite will lower production cost with same or better Li-ion performance. Synthetic graphite for Li-ion sells for around US \$10,000 per ton whereas spherical graphite made from natural flake sells for US \$7,000 (2015 prices). Unprocessed natural graphite is much cheaper, and besides cost, natural graphite is more environmentally friendly than synthetic graphite; it also forms the base for *graphene*, a scientist's dream.

Graphene

Graphene is an allotrope of carbon in the form of a two-dimensional hexagonal lattice. Presented in a sheet of pure carbon, graphene is only one atom thick. It is flexible, transparent, impermeable to moisture, stronger than diamonds and more conductive than gold. Experts hint to graphene as a miracle material that will improve many products, including the battery.

Graphene anodes are said to hold energy better than graphite anodes and promise a charge time that is ten times faster than what is currently possible with

Li-ion. Load capabilities should also improve; better longevity is another item on the wish-list that needs to be proven.

With traditional graphite anodes, lithium ions accumulate around the outer surface of the anode. Graphene has a more elegant solution by enabling lithium ions to pass through the tiny holes of the graphene sheets measuring 10–20nm.

This promises optimal storage area and easy extraction. Once available, such a battery is estimated to store ten times more energy than Li-ion featuring regular graphite anodes.

Further improvements with graphene are achieved by adding vanadium oxide to the cathode. Experimental batteries with such an enhancement are said to recharge in 20 seconds and retain 90 percent capacity after 1,000 cycles. Graphene is also being tested in supercapacitors to improve the specific energy density, as well as in solar cells. Figure 3-21 illustrates the unique lattice of graphene made visible with scanning probe microscopy (SPM).

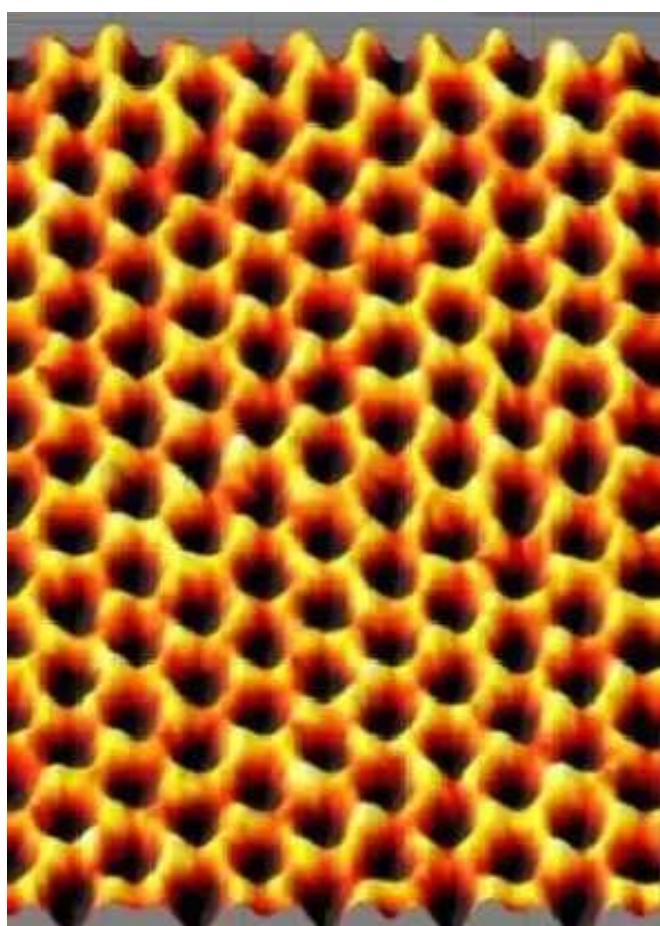


Figure 3-21: Scanning probe microscopy (SPM) shows an image of graphene.

Graphene is a sheet of pure carbon that is one atom thick. It is flexible, transparent, impermeable to moisture, stronger than diamonds and more conductive than gold. Each carbon atom possesses three

moisture, stronger than diamonds and more conductive than gold. Each carbon atom possesses three electrons that bind with the nearest neighbor atom electron, creating a chemical bond.

Source: U.S. Army Materiel Command

Scientists have theorized about the wonders of graphene for decades, but no commercial products exist yet that makes exclusive use of this apparent miracle material. It is likely that the marvel of graphene has been utilized unknowingly for centuries in pencils and other products. A better understanding of its mechanism will eventually lead to improved products.

Meanwhile we take the many wonderful breakthroughs published by academia and stock promoters with a grain of salt. We will embrace the super battery when it arrives but pledge to honor what we currently have by taking better care of it in the workforce.

Cobalt

Cobalt was discovered by Swedish chemist Georg Brandt in 1739. It is a hard, lustrous, silver-gray metal that is extracted as a by-product when mining nickel and copper. Besides serving as a cathode material of many Li-ion batteries, cobalt is also used to make powerful magnets, high-speed cutting tools, and high-strength alloys for jet engines and gas turbines. Cobalt compounds have been employed for centuries to color porcelain, glass, pottery, tile and enamel; it is also important in human nutrition as part of vitamin B12. Figure 3-22 illustrates the breakdown of cobalt uses.

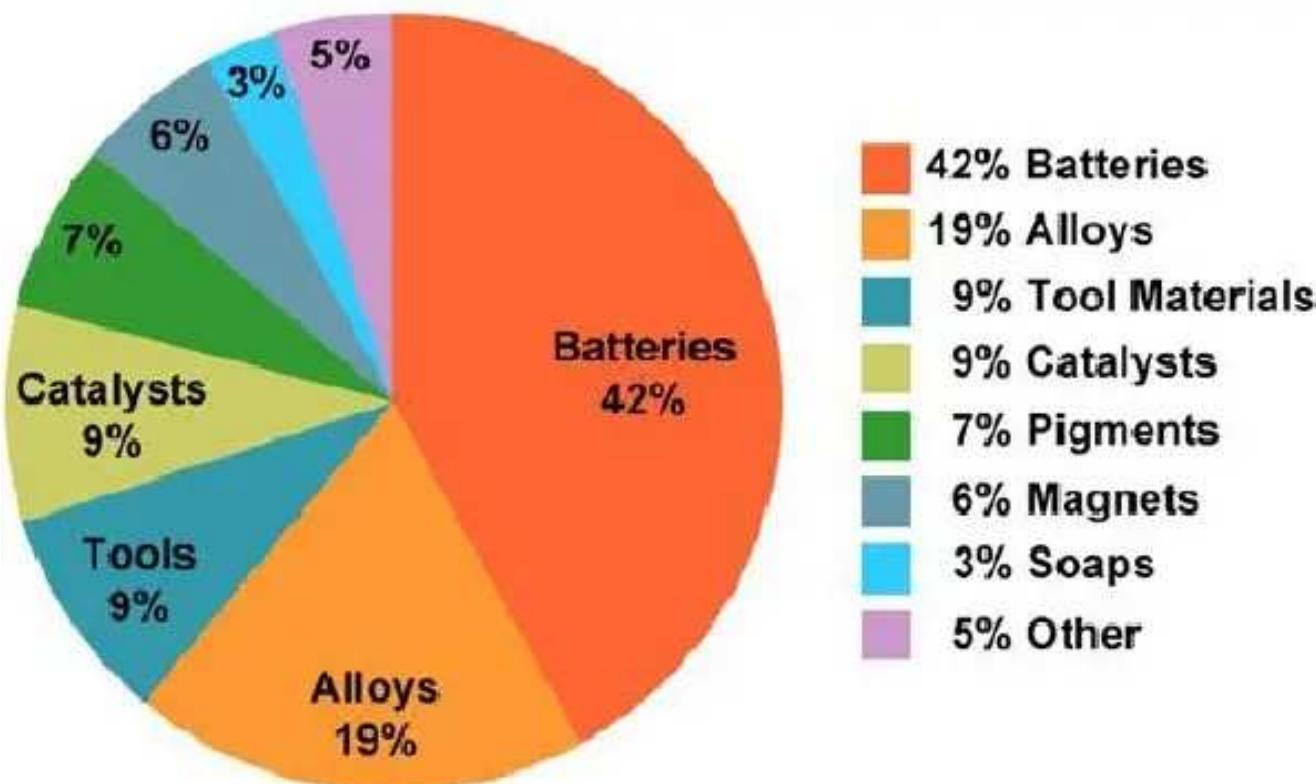


Figure 3-22: Use of cobalt in industry.

Cobalt is mostly retrieved as a byproduct from copper and nickel production. High cost entices battery manufacturers to seek alternatives, but cobalt cannot be entirely eliminated.

Source: CDI, Roskill, MMTA, Industry Sources

Being mostly a byproduct in the production of copper and nickel, the pricing follows the demand of these primary metals. This can lead to an over-supply of cobalt, as was the case in 2015. Cobalt prices were higher in 2010 and they are expected to pick up as the demand for large Li-ion batteries increases.

Even at reduced prices, a ton of high grade cobalt runs at about US \$28,000. This compares to US \$6,000 for a ton of lithium carbonate. Lithium carbonate is a crystalline salt that is also used in glass and ceramic industries, as well as in medicine.

According to the British Geological Survey (2014), the Democratic Republic of Congo has a 50 percent share of worldwide cobalt production; China, Canada, Australia and Russia are also major contributors. The reuse of cobalt by recycling Li-ion batteries is only partially successful because of the refinements needed to bring the material back to battery-grade. (See “How to

refinements needed to bring the material back to battery grade. (See “How to Recycle Batteries” on page 209.) There should be no shortage of cobalt as the world has ample reserves.

Cobalt was the first cathode material for commercial Li-ion batteries, but a high price entices manufacturers to substitute the material. Cobalt blended with nickel, manganese and aluminum creates powerful cathode materials that are more economical and offer enhanced performance to pure cobalt. (See “Types of Lithium-ion Batteries” on page 61.)

Battery Raw Materials

Batteries use diverse elements, which are harvested from the earth’s crust. It is thought provoking that most of these materials are also shared by plants and living beings. We are made from stardust and anything that grows and moves comes from these resources. As with all living organisms, the substances for batteries are chosen carefully and in the right amount to achieve a harmonious interaction. Too much of one part could spoil a fine balance.

Aluminum Aluminum is a silvery-white, soft, nonmagnetic metal with symbol Al. Derived from bauxite, it is the third most abundant element in the earth’s crust after oxygen and silicon. When exposed to air, aluminum forms a passivation layer that protects the metal from corrosion. Aluminum is used as cathode material in some lithium-ion batteries.

Antimony Antimony is a brittle lustrous white metallic element with symbol Sb. It was discovered in 3000 BC and mistaken for lead. The main producer is China and the metal is used in lead acid batteries to reinforce the lead plates, reduce maintenance and enhance performance. Other applications are flame-proofing materials, producing low friction applications, improving material characteristics by mixing Sb with other alloys and building semiconductors.

Cadmium Cadmium is a soft bluish-white metal with symbol Cd. Discovered in 1817 in Germany, cadmium is a by-product of zinc

Discovered in 1817 in Germany, cadmium is a by-product of zinc production and was used as a pigment and plating on steel to resist corrosion. Cadmium is used as the anode material for the

nickel-cadmium battery but the Restrictions of Hazardous Substances Directives banned the batteries for commercial use.

Calcium Calcium is a soft gray alkaline metal with symbol Ca that was discovered by Humphry Davy (1778–1829). It is the fifth most abundant element by mass in the earth's crust and plays an essential role for living organisms to build bone, teeth and shells. Calcium improves the mechanical strength of lead plates in lead acid batteries and enhances performance.

Chloride Chloride is a negatively charged ion that forms when chlorine gains an electron or when hydrogen chloride is dissolved in water or in other solvents. Chloride salts, such as sodium chloride, are used as table salt and to preserve food. Chloride is also present in body fluids as well as in the electrolyte of batteries.

Iron Iron is the most common element on earth by mass. The symbol Fe comes from Latin “ferrum.” Iron metal has been used since ancient times, although copper alloys with lower melting temperatures came before iron. Pure iron is relatively soft and it can be hardened with carbon. Iron compounds play an important role in biology and are also used in the lithium iron phosphate oxide battery.

Lead Lead is a soft, malleable heavy metal in the carbon group with symbol Pb. It is used in lead acid batteries, bullets and weights and as a radiation shield. Lead has the highest atomic number of all stable elements and is toxic if ingested; it damages the nervous system and causes brain disorders. Lead poisoning has been documented from ancient Rome, Greece and China. (See “Health Concerns with Batteries” on page 198.)

Manganese Manganese with symbol Mn is produced by mining iron and other minerals. It is named after the region of “Magnesia” in Greece where the black mineral was found. Manganese is used to prevent steel corrosion and serves as cathode material in Li-ion, zinc-carbon and alkaline batteries.

Nickel Nickel with symbol Ni is a silvery-white lustrous metal with a slight golden tinge. It can be traced back to 3500 BC. Nickel is mostly confined to larger nickel–iron meteorites; on earth it is found in combination with iron. Mythology links the name nickel to Old Nick, a mischievous gnome who argued that copper-nickel ores resisted refinement into copper. Nickel is well suited for battery electrodes.

Silver Silver (Ag) is a soft, white, lustrous metal that has the highest electrical and thermal conductivity of any metals. It occurs naturally but most of it is produced as a by-product of copper, gold, lead and zinc refining. Silver was used for monetary coins together with the more valuable gold. In industry, silver is used in solar panels and water filtration, as well as jewelry and high-value silverware. Other uses are electrical contacts and conductors, mirrors, window coatings, photographic film and X-rays. In medicine, silver compounds serve as disinfectants that are added to bandages and wound-dressings. Silver is also found in the silver-zinc battery.

Sodium Sodium, with symbol Na, is a soft, silver-white, highly reactive metal that belongs to the six elements in the periodic table with a single electron in its outer shell. By donating the electron, the atom becomes positively charged. Sodium is the sixth most abundant element in the earth’s crust but is derived from minerals. It was first isolated by Humphry Davy in 1807 by electrolysis of sodium hydroxide. Sodium compounds are used for soap-making and de-icing agents, and, not to forget, edible

salt on our dining room tables. It is an essential element for living beings and plants; it is also used in sodium-sulfur and lithium-

sulfur batteries.

Spinel Spinel is a hard glassy mineral consisting of an oxide of magnesium and aluminum that forms a three-dimensional chemical structure. Spinels were known as rubies, and now belong to the most famous gemstones in shades of red, blue, green, yellow, brown and black. Manganese-based Li-ion batteries consist of a spinel structure in which the cathode forms a three-dimensional framework that appears after initial formation. Spinel batteries are known for their low resistance.

Sulfur Sulfur (or sulphur) is a bright yellow non-metal chemical element with symbol S. It occurs naturally and is sought after by mineral collectors for its distinct colors and shapes. Sulfur was known in ancient India, Greece, China and Egypt; the Bible refers to it as brimstone, meaning burning stone. Sulfur has the odor of rotting eggs; fumes from burning sulfur were used in fumigation and as a healing agent. Sulfur made the best gunpowder and is also used in matches, insecticides and fungicides. The largest industrial use is fertilizer because it is an essential element for all life. Extracted from salt domes in the past, almost all sulfur is now a by-product of gas and petroleum production. Sulfur compounds are also used in the sodium-sulfur battery.

Tin Tin (Sn) is a silvery, malleable metal that does not oxidize easily in the air. Appearing after bronze in ancient times, the first pure metallic tin was produced in 600 BC. Today, it is combined with many alloys, most notably tin/lead solder and corrosion-resistant tin plating of steel. Low toxicity makes tin-plated metal suitable for food packaging. Tin is also found in batteries.

Titanate Titanate usually refers to inorganic compounds composed of

Titanate

Titanate usually refers to inorganic compounds composed of titanium oxides. The materials are white and have a high melting point, making them suitable for furnaces. Titanate is also used for

anode material of some lithium-based batteries.

Vanadium

Vanadium is a hard, silvery gray metal with symbol V. Discovered in 1801 in Mexico, vanadium is found in about 65 minerals, and the metal forms a stable oxide layer once isolated. Vanadium also occurs naturally in fossil fuel deposits; it is produced in China and Russia from steel smelter slag and other by-products, including uranium mining. Vanadium is used for specialty steel alloys such as high-speed tools, including the flow battery.

Zinc

Zinc (Zn) is chemically similar to magnesium; combining zinc with copper turns into brass, an alloy that has been used since the 10th century BC in Judea and the 7th century BC in Greece. Zinc metal was not produced on a large scale until the 12th century in India and the late 1500s in Europe. By 1800, Luigi Galvani and Alessandro Volta uncovered the electrochemical properties of zinc for batteries. Other uses are corrosion-resistant zinc plating of iron and light metal castings. It is also an ingredient in anti-dandruff shampoos. Zinc is an essential mineral for our development and well-being. Zinc deficiency affects about two billion people in the developing world. The symptoms are growth retardation, delayed sexual maturation, vulnerability to infection and diarrhea. Excess zinc can lead to lethargy and copper deficiency.

Oxide Definitions

With the exception of gold, platinum and other noble metals, oxides form when oxygen bonds with the elements.

Oxide

A chemical compound with at least one oxygen atom and another

Oxide A chemical compound with at least one oxygen atom and another element.

Monoxide Any oxide that contains one oxygen atom.

Dioxide An oxide containing two oxygen atoms in its molecule or empirical formula.

Trioxide An oxide containing three atoms of oxygen in its molecule or empirical formula

Hydroxide An inorganic chemical compound with one hydrogen and one oxygen atom.

Solid oxide Elements that are being oxidized by oxygen in air or in water.

Peroxide Compound containing an oxygen–oxygen single bond.

Oxyhydroxide Mixed oxide and hydroxide.

* IATA (International Air Transport Association) works with airlines and the air transport industry to promote safe, reliable, secure and economical air travel.

Chapter 4 | Charge Methods

A good battery charger provides the base for batteries that are durable and perform well. In a price-sensitive market, chargers often receive low priority and get the “after-thought” status. Battery and charger must go together like a horse and carriage. Prudent planning gives the power source top priority by placing it at the beginning of the project rather than after the hardware is completed, as is a common practice. Engineers are often unaware of the complexity involving the power source, especially when charging under adverse conditions.

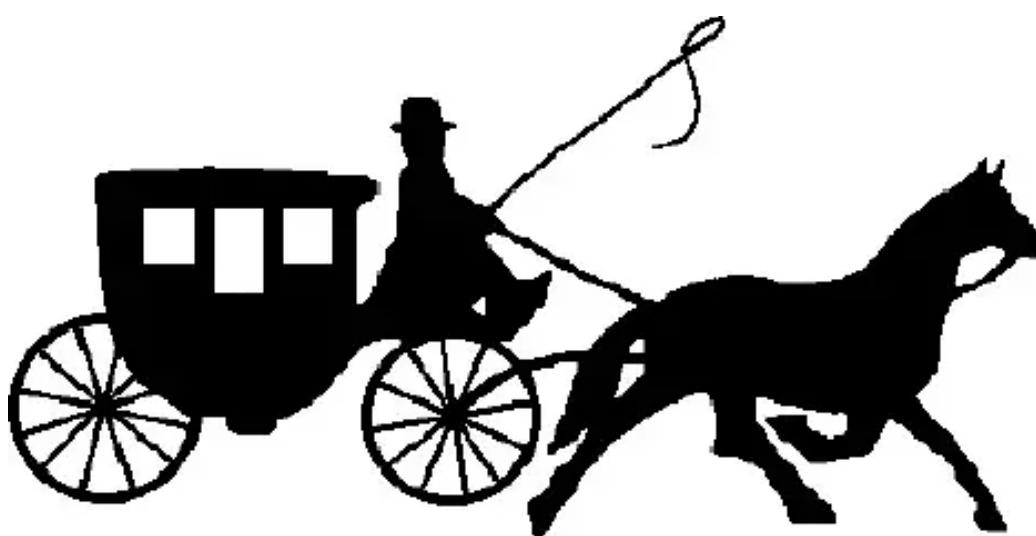


Figure 4-1: Battery and charger must go together like a horse and carriage.

One party does not deliver without the other

All about Chargers

Chargers are commonly identified by their charging speed. Consumer products come with a low-cost personal charger that performs well when used as directed.

The industrial charger is often made by a third party and includes special features, such as charging at adverse temperatures. Although batteries operate

below freezing, not all chemistries can be charged when cold and most Li-ions fall into this category. Lead- and nickel-based batteries accept charge when cold but at a lower rate. (More on page 148.)

Some Li-ion chargers (Cadex) include a wake-up feature, or “boost,” (page 253) to allow recharging if a Li-ion battery has fallen asleep due to over-discharge. A sleep condition can occur when storing the battery in a discharged state in which self-discharge brings the voltage to the cutoff point. A regular charger treats such a battery as unserviceable and the pack is often discarded. Boost applies a small charge current to raise the voltage to between 2.2V/cell and 2.9V/cell to activate the protection circuit, at which point a normal charge commences. Caution is required if a Li-ion has dwelled below 1.5V/cell for a week or longer. Dendrites may have developed that could compromise safety. (Figure 8-12 on page 226 examines the elevated self-discharge after a Li-ion cell had been exposed to deep discharge.)

Lead- and lithium-based chargers operate on *constant current constant voltage (CC/CV)*. The charge current is constant and the voltage is capped when it reaches a set limit. Reaching the voltage limit, the battery saturates; the current drops until the battery can no longer accept further charge and the fast charge terminates. Each battery has its own low-current threshold.

Nickel-based batteries charge with constant current and the voltage is allowed to rise freely. This can be compared to lifting a weight with a rubber band where the hand advances higher than the load. Full charge detection occurs when observing a slight voltage drop after a steady rise. To safeguard against anomalies, such as shorted or mismatched cells, the charger should include a plateau timer to assure a safe charge termination if no voltage delta is detected. Temperature sensing should also be added that measures temperature rise over time. Such a method is known as *delta temperature over delta time*, or dT/dt , and works well with rapid and fast charge.

A temperature rise is normal with nickel-based batteries, especially when reaching the 70 percent charge level. A decrease in charge efficiency causes this,

and the charge current should be lowered to limit stress. When “ready,” the charger switches to trickle charge and the battery must cool down. If the temperature stays above ambient, then the charger is not performing correctly

and the battery should be removed because the trickle charge could be too high.

NiCd and NiMH should not be left in the charger unattended for weeks and months. Until required, store the batteries in a cool place and apply a charge before use.

Lithium-based batteries should always stay cool on charge. Discontinue the use of a battery or charger if the temperature rises more than 10°C (18°F) above ambient under a normal charge. Li-ion cannot absorb over-charge and does not receive trickle charge when full. It is not necessary to remove Li-ion from the

charger, however, if not used for a week or more, it is best to place the pack in a cool place and recharge before use.

Types of Chargers

The most basic charger was the *overnight charger*, also known as a slow charger. This goes back to the old nickel-cadmium days where a simple charger applied a fixed charge of about 0.1C (one-tenth of the rated capacity) as long as the battery was connected. Slow chargers have no full-charge detection; the charge stays engaged and a full charge of an empty battery takes 14–16 hours. When fully charged, the slow charger keeps NiCd lukewarm to the touch. Because of its reduced ability to absorb over-charge, NiMH should not be charged on a slow charger. Low-cost consumer chargers charging AAA, AA and C cells often use this charge method, so do some children’s toys. Remove the batteries when warm.

The *rapid charger* falls between the slow and fast charger and is used in consumer products. The charge time of an empty pack is 3–6 hours. When full, the charger switches to “ready.” Most rapid chargers include temperature sensing

to safely charge a faulty battery.

The *fast charger* offers several advantages and the obvious one is shorter

charge times. This demands tighter communication between the charger and battery. At a charge rate of 1C, which a fast charger uses, a fully discharged or empty NiCd and NiMH charges in a little more than an hour. (See “What Is C-

rate?” on page 131.) As the battery approaches full charge, some nickel-based chargers reduce the current to adjust to the lower charge acceptance. The fully charged battery switches the charger to trickle charge, also known as maintenance charge. Most of today’s nickel-based chargers have a reduced trickle charge to also accommodate NiMH.

Li-ion has minimal losses during charge and the coulombic efficiency is better than 99 percent. At 1C, the battery charges to 70 percent state-of-charge (SoC) in less than an hour; the extra time is devoted to the saturation charge. Li-ion does not require the saturation charge as lead acid does; in fact it is better not to fully charge Li-ion — the batteries will last longer but the runtime will be a little less. Of all chargers, Li-ion is the simplest. No trickery applies that promises to improve battery performance as is often claimed by makers of chargers for lead- and nickel-based batteries. Only the rudimentary CC/CV method works.

Lead acid cannot be fast charged and the term “fast-charge” is a misnomer. Most lead acid chargers charge the battery in 14–16 hours; anything slower is a compromise. Lead acid can be charged to 70 percent in about 8 hours; the all-important saturation charge takes up the remaining time. A partial charge is fine provided the lead acid occasionally receives a fully saturated charge to prevent sulfation.

The standby current on a charger should be low to save energy. Energy Star assigns five stars to mobile phone chargers and other small chargers drawing 30mW or less on standby. Four stars go to chargers with 30–150mW draw, three stars to 150–250mW and two stars to 250–350mW. The average consumption is 300mW and these units get one star. Energy Star aims to reduce current

consumption of personal chargers that are mostly left plugged in when not in use. There are over one billion such chargers connected to the grid globally at any given time.

Simple Guidelines when Buying a Charger

- Use the correct charger for each battery chemistry. Most serve one chemistry only. Make sure that the battery voltage agrees with the charger. Do not charge if different.
- The Ah rating of a battery can be marginally different than specified. Charging a larger battery will take a bit longer than a smaller pack and vice versa. Do not charge if the Ah rating deviates too much (more than 25 percent).
- A high-wattage charger shortens the charge time but there are limitations as to how fast a battery can be charged. Ultra-fast charging causes stress. (See following chapter.)
- A lead acid charger should switch to float charge when fully saturated; a nickel-based charger must switch to trickle charge when full. Li-ion cannot absorb overcharge and receives no trickle charge. Trickle charge and float charges compensate for the losses incurred by self-discharge.
- Chargers should have a temperature override to end charge on a faulty battery.
- Observe charge temperature. Lead and lithium-based batteries must stay cool; nickel-based batteries get warm towards the end of charge but must cool down on “ready.” Li-ion should not rise more than 10°C (18°F) above ambient when reaching full charge.
- Check battery temperature when using a low-cost charger. Remove battery when warm.
- Charge at room temperature. Charge acceptance drops when cold. Li-ion cannot be charged below freezing.

Ultra-fast Charging

Nowhere is ultra-fast charging in bigger demand than with the electric vehicle. Recharging an EV in minutes replicates the convenience of filling 50 liters (13

gallons) of fuel into a tank that delivers 600kWh of energy. Such large energy storage in an electrochemical device is not practical as a battery with such a capacity would weigh 6 tons. Most Li-ion only produces about 150Wh per kg;

the energy from fossil fuel is roughly 100 times higher.

Charging an EV will always take longer than filling a tank, and the battery will always deliver less energy per weight than fossil fuel. Breaking the rule of law and forcing ultra-fast charging adds stress, even if the battery is designed for such a purpose. We must keep in mind that a battery is sluggish in nature. Like an aging man, its physical condition becomes less ideal with use and age. So is the ability to fast-charge.

Whether it's an EV, e-bike, a flying object, a portable device or a hobby gadget, the following conditions must be respected when charging a battery ultra-fast:

1. The battery must be designed to accept an ultra-fast charge and must be in good condition.
2. Ultra-fast charging only applies during the first charge phase. The charge current should be lowered after the battery reaches 70 percent state-of-charge (SoC).
3. All cells in the pack must be balanced and have ultra-low resistance. Aging cells often diverge in capacity and resistance, causing mismatch and undue stress on the weaker cells.
4. Ultra-fast charging can only be done under moderate temperatures as low temperature slows the chemical reaction. Unused energy turns into gassing, metal-plating and heat.

An ultra-fast charger can be compared to a high-speed train (Figure 4-2) traveling at 300km per hour (188 mph). Increasing power is relatively simple. It's the track that governs the permissible speed of a train and not the machinery. In the same manner, the condition of the battery dictates the charging speed.



Figure 4-2: Ultra-fast charging can be compared to a high-speed train.

Powerful machinery is easy to build, but it's the track that limits the speed.

A well-designed ultra-fast charger evaluates the condition of the “chemical battery” and makes adjustments according to the ability to receive charge. The charger should also include temperature compensations and other safety features to lower the charge current when certain conditions exist and halt the charge if the battery is under undue stress.

A “smart” battery running on SMBus or other protocols is responsible for the charge current. The system observes the battery condition and lowers or discontinues the charge if an anomaly occurs. Common irregularities are cell imbalance or the need for calibration. Some “smart” batteries stop functioning if the error is not corrected.

The maximum charge current a Li-ion can accept is mainly governed by cell design. The goal is to avoid lithium-plating on the anode and to keep the temperature under control. A thin anode with high porosity and small graphite particles enables ultra-fast charging because of the large surface area. Power Cells can be charged and discharged at high currents, but the energy density is low. Energy Cells, in comparison, have a thicker anode and lower porosity and

the charge rate should be 1C or less. Some hybrid Cells in NCA (nickel-cobalt-aluminum) can be charged above 1C with only moderate stress.

Apply the ultra-fast charge only when necessary. A well-designed ultra-fast charger should have charge-time selection to give the user the option to choose the least stressful charge for the time allotted. Figure 4-3 compares the cycle life of a typical lithium-ion battery when charged and discharged at 1C, 2C and 3C rates. The longevity can further be prolonged by charging and discharging below 1C; 0.8C is the recommended rate.

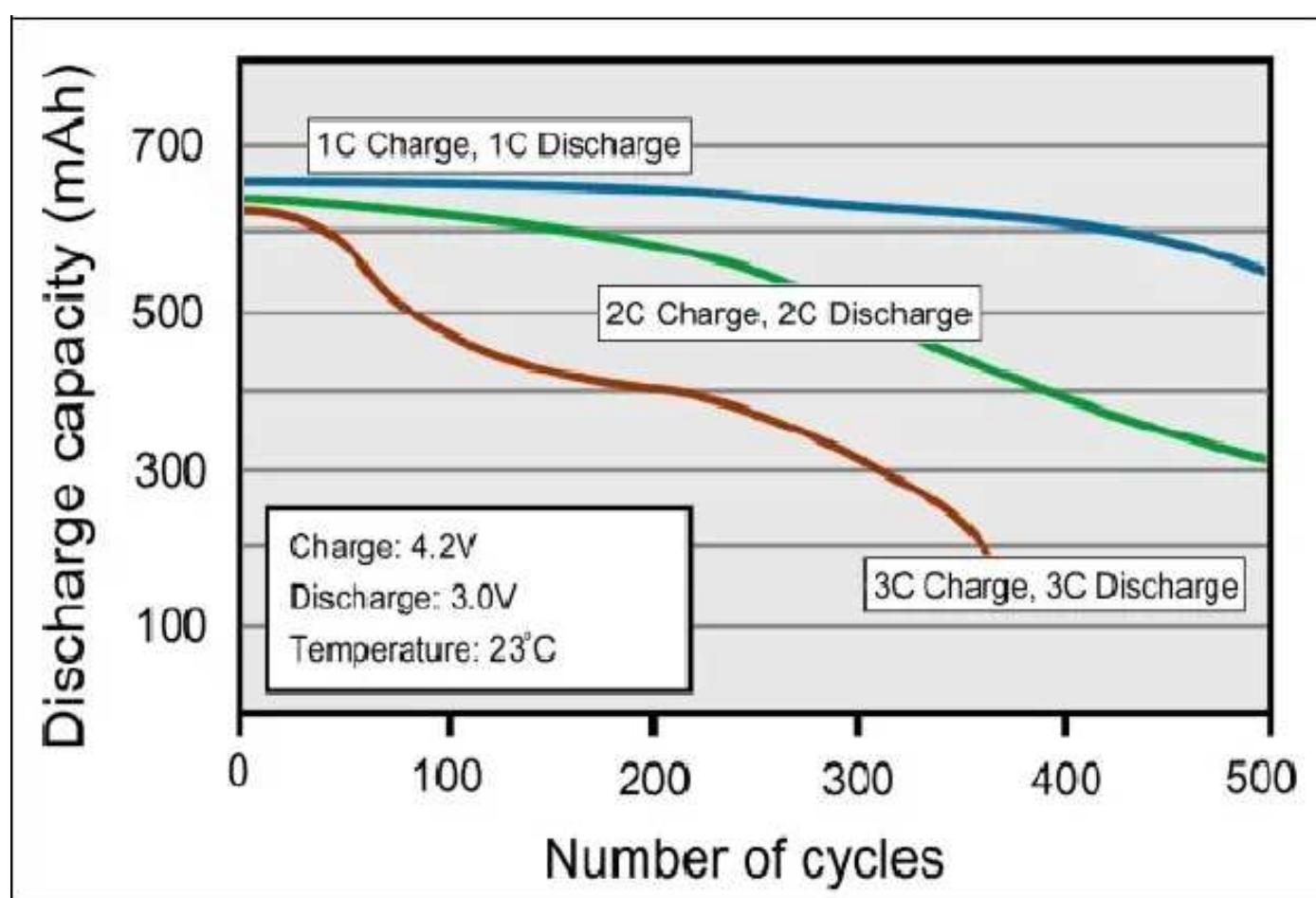


Figure 4-3: Cycle performance of Li-ion with 1C, 2C and 3C charge and discharge.

Charging and discharging Li-ion above 1C reduces service life. Use a slower charge and discharge if possible. This rule applies to most batteries.

Summary

All batteries perform best at room temperature and with a moderate charge and discharge. Such a sheltered life style does not always reflect real world situations where a compact pack must be charged quickly and deliver high currents. Such

typical applications are drones and remote control devices for the hobbyist. Expect a short cycle life when a small pack must give all it has.

If fast charging and high load requirements are prerequisites, use the rugged Power Cell; however, this will increase battery size and weight. An analogy is a heavy diesel engine to run a truck instead of a souped-up engine designed for a sports car. The big diesel will outlive the light engine even if both have identical horsepower. Going heavier will be more economical in the long run. Table 4-4 summarizes the charge characteristics of common rechargeable batteries.

Type	Chemistry	C-rate	Time	Temperatures	Charge termination
Slow charger	NiCd Lead acid	0.1C	14h	0°C to 45°C (32°F to 113°F)	Continuous low charge or fixed timer. Subject to overcharge. Remove battery when charged.
Rapid charger	NiCd, NiMH, Li-ion	0.3–0.5C	3-6h	10°C to 45°C (50°F to 113°F)	Senses battery by V, current, temperature and time-out timer.
Fast charger	NiCd, NiMH, Li-ion	1C	1h+	10°C to 45°C (50°F to 113°F)	Same as a rapid charger with faster service.
Ultra-fast charger	Li-ion, NiCd, NiMH	1–10C	10-60 minutes	10°C to 45°C (50°F to 113°F)	Applies ultra-fast charge to 70% SoC; specialty batteries only.

Table 4-4: Charger characteristics. Each chemistry uses a unique charge termination.

Simple Guidelines Regarding Chargers

- If possible, charge at a moderate rate. Ultra-fast charging always causes stress.
- Fast and ultra-fast charge fills the battery only partially; a slower saturation charge completes the charge. Unlike lead acid, Li-ion does not need the saturation charge but the capacity will be a bit lower.
- Do not apply fast charge when the battery is cold or hot. Only charge at moderate temperatures. Avoid fast charging an aged or low-performing battery.

What Is C-rate?

Charge and discharge rates of a battery are governed by *C*-rates. The capacity of

Charge and discharge rates of a battery are governed by C-rates. The capacity of a battery is commonly rated at 1C, meaning that a fully charged battery rated at 1Ah should provide 1A for one hour. The same battery discharging at 0.5C

should provide 500mA for two hours, and at 2C it delivers 2A for 30 minutes. Losses at fast discharges reduce the discharge time and these losses also affect charge times.

C-rate	Time
5C	12 min
2C	30 min
1C	1h
0.5C or C/2	2h
0.2C or C/5	5h
0.1C or C/10	10h
0.05C or C/20	20h

Table 4-5: C-rate and service times when charging and discharging batteries

A C-rate of 1C is also known as a one-hour discharge; 0.5C or C/2 is a two-hour discharge and 0.2C or C/5 is a 5-hour discharge. Some high-performance batteries can be charged and discharged above 1C with moderate stress. Table 4-5 illustrates typical times at various C-rates.

The battery capacity, or the amount of energy a battery can hold, can be measured with a battery analyzer. (See “Battery Test Equipment” on page 288.)

The analyzer discharges the battery at a calibrated current while measuring the time until the end-of-discharge voltage is reached. For lead acid, the end-of-discharge is typically 1.75V/cell, for NiCd/NiMH 1.0V/cell and for Li-ion 3.0V/cell. If a 1Ah battery provides 1A for one hour, an analyzer displaying the results in percentage of the nominal rating will show 100 percent. If the discharge lasts 30 minutes before reaching the end-of-discharge cutoff voltage, then the battery has a capacity of 50 percent. A new battery is sometimes overrated and can produce more than 100 percent capacity; others are underrated and never reach 100 percent, even after priming.

and never reach 100 percent, even after priming.

When discharging a battery with a battery analyzer capable of applying different C-rates, a higher C-rate will produce a lower capacity reading and vice

versa. By discharging the 1Ah battery at the faster 2C-rate, or 2A, the battery should ideally deliver the full capacity in 30 minutes. The sum should be the same since the identical amount of energy is dispensed in a shorter time. In

reality, internal losses turn some of the energy into heat and lower the resulting capacity to about 95 percent or less. Discharging the same battery at 0.5C, or 500mA over 2 hours, will likely increase the capacity to above 100 percent.

To obtain a reasonably good capacity reading, manufacturers commonly rate alkaline and lead acid batteries at a very low 0.05C, or a 20-hour discharge. Even at this slow discharge rate, lead acid seldom attains a 100 percent capacity as the batteries are over-rated. Manufacturers provide capacity offsets to adjust for the discrepancies if discharged at a higher C-rate than specified. (See “How to Calculate Battery Runtime” (Peukert Law) on page 171.) Figure 4-6 illustrates the discharge times of a lead acid battery at various loads expressed in C-rate.

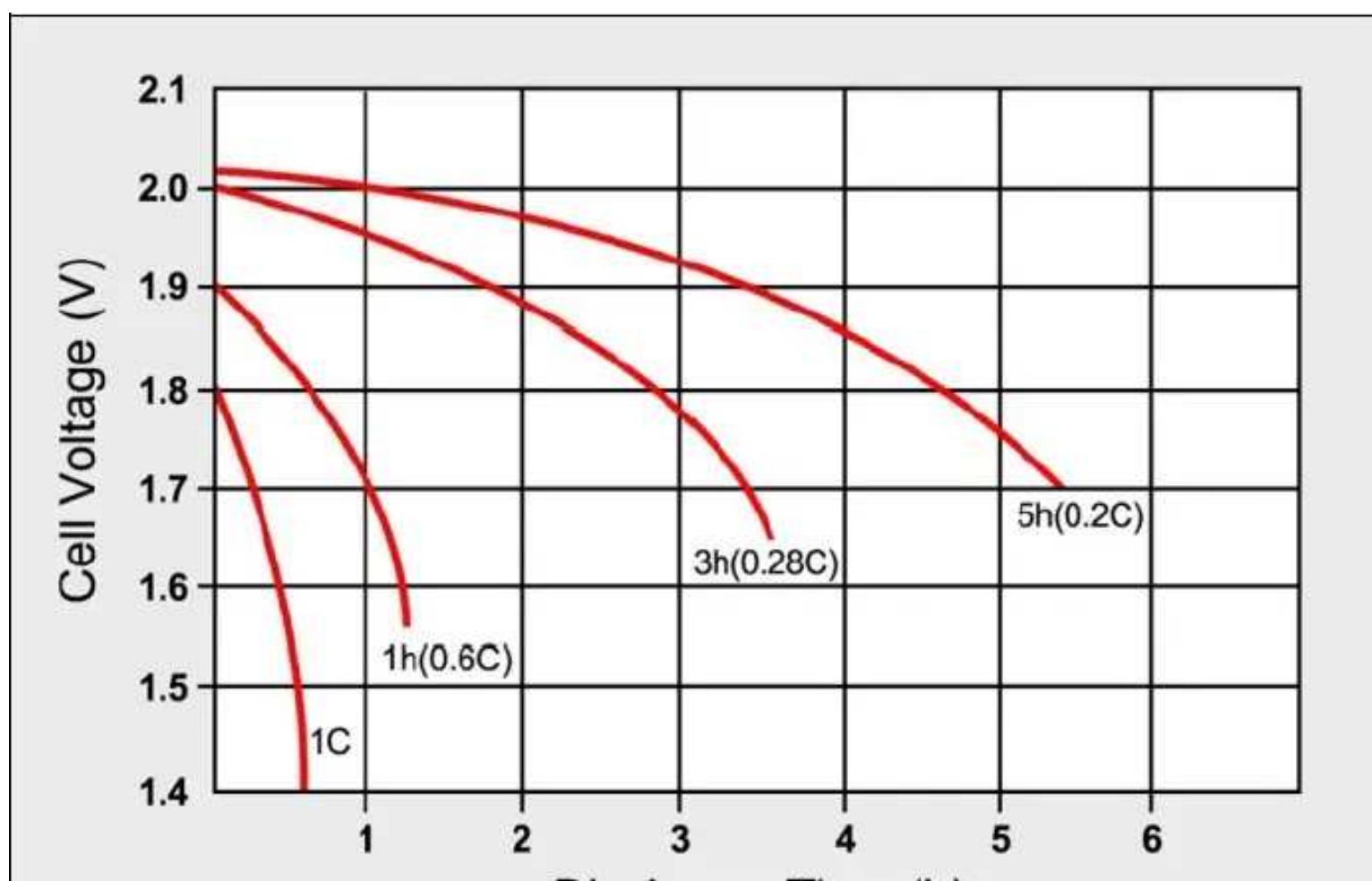


Figure 4-6: Typical discharge curves of lead acid as a function of C-rate.

Smaller batteries are rated at a 1C discharge rate. Due to sluggish behavior, lead acid is rated at 0.2C (5h) and 0.05C (20h).

While lead- and nickel-based batteries can be discharged at a high rate, the protection circuit prevents the Li-ion Energy Cell from discharging above 1C. The Power Cell with nickel, manganese and/or phosphate active material can tolerate discharge rates of up to 10C and the current threshold is set higher accordingly.

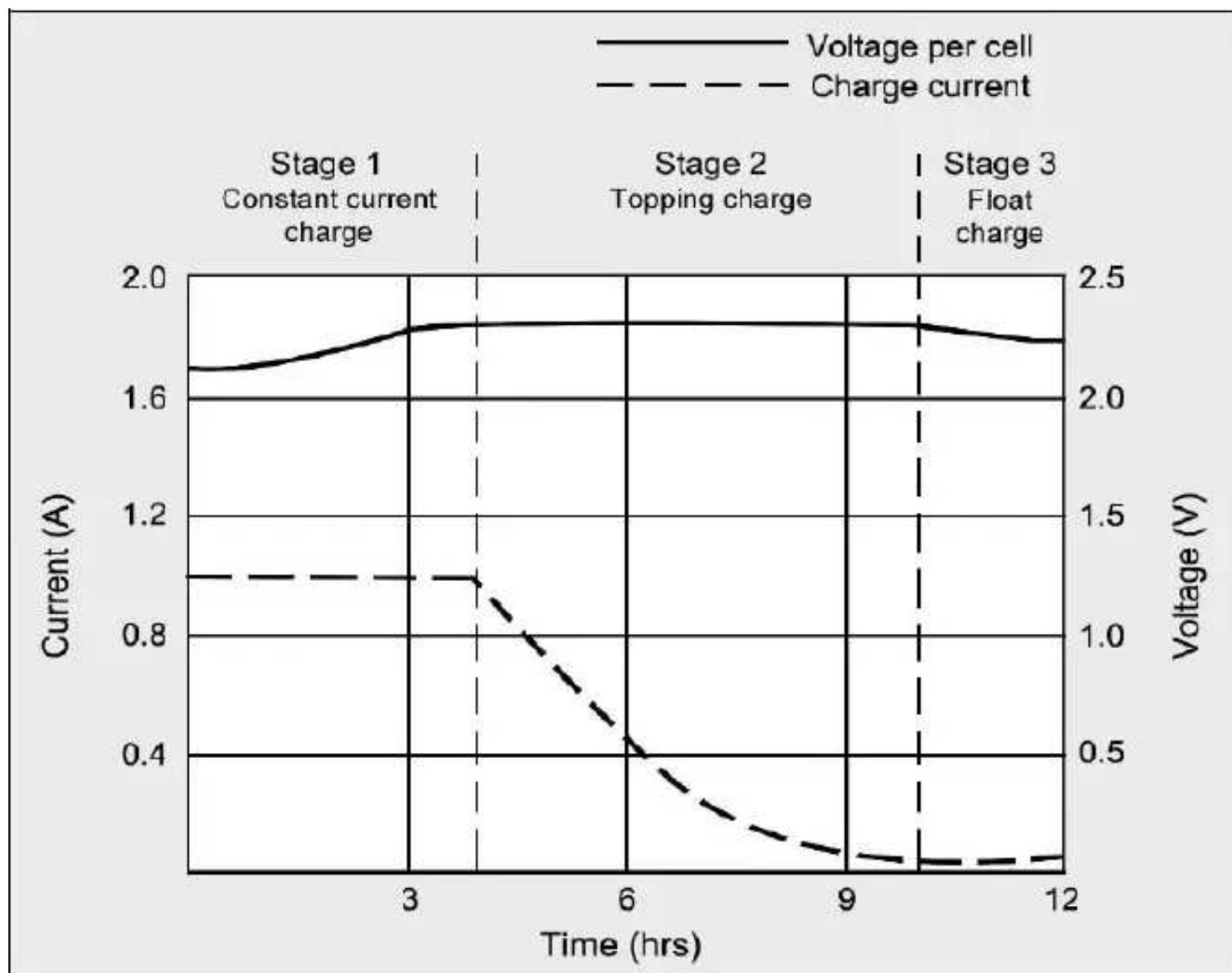
Charging Lead Acid

The lead acid battery uses the constant current constant voltage (CC/CV) charge method. A regulated current raises the terminal voltage until the upper charge voltage limit is reached, at which point the current drops due to saturation. The charge time is 12–16 hours and up to 36–48 hours for large stationary batteries. With higher charge currents and multi-stage charge methods, the charge time can be reduced to 8–10 hours; however, without full topping charge. Lead acid is sluggish and cannot be charged as quickly as other battery systems.

Lead acid batteries should be charged in three stages. These are [1] constant-current charge, [2] topping charge and [3] float charge. The constant-current charge applies the bulk of the charge and takes up roughly half of the required charge time; the topping charge continues at a lower charge current and provides saturation, and the float charge compensates for the loss caused by self-discharge.

During the constant-current charge, the battery charges to about 70 percent in 5–8 hours; the remaining 30 percent is filled with the slower topping charge that lasts another 7–10 hours. The topping charge is essential for the well-being of the battery and can be compared to a little rest after a good meal. If continually deprived, the battery will eventually lose the ability to accept a full charge and the performance will decrease due to sulfation. The float charge in

charge and the performance will decrease due to sulfation. The float charge in the third stage maintains the battery at full charge. Figure 4-7 illustrates these three stages.



Stage 1: Voltage rises at constant current to V-peak.

Stage 2: Current drops; full charge is reached when current levels off

Stage 3: Voltage is lowered to float charge level

Figure 4-7: Charge stages of a lead acid battery.

The battery is fully charged when the current drops to a set low level. The float voltage is reduced. Float charge compensates for self-discharge that all batteries exhibit.

Courtesy of Cadex

The switch from Stage 1 to 2 occurs seamlessly and happens when the battery reaches the set voltage limit. The current begins to drop as the battery starts to saturate; full charge is reached when the current decreases to 3–5 percent of the Ah rating. A battery with high leakage may never attain this low saturation current, and a plateau timer takes over to end the charge.

saturation current, and a plateau timer takes over to end the charge.

The correct setting of the charge voltage limit is critical and ranges from 2.30V to 2.45V per cell. Setting the voltage threshold is a compromise and

battery experts refer to this as “dancing on the head of a needle.” On one hand, the battery must be fully charged to get maximum capacity and avoid sulfation on the negative plate; on the other hand, over-saturation by not switching to float charge causes grid corrosion on the positive plate. This also leads to gassing and water-loss.

Temperature changes the voltage and this makes “dancing on the head of a needle” more difficult. A warmer ambient requires a slightly lower voltage threshold and a colder temperature prefers a higher setting. Chargers exposed to temperature fluctuations include temperature sensors to adjust the charge voltage for optimum charge efficiency.

The charge temperature coefficient of a lead acid cell is $-3\text{mV}/^\circ\text{C}$.

Establishing 25°C (77°F) as the midpoint, the charge voltage should be reduced by 3mV per cell for every degree above 25°C and increased by 3mV per cell for every degree below 25°C . If this is not possible, it is better to choose a lower voltage for safety reasons. Table 4-8 compares the advantages and limitations of various peak voltage settings.

	2.30V to 2.35V/cell	2.40V to 2.45V/cell
Advantages	Maximum service life; battery stays cool; charge temperature can exceed 30°C (86°F).	Higher and more consistent capacity readings; less sulfation.
Limitations	Slow charge time; capacity readings may be inconsistent and declining with each cycle. Sulfation may occur without equalizing charge.	Subject to corrosion and gassing. Needs water refill. Not suitable for charging at high room temperatures, causing severe overcharge.

Table 4-8: Effects of charge voltage on a small lead acid battery.

Cylindrical lead acid cells have higher voltage settings than VRLA and starter batteries.

Once fully charged through saturation, the battery should not dwell at the topping voltage for more than 48 hours and must be reduced to the float voltage

level. This is especially critical for sealed systems because they are less tolerant to overcharge than the flooded type. Charging beyond the specified limits turns redundant energy into heat and the battery begins to gas.

The recommended float voltage of most flooded lead acid batteries is 2.25V to 2.27V/cell. Large stationary batteries at 25°C (77°F) typically float at 2.25V/cell. Manufacturers recommend lowering the float charge when the ambient temperature rises above 29°C (85°F).

Not all chargers feature float charge and very few road vehicles have this provision. If your charger stays on topping charge and does not drop below 2.30V/cell, remove the charge after 48 hours of charging. Recharge every 6 months while in storage; AGM every 6–12 months.

These described voltage settings apply to flooded cells and batteries with a pressure relief valve of about 34kPa (5psi). Cylindrical sealed lead acid, such as the Hawker Cyclon cell, requires higher voltage settings and the limits should be set to manufacturer's specifications. Failing to apply the recommended voltage will cause a gradual decrease in capacity due to sulfation. The Hawker Cyclon cell has a pressure relief setting of 345kPa (50psi). This allows some recombination of the gases generated during charge.

Aging batteries pose a challenge when setting the float charge voltage because each cell has its own unique condition. Connected in a string, all cells receive the same charge current and controlling individual cell voltages as each reaches full capacity is almost impossible. Weak cells may go into overcharge while strong cells remain in a starved state. A float current that is too high for the faded cell might sulfate the strong neighbor due to undercharge. Cell-balancing devices are available that compensate for the differences in voltages caused by cell imbalance.

Ripple voltage also causes a problem with large stationary batteries. A voltage peak constitutes an overcharge, causing hydrogen evolution, while the valley induces a brief discharge that creates a starved state resulting in electrolyte depletion. Manufacturers limit the ripple on the charge voltage to 5 percent.

Much has been said about pulse charging of lead acid batteries to reduce sulfation. The results are inconclusive and manufacturers as well as service

technicians are divided on the benefit. If sulfation could be measured and the right amount of pulsing applied, then the remedy could be beneficial; however giving a cure without knowing the underlying side effects can be harmful to the battery.

Most stationary batteries are kept on float charge and this works reasonably well. Another method is the *hysteresis charge* that disconnects the float current when the battery goes to standby mode. The battery is essentially put in storage and is only “borrowed” from time to time to apply a topping-charge to replenish lost energy due to self-discharge, or when a load is applied. This mode works well for installations that do not draw a load when on standby.

Lead acid batteries must always be stored in a charged state. A topping charge should be applied every 6 months to prevent the voltage from dropping below 2.05V/cell and causing the battery to sulfate. With AGM, these requirements can be relaxed.

Measuring the open circuit voltage (OCV) while in storage provides a reliable indication as to the state-of-charge of the battery. A cell voltage of 2.10V at room temperature reveals a charge of about 90 percent. This battery is in good condition and needs only a brief full charge prior to use.

Observe the storage temperature when measuring the open circuit voltage. A cool battery lowers the voltage slightly and a warm one increases it. Using OCV to estimate state-of-charge works best when the battery has rested for a few hours, because a charge or discharge agitates the battery and distorts the voltage.

Some buyers do not accept shipments of new batteries if the OCV at incoming inspection is below 2.10V per cell. A low voltage suggests a partial charge due to long storage or a high self-discharge caused by a micro-short. Battery users have found that a pack arriving at a lower than specified voltage has a higher failure rate than those with higher voltage. Although in-house

service can often bring such batteries to full performance, the time and equipment required adds to operational costs. (Note that the 2.10V/cell acceptance threshold does not apply to all lead acid types equally.)

Watering

Watering is the single most important step in maintaining a flooded lead acid battery; a requirement that is all too often neglected. The frequency of watering depends on usage, charge method and operating temperature. Over-charging also leads to water consumption.

A new battery should be checked every few weeks to estimate the watering requirement. This assures that the top of the plates are never exposed. A naked plate will sustain irreversible damage through oxidation, leading to reduced capacity and lower performance.

If low on electrolyte, immediately fill the battery with distilled or de-ionized water. Tap water may be acceptable in some regions. Do not fill to the correct level before charging as this could cause an overflow during charging. Always top up to the desired level after charging. Never add electrolyte as this would upset the specific gravity and promote corrosion. Watering systems eliminate low electrolyte levels by automatically adding the right amount of water.

Equalizing Charge

Stationary batteries are almost exclusively lead acid and some maintenance is required, one of which is equalizing charge. Applying a periodic equalizing charge brings all cells to similar levels by increasing the voltage to 2.50V/cell, or 10 percent higher than the recommended charge voltage.

An equalizing charge is nothing more than a deliberate overcharge to remove sulfate crystals that build up on the plates over time. Left unchecked, sulfation can reduce the overall capacity of the battery and render the battery unserviceable in extreme cases. An equalizing charge also reverses acid stratification, a condition where acid concentration is greater at the bottom of the battery than at the top.

battery than at the top.

Experts recommend equalizing services once a month to once or twice a year. A better method is to apply a fully saturated charge and then compare the

specific gravity readings (SG) on the individual cells of a flooded lead acid battery with a hydrometer. Only apply equalization if the SG difference between the cells is 0.030.

During equalizing charge, check the changes in the SG reading every hour and disconnect the charge when the gravity no longer rises. This is the time when no further improvement is possible and a continued charge would have a negative effect on the battery.

The battery must be kept cool and under close observation for unusual heat rise and excessive venting. Some venting is normal and the hydrogen emitted is highly flammable. The battery room must have good ventilation as hydrogen gas becomes explosive at a concentration of 4 percent.

Equalizing VRLA and other sealed batteries involves guesswork. Observing the differences in cell voltage does not give a conclusive solution and good judgment plays a pivotal role when estimating the frequency and duration of the service. Some manufacturers recommend monthly equalizations for 2–16 hours. Most VRLAs vent at 34kPa (5psi), and repeated venting leads to the depletion of the electrolyte, which can lead to a dry-out condition. Not all chargers feature equalizing charge. If not available, the service should be performed with a dedicated device.

How to Charge with a Power Supply

Batteries can be charged manually with a power supply featuring user-adjustable voltage and current limiting. I stress *manual* because charging needs the know-how and can never be left unattended; charge termination is not automated. Because of difficulties in detecting full charge with nickel-based batteries, I recommend charging only lead and lithium-based batteries manually.

Lead Acid

Before connecting the battery, make sure the leads are clean and tight.

Before connecting the battery, calculate the charge voltage according to the number of cells in series, and then set the desired voltage and current limit. To charge a 12-volt lead acid battery (six cells) to a voltage limit of 2.40V, set the

voltage to 14.40V (6×2.40). Select the charge current according to battery size. For lead acid, this is between 10 and 30 percent of the rated capacity. A 10Ah battery at 30 percent charges at about 3A; the percentage can be lower. An 80Ah starter battery may charge at 8A. (A 10 percent charge rate is equal to 0.1C.)

Observe the battery temperature, voltage and current during charge. Charge only at ambient temperatures in a well-ventilated room. Once the battery is fully charged and the current has dropped to 3 percent of the rated Ah, the charge is completed. Disconnect the charge. Also disconnect the charge after 16–24 hours if the current has bottomed out and cannot go lower; high self-discharge (soft electrical short) can prevent the battery from reaching the low saturation level. If you need float charge for operational readiness, lower the charge voltage to about 2.25V/cell.

You can also use the power supply to equalize a lead acid battery by setting the charge voltage 10 percent higher than recommended. The time in overcharge is critical and must be carefully observed.

A power supply can also reverse sulfation. Set the charge voltage above the recommended level, adjust the current limiting to the lowest practical value and observe the battery voltage. A totally sulfated lead acid may draw very little current at first and as the sulfation layer dissolves, the current will gradually increase. Elevating the temperature and placing the battery on an ultrasound vibrator may also help in the process. If the battery does not accept a charge after 24 hours, restoration is unlikely. (See “Sulfation” of page 238.)

Lithium-ion

Lithium-ion charges similarly to lead acid and you can also use the power supply but exercise extra caution. Check the full charge voltage, which is commonly 4.20V/cell, and set the threshold accordingly. Make certain that none of the cells connected in series exceeds this voltage. (The protection circuit in a commercial pack does this.) Full charge is reached when the cell(s) reach 4.20V/cell voltage.

pack does this.) Full charge is reached when the cell(s) reach 4.20V/cell voltage and the current drops to 3 percent of the rated current, or has bottomed out and cannot go down further. Once fully charged, disconnect the battery. Never allow

a cell to dwell at 4.20V for more than a few hours.

Please note that not all Li-ion batteries charge to the voltage threshold of 4.20V/cell. Lithium iron phosphate typically charges to the cut-off voltage of 3.65V/cell and lithium-titanate to 2.85V/cell. Some Energy Cells may accept 4.30V/cell and higher. (See “Types of Lithium-ion Batteries” on page 61.)

NiCd and NiMH

Charging nickel-based batteries with a power supply is challenging because the full-charge detection is rooted in a voltage signature that varies with the applied charge current. If you must charge NiCd and NiMH with a regulated power supply, use the temperature rise on a 0.3–1C rapid charge as an indication of full charge. When charging at a low current, estimate the level of remaining charge

and calculate the charge time. An empty 2Ah NiMH will charge in about 3 hours at 750–1,000mA. The trickle charge, also known as maintenance charge, must be reduced to 0.05C. (See “Charging Nickel-cadmium” on page 139 and “Charging Nickel-metal-hydride” on page 142.)

Battery as a Buffer

The main purpose of a stationary battery is to provide power during power outage. Battery banks are also designed to provide extra power during high-traffic periods when the AC power supply does not have sufficient capacity to feed the system. In this case, the battery acts as a buffer similar to the battery in a hybrid car that assists in acceleration.

Cellular repeater towers are an example where the backup battery serves as a buffer. The batteries get fully charged during off-peak periods and go into discharge mode to assist the AC power supply during the peak times.

When relying on the battery as buffer, make certain that the battery has enough time to charge between peak periods. The net charge must always be greater than what was drawn from the battery. Avoid deep discharges as this

greater than what was drawn from the battery. Avoid deep discharges as this would wear down the battery prematurely. Note that stationary and starter batteries are not made for deep cycling. If periodic cycling is needed, choose a deep-cycle battery.

Simple Guidelines for Charging Lead Acid Batteries

- Charge in a well-ventilated area. Hydrogen gas generated during charging is explosive.
- Choose the appropriate charge program for flooded, gel and AGM batteries. Check manufacturer's specifications on recommended voltage thresholds.
- Recharge lead acid batteries after each use to prevent sulfation. Do not store on low charge.
- The plates of flooded batteries must always be fully submerged in electrolyte. Fill the battery with distilled or de-ionized water to cover the plates if low. Tap water may be acceptable in some regions. Never add electrolyte.
- Fill water level to designated level *after* charging. Overfilling when the battery is on low charge can cause acid spillage during charging.
- The formation of gas bubbles in a flooded lead acid indicates that the battery is reaching full state-of-charge. (Hydrogen appears on negative plate and oxygen on positive plate).
- Lower the float charge voltage if the ambient temperature is higher than 29°C (85°F).
- Do not allow a lead acid to freeze. An empty battery freezes sooner than one that is fully charged. Never charge a frozen battery.
- Avoid charging at temperatures above 49°C (120°F).

Charging Nickel-cadmium

Battery manufacturers recommend that new batteries be slow-charged for 16–24 hours before use. A slow charge brings all cells in a battery pack to an equal charge level. This is important because each cell within the nickel-cadmium battery pack is self-discharging at its own rate. Each cell has its own individual

battery may have self-discharged at its own rate. Furthermore, during long storage the electrolyte tends to gravitate to the bottom of the cell and the initial slow charge helps in the redistribution to eliminate dry spots on the separator.

Battery manufacturers do not fully format nickel- and lead-based batteries before shipment. The cells reach optimal performance after priming that involves several charge/discharge cycles. This is part of normal use; it can also be done with a battery analyzer. Quality cells are known to perform to full specifications after only 5–7 cycles; others may take 50–100 cycles. Peak capacity occurs between 100–300 cycles, after which the performance starts to drop gradually.

Most rechargeable cells include a safety vent that releases excess pressure if incorrectly charged. The vent on a NiCd cell opens at 1,000–1,400kPa (150–200psi). Pressure released through a re-sealable vent causes no damage; however, with each venting event some electrolyte escapes and the seal may begin to leak. The formation of a white powder at the vent opening makes this visible. Multiple venting eventually results in a dry-out condition. A battery should never be stressed to the point of venting.

Full-charge Detection by Temperature

Full-charge detection of sealed nickel-based batteries is more complex than that of lead acid and lithium-ion. Low-cost chargers often use temperature sensing to end the fast charge, but this can be inaccurate. The core of a cell is several degrees warmer than the skin where the temperature is measured, and the delay that occurs causes over-charge. Charger manufacturers use 50°C (122°F) as temperature cutoff. Although any prolonged temperature above 45°C (113°F) is harmful to the battery, a brief overshoot is acceptable as long as the battery temperature drops quickly when the “ready” light appears.

Advanced chargers no longer rely on a fixed temperature threshold but sense the rate of temperature increase over time, also known as delta temperature over delta time, or dT/dt . Rather than waiting for an absolute temperature to occur, dT/dt uses the rapid temperature increase towards the end of charge to signal a “ready” light. The advantage of this method is that it is less prone to error due to variations in ambient temperature.

trigger the “ready” light. The delta temperature method keeps the battery cooler than a fixed temperature cutoff, but the cells need to charge reasonably fast to trigger the temperature rise. Charge termination occurs when the temperature

rises 1°C (1.8°F) per minute. If the battery cannot achieve the needed temperature rise, an absolute temperature cutoff set to 60°C (140°F) terminates the charge.

Chargers relying on temperature inflict harmful overcharges when a fully charged battery is repeatedly removed and reinserted. This is the case with chargers in vehicles and desktop stations where a two-way radio is being detached with each use. Reconnection initiates a new charge cycle that requires reheating of the battery.

Li-ion systems have an advantage in that voltage governs state-of-charge. Reinserting a fully charged Li-ion battery immediately pushes the voltage to the full-charge threshold, the current drops and the charger turns off shortly without needing to create a temperature signature.

Full-charge Detection by Voltage Signature

Advanced chargers terminate charge when a defined voltage signature occurs. This provides a more precise full-charge detection of nickel-based batteries than temperature-based methods. The charger looks for a voltage drop that occurs when the battery has reached full charge. This method is called *negative delta V* (NDV).

NDV is the recommended full-charge detection method for chargers applying a charge rate of 0.3C and higher. It offers a quick response time and works well with a partially or fully charged battery. When inserting a fully charged battery, the terminal voltage rises quickly and then drops sharply to trigger the ready state. The charge lasts only a few minutes and the cells remain cool. NiCd chargers with NDV detection typically respond to a voltage drop of 5mV per cell.

To achieve a reliable voltage signature, the charge rate must be 0.5C and higher. Slower charging produces a less defined voltage drop, especially if the

cells are mismatched in which case each cell reaches full charge at a different time point. To assure reliable full-charge detection, most NDV chargers also use a voltage plateau detector that terminates the charge when the voltage remains in

a steady state for a given time. These chargers also include delta temperature, absolute temperature and a time-out timer.

Fast charge improves the charger efficiency. At 1C charge rate, the efficiency of a standard NiCd is 91 percent and the charge time is about an hour (66 minutes at 91 percent). On a slow charger, the efficiency drops to 71 percent, prolonging the charge time to about 14 hours at 0.1C.

During the first 70 percent of charge, the efficiency of a NiCd is close to 100 percent. The battery absorbs almost all energy and the pack remains cool. NiCd batteries designed for fast charging can be charged with currents that are several times the C-rating without extensive heat buildup. In fact, NiCd is the only battery that can be ultra-fast charged with minimal stress. Cells made for ultra-fast charging can be charged to 70 percent in minutes.

Figure 4-9 shows the relationship of cell voltage, pressure and temperature of a charging NiCd. Everything goes well up to about 70 percent charge, when charge efficiency drops. The cells begin to generate gases, the pressure rises and the temperature increases rapidly. To reduce battery stress, some chargers lower the charge rate past the 70 percent mark.

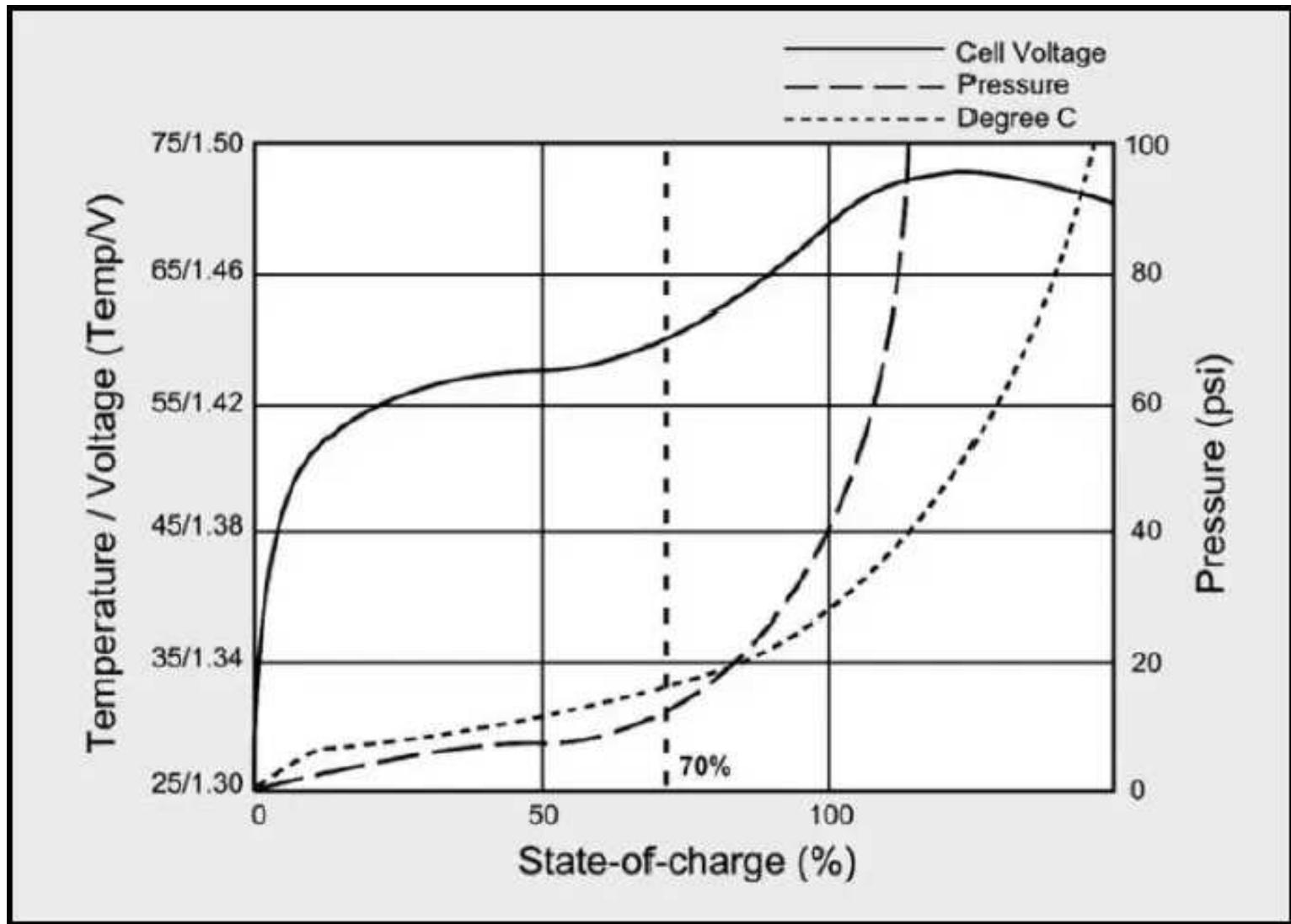


Figure 4-9: Charge characteristics of a NiCd cell.

Charge efficiency is high up to 70% SoC and then charge acceptance drops. NiMH is similar to NiCd. Charge efficiency measures the battery's ability to accept charge and has similarities with coulombic efficiency.

Courtesy of Cadex

Ultra-high-capacity NiCd batteries tend to heat up more than standard NiCds when charging at 1C and higher and this is partly due to increased internal resistance. Applying a high current at the initial charge and then tapering off to a lower rate as the charge acceptance decreases is a recommended fast charge method for these more fragile batteries.

Interspersing discharge pulses between charge pulses is known to improve charge acceptance of nickel cadmium batteries. Currents of around “1C”

charge acceptance of nickel-based batteries. Commonly referred to as a “burp” or “reverse load” charge, this method assists in the recombination of gases generated during charge. The result is a cooler and more effective charge than

with conventional DC chargers. The method is also said to reduce the “memory” effect as the battery is being exercised with pulses. (See “Memory: Myth or Fact?” on page 246.) While pulse charging may be valuable for NiCd and NiMH batteries, this method does not apply to lead- and lithium-based systems. These batteries work best with a pure DC voltage.

After full charge, the NiCd battery receives a trickle charge of 0.05–0.1C to compensate for self-discharge. To reduce possible overcharge, charger designers aim for the lowest possible trickle charge current. In spite of this, it is best not to leave nickel-based batteries in a charger for more than a few days. Remove them and recharge before use.

Charging Flooded Nickel-cadmium Batteries

Flooded NiCd is charged with a constant voltage to about 1.55V/cell. The current is then reduced to 0.1C and the charge continues until 1.55V/cell is reached again. At this point, a trickle charge is applied and the voltage is allowed to float freely. Higher charge voltages are possible but this generates excess gas and causes rapid water depletion. NDV is not applicable as the flooded NiCd does not absorb gases because it is not under pressure.

Charging Nickel-metal-hydride

The charge algorithm for NiMH is similar to NiCd with the exception that NiMH is more complex. Negative Delta V to detect full charge is faint, especially when charging at less than 0.5C. A mismatched or hot pack reduces the symptoms further.

NDV in a NiMH charger should respond to a voltage drop of 5mV per cell or less. This requires electronic filtering to compensate for noise and voltage fluctuations induced by the battery and the charger. Well-designed NiMH chargers include NDV, voltage plateau, delta temperature (dT/dt), temperature

threshold and time-out timers into the full-charge detection algorithm. These “or-gates” utilize whatever comes first. Many chargers include a 30-minute topping charge of 0.1C to boost the capacity by a few percentage points.

Some advanced chargers apply an initial fast charge of 1C. When reaching a certain voltage threshold, a rest of a few minutes is added, allowing the battery to cool down. The charge continues at a lower current and then applies further current reductions as the charge progresses. This scheme continues until the battery is fully charged. Known as the “step-differential charge,” this method works well for all nickel-based batteries.

Chargers utilizing the step-differential or other aggressive charge methods achieve a capacity gain of about 6 percent over a more basic charger. Although a higher capacity is desirable, filling the battery to the brim adds stress and shortens the overall battery life. Rather than achieving the expected 350–400 service cycles, the aggressive charger might exhaust the pack after 300 cycles.

NiMH dislikes overcharge, and the trickle charge is set to around 0.05C. NiCd is better at absorbing overcharge and the original NiCd chargers had a trickle charge of 0.1C. The differences in trickle charge current and the need for more sensitive full-charge detection render the original NiCd charger unsuitable for NiMH batteries. A NiMH in a NiCd charger would overheat, but a NiCd in a NiMH charger functions well. Modern chargers accommodate both battery systems.

It is difficult, if not impossible, to slow charge a NiMH battery. At a C-rate of 0.1C to 0.3C, the voltage and temperature profiles do not exhibit defined characteristics to trigger full-charge detection, and the charger must depend on a timer. Harmful overcharge can occur when charging partially or fully charged batteries, even if the battery remains cold.

The same scenario occurs if the battery has lost capacity and can only hold half the charge. In essence, this battery has shrunk to half the size while the fixed timer is programmed to apply a 100 percent charge without regard for battery condition.

Many battery users complain about shorter than expected service life and the fault might lie in the charger. Low-priced consumer chargers are prone to incorrect charging. If you want to improve battery performance with a low-cost

charger, estimate the battery state-of-charge and set the charge time accordingly. Remove the batteries when presumed full.

If your charger charges at a high charge rate, do a temperature check. Lukewarm indicates that the batteries may be full. It is better to remove the batteries early and recharge before each use than to leave them in the charger for eventual use.

Simple Guidelines for Charging Nickel-based Batteries

- The charge efficiency of nickel-based is close to 100 percent up to 70 percent charge. The pack remains cool but it begins to warm up with decreased efficiency towards full charge.
- Nickel-based batteries must cool down on trickle charge. If warm, trickle charge is too high.
- Consumer chargers do not always terminate the charge correctly. Remove the batteries when warm to the touch. Discontinue using a charger that “cooks” batteries.
- Charge at room temperature. Do not charge when hot or at freezing temperatures.
- Nickel-based batteries are best fast charged; a lingering slow charge causes “memory.”
- Nickel- and lithium-based batteries require different charge algorithms. A NiMH charger can also charge NiCd; a NiCd charger would overcharge NiMH.
- Do not leave a nickel-based battery in the charger for more than a few days. If possible, remove the packs and apply a brief charge before use.

Charging Lithium-ion

Charging and discharging batteries is a chemical reaction, but Li-ion is claimed to be the exception. Battery scientists talk about energies flowing in and out of the battery as part of ion movement between anode and cathode. This claim

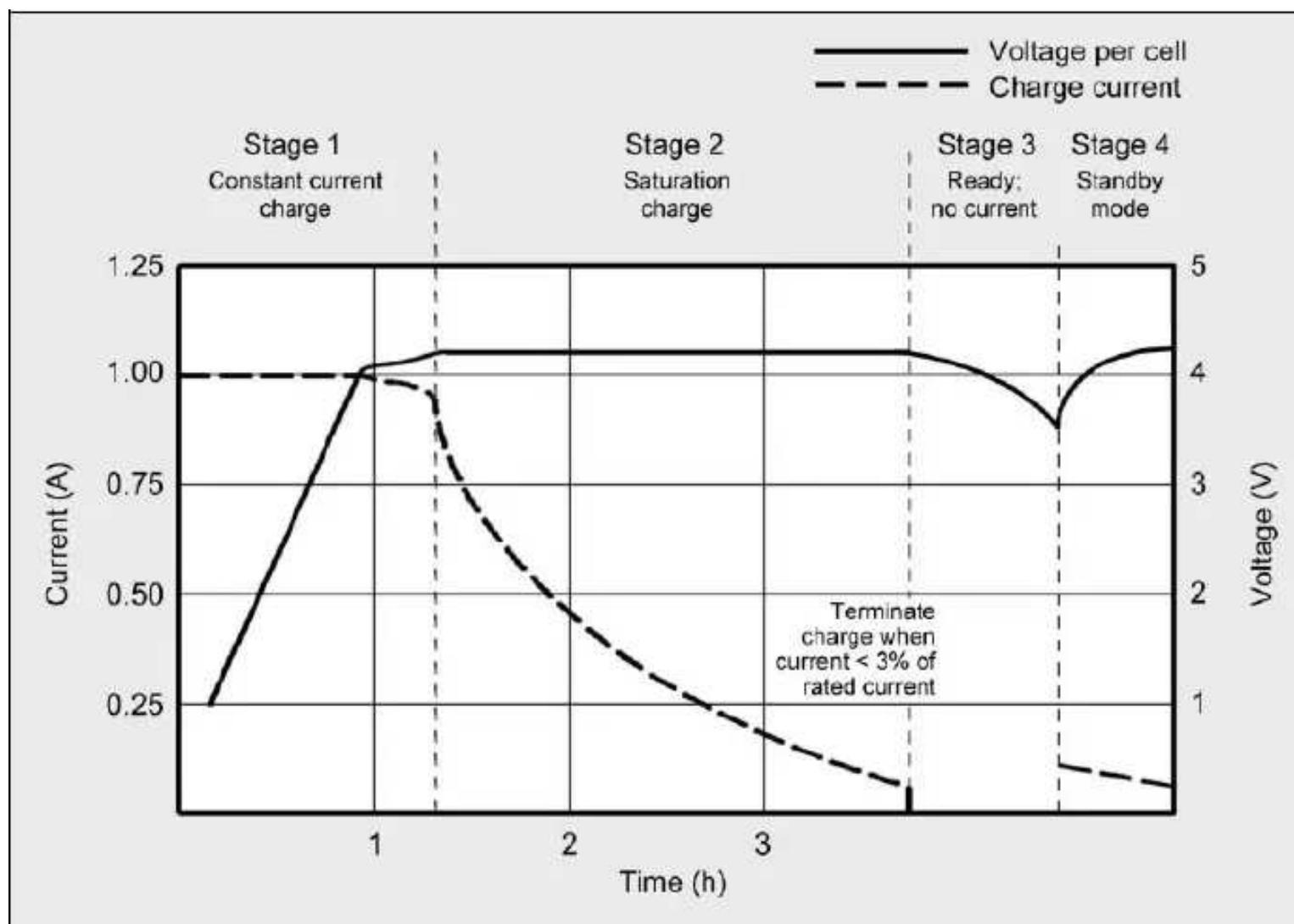
carries merits but if the scientists were totally right, then the battery would live forever. They blame capacity fade on ions getting trapped, but as with all battery systems, internal corrosion and other degenerative effects still play a role.

The Li ion charger is a voltage-limiting device that has similarities to the lead acid system. The differences with Li-ion lie in a higher voltage per cell, tighter voltage tolerances and the absence of trickle or float charge at full charge. While lead acid offers some flexibility in terms of voltage cut off, manufacturers of Li-ion cells are very strict on the correct setting because Li-ion cannot accept overcharge. The so-called miracle charger that promises to prolong battery life and gain extra capacity with pulses and other gimmicks does not exist. Li-ion is a “clean” system and only takes what it can absorb.

Charging Cobalt-blended Li-ion

Li-ion with the traditional cathode materials of cobalt, nickel, manganese and aluminum typically charge to 4.20V/cell. The tolerance is $\pm 50\text{mV}/\text{cell}$. Some nickel-based varieties charge to 4.10V/cell; high capacity Li-ion may go to 4.30V/cell and higher. Boosting the voltage increases capacity, but going beyond specification stresses the battery and compromises safety. Protection circuits built into the pack do not allow exceeding the set voltage.

Figure 4-10 shows the voltage and current signature as lithium-ion passes through the stages for constant current and topping charge. Full charge is reached when the current decreases to between 3 and 5 percent of the Ah rating.



Stage 1:
Voltage rises at
fixed current

Stage 2:
Voltage peaks,
current decreases

Stage 3:
Charge
terminates

Stage 4:
Occasional
topping charge

Figure 4-10: Charge stages of lithium-ion.

Li-ion is fully charged when the current drops to a set level. In lieu of trickle charge, some chargers apply a topping charge when the voltage drops.

Courtesy of Cadex

The advised charge rate of an Energy Cell is between 0.5C and 1C; the complete charge time is about 2–3 hours. Manufacturers of these cells recommend charging at 0.8C or less to prolong battery life; however, most Power Cells can take a higher charge C-rate with little stress. Charge efficiency is about 99 percent and the cell remains cool during charge.

Some Li-ion packs may experience a temperature rise of about 5°C (9°F) when reaching full charge. This could be due to the protection circuit and/or elevated internal resistance. Discontinue using the battery or charger if the

temperature rises more than 10°C (18°F) under moderate charging speeds.

Full charge occurs when the battery reaches the voltage threshold and the current drops to 3 percent of the rated current. A battery is also considered fully charged if the current levels off and cannot go down further. Elevated self-discharge might be the cause of this condition.

Increasing the charge current does not hasten the full-charge state by much. Although the battery reaches the voltage peak quicker, the saturation charge will take longer accordingly. With higher current, Stage 1 is shorter but the saturation during Stage 2 will take longer. A high current charge will, however, quickly fill the battery to about 70 percent.

Li-ion does not need to be fully charged as is the case with lead acid, nor is it desirable to do so. In fact, it is better not to fully charge because a high voltage stresses the battery. Choosing a lower voltage threshold or eliminating the saturation charge altogether, prolongs battery life but this reduces the runtime. Chargers for consumer products go for maximum capacity and cannot be adjusted; extended service life is perceived less important.

Some lower-cost consumer chargers may use the simplified “charge-and-run” method that charges a lithium-ion battery in one hour or less without going to the Stage 2 saturation charge. “Ready” appears when the battery reaches the voltage threshold at Stage 1. State-of-charge (SoC) at this point is about 85 percent, a level that may be sufficient for many users.

Certain industrial chargers set the charge voltage threshold lower on purpose to prolong battery life. Table 4-11 illustrates the estimated capacities when charged to different voltage thresholds with and without saturation charge.

Charge V/cell	Capacity at cutoff voltage	Charge time	Capacity with full saturation
3.8	60%	120 min	~65%
3.9	70%	135 min	~75%
4.0	75%	150 min	~80%
4.1	80%	165 min	~90%
4.2	85%	180 min	100%

Table 4-11: Typical charge characteristics of lithium-ion.

Adding full saturation boosts the capacity by about 10% but shortens life.

When the battery is first put on charge, the voltage shoots up quickly. This behavior can be compared to lifting a weight with a rubber band, causing a lag. The capacity will eventually catch up when the battery is almost fully charged (Figure 4-12). This charge characteristic is typical of all batteries. The higher the charge current is, the larger the rubber-band effect will be. Cold temperatures or charging a cell with high internal resistance amplifies the effect.

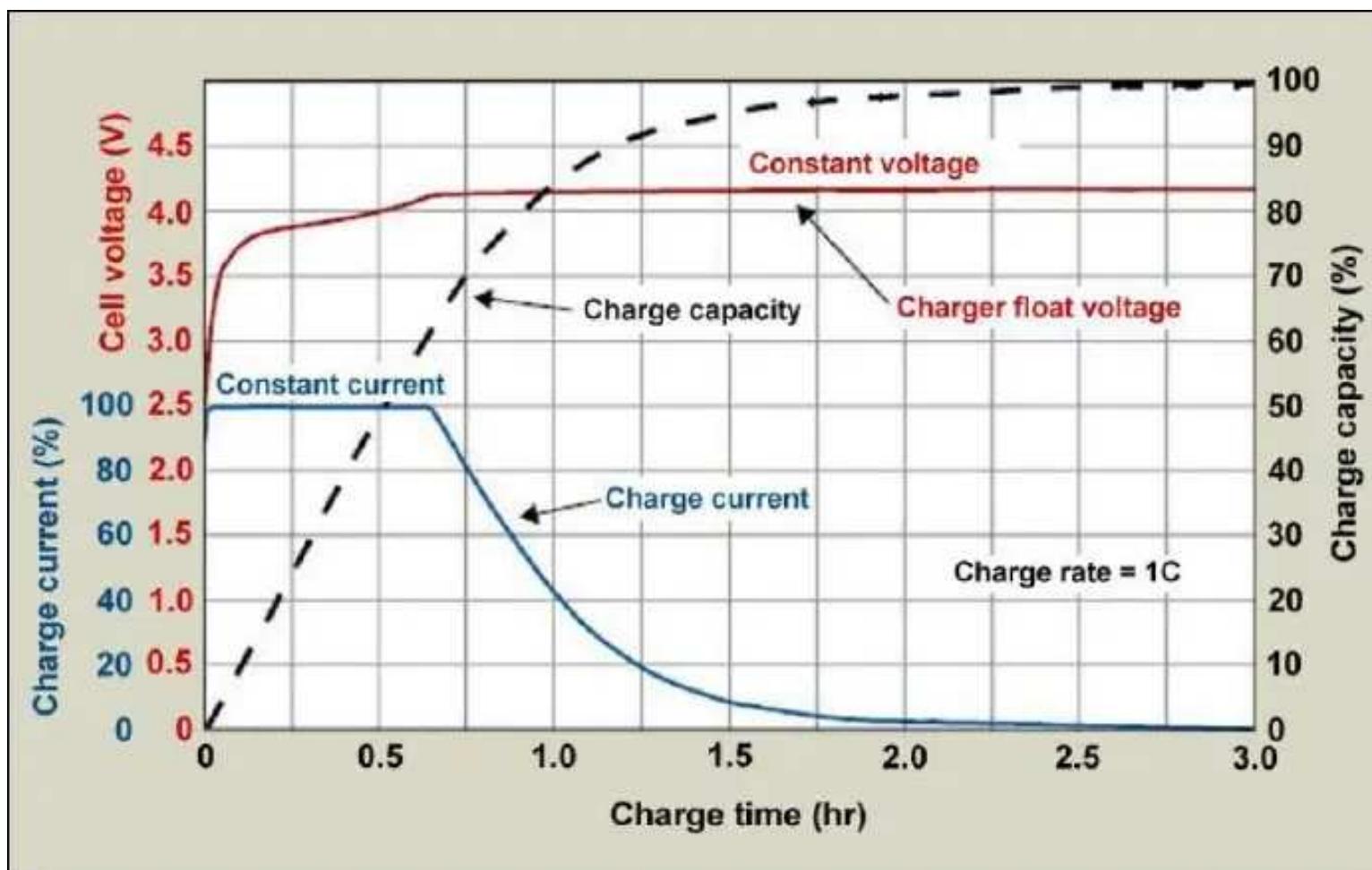


Figure 4-12: Volts/capacity vs. time when charging Li-ion.

The capacity trails the charge voltage like lifting a heavy weight with a rubber band.

Estimating SoC by reading the voltage of a charging battery is impractical; measuring the open circuit voltage (OCV) after the battery has rested for a few hours is a better indicator. As with all batteries, temperature affects the OCV, so

does the active material of Li-ion. SoC of smartphones, laptops and other devices is estimated by coulomb counting. (See “How to Measure State-of-charge” on page 271.)

Li-ion cannot absorb overcharge. When fully charged, the charge current must be cut off. A continuous trickle charge would cause plating of metallic lithium and compromise safety. To minimize stress, keep the lithium-ion battery at the peak cutoff as short as possible.

Once the charge is terminated, the battery voltage begins to drop. This causes

Once the charge is terminated, the battery voltage begins to drop. This eases the voltage stress. Over time, the open circuit voltage will settle to between 3.70V and 3.90V/cell. Note that a Li-ion battery that has received a fully saturated charge will keep the voltage elevated for a longer time than one that has not received a saturation charge.

When lithium-ion batteries must be left in the charger for operational readiness, some chargers apply a brief topping charge to compensate for the small self-discharge the battery and its protective circuit consume. The charger may kick in when the open circuit voltage drops to 4.05V/cell and turn off again at 4.20V/cell. Chargers made for operational readiness, or standby mode, often let the battery voltage drop to 4.0V/cell and recharge to only 4.05V/cell instead of the full 4.20V/cell. This reduces voltage-related stress and prolongs battery life.

Some portable devices sit in a charge cradle in the ON position. The current drawn through the device is called the *parasitic load* and can distort the charge cycle. Battery manufacturers advise against parasitic loads while charging because they induce mini-cycles. This cannot always be avoided and a laptop connected to the AC main is such a case. The battery might be charged to 4.20V/cell and then discharged by the device. The stress level on the battery is high because the cycles occur at the high-voltage threshold, often also at elevated temperature.

A portable device should be turned off during charge. This allows the battery to reach the set voltage threshold and current saturation point unhindered.

A parasitic load confuses the charger by depressing the battery voltage and preventing the current in the saturation stage to drop low enough by drawing a leakage current. A battery may be fully charged, but the prevailing conditions will prompt a continued charge, causing stress.

Charging Non-cobalt-blended Li-ion

While the traditional lithium-ion has a nominal cell voltage of 3.60V, Li-phosphate (LiFePO) makes an exception with a nominal cell voltage of 3.20V and charging to 3.65V. Relatively new is the Li-titanate (LTO) with a nominal

cell voltage of 2.40V and charging to 2.85V.

Chargers for these non-cobalt-based Li-ions are not compatible with regular 3.60-volt Li-ion. Provision must be made to identify the systems and provide the

correct charging voltage. A 3.60-volt lithium battery in a charger designed for Li-phosphate would not receive sufficient charge; a Li-phosphate in a regular charger would cause overcharge.

Overcharging Li-ion

Lithium-ion operates safely within the designated operating voltages; however, the battery becomes unstable if inadvertently charged to a higher than specified voltage. Prolonged charging above 4.30V on a Li-ion designed for 4.20V/cell will plate metallic lithium on the anode. The cathode material becomes an oxidizing agent, loses stability and produces carbon dioxide (CO_2). The cell pressure rises and if the charge is allowed to continue, the current interrupt device (CID) responsible for cell safety disconnects at 1,000–1,380kPa (145–

200psi). Should the pressure rise further, the safety membrane on some Li-ion bursts open at about 3,450kPa (500psi) and the cell might eventually vent with flame. (More on page 110, “Making Lithium-ion Safe.”)

Venting with flame is connected with elevated temperature. A fully charged battery has a lower thermal runaway temperature and vents sooner than one that is partially charged. All lithium-based batteries are safer at a lower charge, and this is why authorities mandate air shipment of Li-ion at 30 percent state-of-charge rather than at full charge. (See page 204.) The thermal threshold for Li-cobalt at full charge is 130–150°C (266–302°F); nickel-manganese-cobalt (NMC) is 170–180°C (338–356°F) and Li-manganese is about 250°C (482°F). Li-phosphate enjoys better temperature stabilities than manganese.

Lithium-ion is not the only battery that poses a safety hazard if overcharged. Lead- and nickel-based batteries are also known to melt down and cause fire if improperly handled. Properly designed charging equipment is paramount for all battery systems and temperature sensing is a reliable watchman.

Summary

Charging lithium-ion batteries is simpler than nickel-based systems. The charge circuit is straight forward; voltage and current limitations are easier to

accommodate than analyzing complex voltage signatures, which change as the battery ages. The charge process can be intermittent, and Li-ion does not need saturation as is the case with lead acid. This offers a major advantage for

renewable energy storage such as a solar panel and wind turbine, which cannot always fully charge the battery. The absence of trickle charge further simplifies the charger. Equalizing charger, as is required with lead acid, is not necessary with Li-ion.

Simple Guidelines for Charging Lithium-based Batteries

- Turn off the device or disconnect the load on charge to allow the current to drop unhindered during saturation. A parasitic load confuses the charger.
- Charge at a moderate temperature. Do not charge at freezing temperature.
- Lithium-ion does not need to be fully charged; a partial charge is better.
- Not all chargers apply a full topping charge and the battery may not be fully charged when the “ready” signal appears; a 100 percent charge on a fuel gauge may be a lie.
- Discontinue using charger and/or battery if the battery gets excessively warm.
- Apply some charge to an empty battery before storing (40–50 percent SoC is ideal). See [How to Store Batteries](#) on page 193.

Charging at High and Low Temperatures

Batteries operate over a wide temperature range, but this does not give permission to also charge them at these conditions. The charging process is more delicate than discharging and special care must be taken. Extreme cold and high heat reduce charge acceptance, so the battery must be brought to a moderate temperature before charging.

temperature before charging.

Older battery technologies, such as lead acid and NiCd, have higher charging tolerances than newer systems. This allows them to charge below

freezing but at a reduced C-charge rate. When it comes to cold-charging NiCd is hardier than NiMH. Table 4-13 summarizes the permissible charge and discharge temperatures of common batteries. The table excludes batteries that are designed to charge outside these parameters.

Low-temperature Charge

Fast charging of most batteries is limited to 5°C to 45°C (41°F to 113°F); for best results consider narrowing the temperature bandwidth to between 10°C and 30°C (50°F and 86°F) as the ability to recombine oxygen and hydrogen diminishes when charging nickel-based batteries below 5°C (41°F). If charged too quickly, pressure builds up in the cell that can lead to venting. Reduce the charge current of all nickel-based batteries to 0.1C when charging below freezing.

Battery type	Charge temperature	Discharge temperature	Charge advisory
Lead acid	-20°C to 50°C (-4°F to 122°F)	-20°C to 50°C (-4°F to 122°F)	Charge at 0.3C or less below freezing. Lower V-threshold by 3mV/°C when hot.
NiCd, NiMH	0°C to 45°C (32°F to 113°F)	-20°C to 65°C (-4°F to 149°F)	Charge at 0.1C between -18°C and 0°C Charge at 0.3C between 0°C and 5°C Charge acceptance at 45°C is 70% Charge acceptance at 60°C is 45%
Li-ion	0°C to 45°C (32°F to 113°F)	-20°C to 60°C (-4°F to 140°F)	No charge permitted below freezing. Good charge/discharge performance at higher temperature but shorter life.

Table 4-13: Permissible temperature limits for various batteries. Batteries can be discharged over a large temperature range, but the charge temperature is limited. For best results, charge between 10°C and 30°C (50°F and 86°F). Lower the charge current when cold.

Nickel-based chargers with NDV full-charge detection offer some protection when fast charging at low temperatures; the poor charge acceptance when cold mimics a fully charged battery. This is in part caused by a high

when cold diminishes a fully charged battery. This is in part caused by a high pressure buildup due to the reduced ability to recombine gases at low temperature. Pressure rise and a voltage drop at full charge appear synonymous.

To enable fast charging at all temperatures, some industrial batteries add a

thermal blanket that heats the battery to an acceptable temperature; other chargers adjust the charge rate to prevailing temperatures. Consumer chargers do not have these provisions and the end user is advised to only charge at room temperature.

Lead acid is reasonably forgiving when it comes to temperature extremes, as the starter batteries in our cars reveal. Part of this tolerance is credited to their sluggish behavior. The recommended charge rate at low temperature is 0.3C, which is almost identical to normal conditions. At a comfortable temperature of 20°C (68°F), gassing starts at charge voltage of 2.415V/cell. When going to –20°C (0°F), the gassing threshold rises to 2.97V/cell.

Freezing a lead acid battery leads to permanent damage. Always keep the batteries fully charged because in the discharged state the electrolyte becomes more water-like and freezes earlier than when fully charged. According to BCI, a specific gravity of 1.15 has a freezing temperature of –15°C (5°F). This compares to –55°C (–67°F) for a specific gravity of 1.265 with a fully charged starter battery. Flooded lead acid batteries tend to crack the case and cause leakage if frozen; sealed lead acid packs lose potency and only deliver a few cycles before they fade and need replacement.

Li-ion can be fast charged from 5°C to 45°C (41 to 113°F). Below 5°C, the charge current should be reduced, and no charging is permitted at freezing temperatures. During charge, the internal cell resistance causes a slight temperature rise that compensates for some of the cold. The internal resistance of all batteries rises when cold, prolonging charge times noticeably.

Many battery users are unaware that consumer-grade lithium-ion batteries cannot be charged below 0°C (32°F). Although the pack appears to be charging normally, plating of metallic lithium can occur on the anode during a sub-freezing charge. This is permanent and cannot be removed with cycling.

Batteries with lithium plating are more vulnerable to failure if exposed to vibration or other stressful conditions. Advanced chargers (Cadex) prevent charging Li-ion below freezing.

Advancements are being made to charge Li-ion below freezing temperatures. Charging is indeed possible with most lithium-ion cells but only at very low currents. According to research papers, the allowable charge rate at -30°C (-22°F) is 0.02C . At this low current, the charge time would stretch to over 50 hours, time that is deemed impractical. There are, however, specialty Li-ions that can charge down to -10°C (14°F) at a reduced rate.

High-temperature Charge

Heat is the worst enemy of batteries, including lead acid. Adding temperature compensation on a lead acid charger to adjust for temperature variations is said to prolong battery life by up to 15 percent. The recommended compensation is a 3mV drop per cell for every degree Celsius rise in temperature. If the float

voltage is set to $2.30\text{V}/\text{cell}$ at 25°C (77°F), the voltage should read $2.27\text{V}/\text{cell}$ at 35°C (95°F). Going colder, the voltage should be $2.33\text{V}/\text{cell}$ at 15°C (59°F). These 10°C adjustments represent 30mV change.

Table 4-14 indicates the optimal peak voltage at various temperatures when charging lead acid batteries. The table also includes the recommended float voltage while in standby mode.

Battery status	-40°C (-40°F)	-20°C (-4°F)	0°C (32°F)	25°C (77°F)	40°C (104°F)
Voltage limit on recharge	$2.85\text{V}/\text{cell}$	$2.70\text{V}/\text{cell}$	$2.55\text{V}/\text{cell}$	$2.45\text{V}/\text{cell}$	$2.35\text{V}/\text{cell}$
Float voltage at full charge	$2.55\text{V}/\text{cell}$ or lower	$2.45\text{V}/\text{cell}$ or lower	$2.35\text{V}/\text{cell}$ or lower	$2.30\text{V}/\text{cell}$ or lower	$2.25\text{V}/\text{cell}$ or lower

Table 4-14: Recommended voltage limits when charging and maintaining stationary lead acid batteries on float charge. Voltage compensation prolongs battery life when operating at temperature extremes.

Charging nickel-based batteries when warm lowers oxygen generation, which reduces charge acceptance. Heat fools the charger into thinking that the battery is full charged, but it's not. Figure 4-15 shows a typical graph of

battery is fully charged when it's not. Figure 4-15 shows a strong decrease in charge efficiency from the “100 percent efficiency line” above 30°C (86°F). At 45°C (113°F), the battery can only accept 70 percent of its full capacity; at 60°C (140°F) the charge acceptance is reduced to 45 percent. NDV for full-charge

detection becomes unreliable at higher temperatures, and temperature sensing is essential for backup.

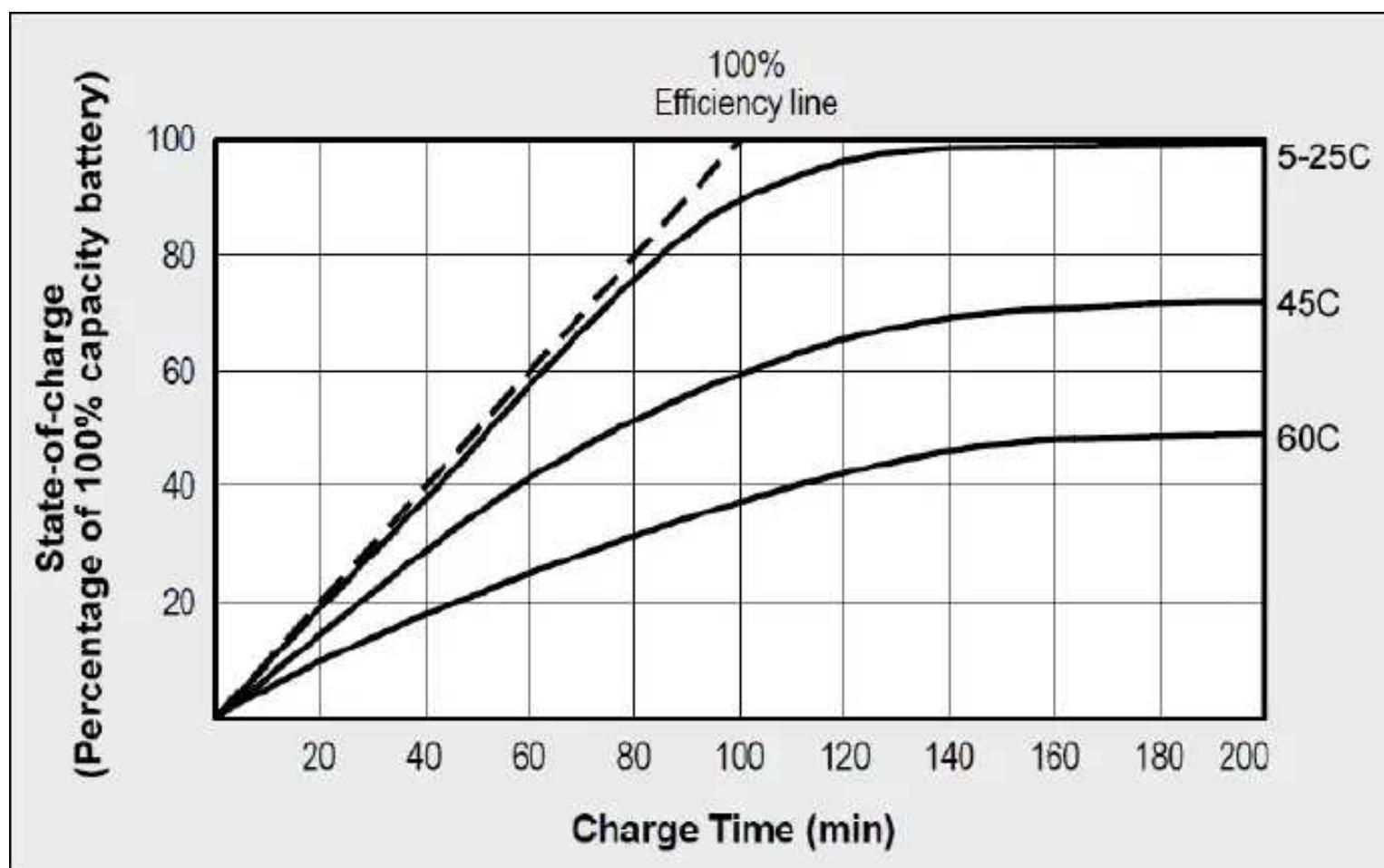


Figure 4-15: NiCd charge acceptance as a function of time with temperature as parameter.

High temperature reduces charge acceptance and departs from the dotted “100% efficiency line.” At 55°C, commercial NiMH has a charge efficiency of 35–40%; newer industrial NiMH attains 75–80%.

Courtesy of Cadex

Li-ion performs well at elevated temperatures but prolonged exposure reduces longevity. Some lithium-based packs are momentarily heated to high temperatures. This applies to batteries in surgical tools that are sterilized at 137°C (280°F) for up to 20 minutes as part of autoclaving. Oil and gas drilling as part of fracking also exposes the battery to high temperatures.

Capacity loss at elevated temperature is in direct relationship with state-of-

charge (SoC). Figure 4-16 illustrates the effect of Li-cobalt (LiCoO_2) that is first cycled at room temperature (RT) and then heated to 130°C (266°F) for 90 minutes and cycled at 20, 50 and 100 percent SoC. There is no noticeable capacity loss at room temperature. At 130°C with a 20 percent SoC, a slight

capacity loss is visible over 10 cycles. This loss is higher with a 50 percent SoC and shows a devastating effect when cycled at full charge.

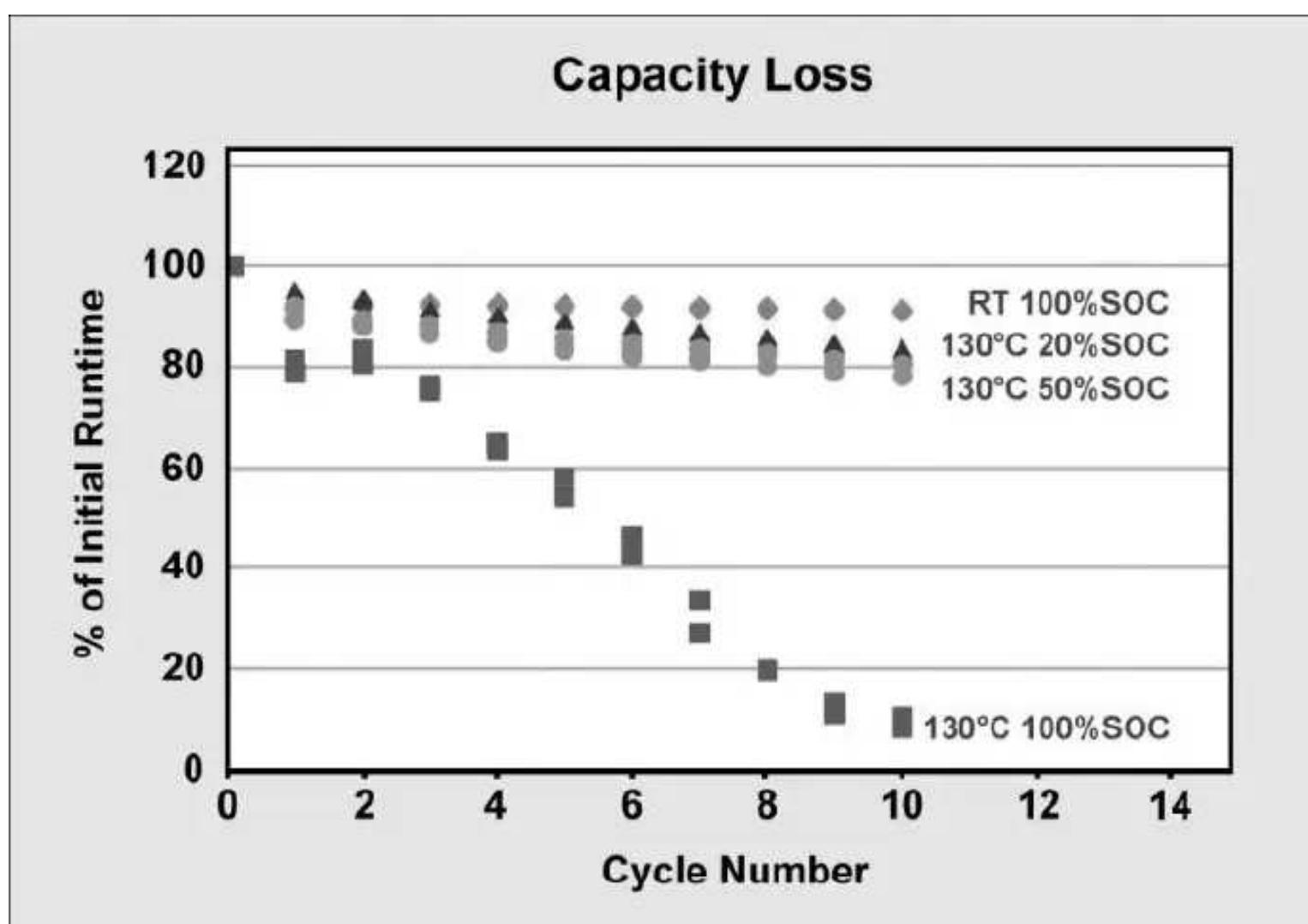


Table 4-16: Capacity loss at room temperature (RT) and 130°C for 90 minutes.

Capacity loss is highest at full SoC. Sterilization of batteries for surgical power tools should be done at low SoC.

Test: LiCoO_2 /Graphite cells were exposed to 130°C for 90 min. at different SoC between each cycle.

Source: Greatbatch Medical

Charging from a USB Port

The Universal Serial Bus (USB) was introduced in 1996 and has since become one of the most widespread and convenient interfaces for electronic devices.

Compaq, DEC, IBM, Intel, NEC and Nortel contributed to the developments

Compaq, DEC, IBM, Intel, NEC and Nortel contributed to the developments with the goal of simplifying the interconnection of peripheral devices to a PC, as well as to allow a greater data transfer rate than was feasible with earlier interfaces. The USB port can also be used to charge personal devices, but with a

current limit of 500mA on the original design, this might have been an afterthought.

A typical USB network consists of a host that is often a PC and peripherals such as a printer, smartphone or camera. Data streams in both directions but the power is unidirectional and always flows from the host to the device. The host cannot take power from an outside source.

With 5V and 500mA available on version USB 1.0 and 2.0, and 900mA on USB 3.0, the USB can charge a small single-cell Li-ion pack. There is, however, a danger of overloading a USB hub when attaching too many gadgets. Charging a device that draws 500mA connected together with other loads will exceed the port's current limit, leading to a voltage drop and a possible system failure. To prevent overload, some hosts include current-limiting circuits that shut down the supply when overdrawn.

The original USB port can only charge a small single-cell Li-ion battery. Charging a 3.6V pack begins by applying a constant current to a voltage peak of 4.20V/cell, at which point the voltage peaks and the current begins to taper off. (See “Charging Lithium-ion” on page 143.) Due to the voltage drop in the cable and connectors, which is about 350mV, as well as losses in the charging circuit, the 5V supply may not be high enough to fully charge the battery. This is a minor problem; the battery will only charge to about 70 percent state-of-charge and deliver a slightly shorter runtime than with a fully saturated charge. The advantage: Li-ion will last longer if not fully charged.

Standard A and B USB plugs, as illustrated in Figure 4-17, feature four pins and a shield. Pin 1 delivers +5VDC and pin 4 forms the ground that also connects to the shield. The two shorter pins, 2 and 3, are marked D- and D+ and carry data. When charging a battery, these pins have no other function than to negotiate current.

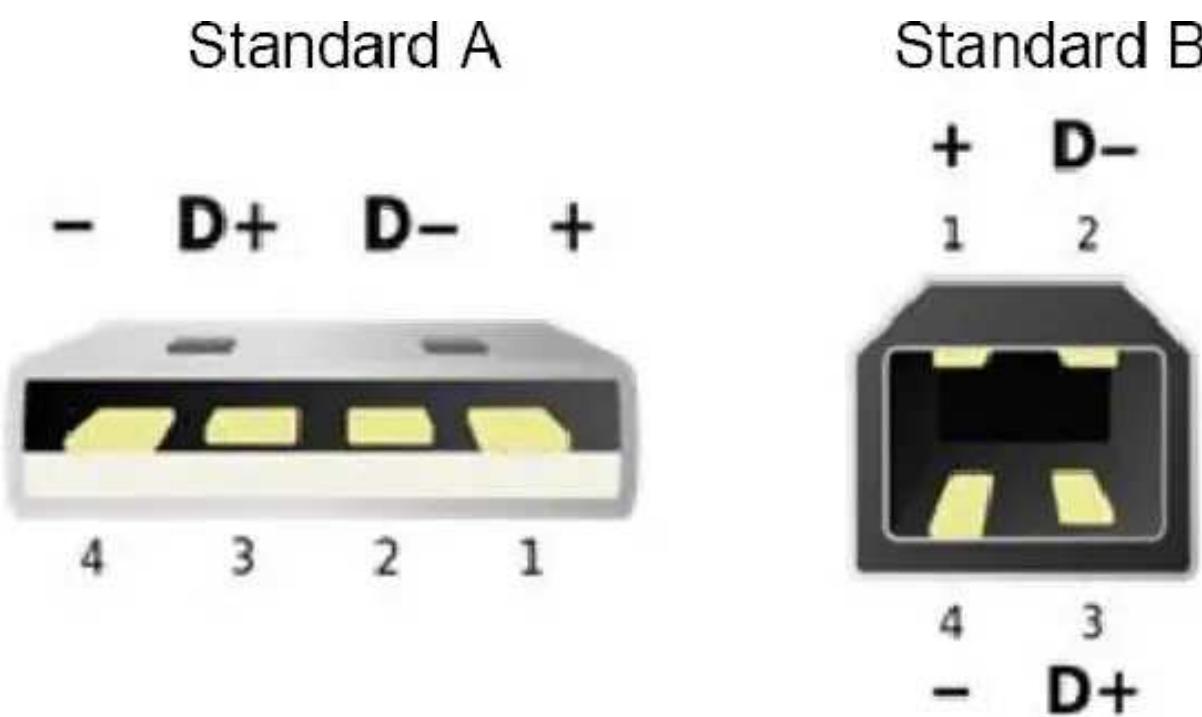


Figure 4-17: Pin configuration of standard A and standard B USB connectors, viewed from the mating end of the plugs.

Pin 1 carries +5VDC (red wire) and 4 is ground (black wire). The housing connects to the ground and provides shielding. Pin 2 (D-, white wire) and pin 3 (D+, green wire) carry data.

Besides the standard type-A and type-B configurations with 4 pins, there are also the USB Mini-A, Mini-B, Micro-A and Micro-B that include an ID pin to permit detection of which cable end is plugged in. The outer pin-1 is positive and pin-4 is negative. USB cables are generally standard type-A on one end and either type-B, Mini-B or Micro-B on the other. The new type-C connector described later features 24 pins and runs on the USB 3.1 standard.

Power Delivery

USB 2.0 with a current of 500mA has limitations when charging a larger smartphone or tablet battery. Keeping the smartphone running on a bright screen during charge could result in a net discharge of the battery as the USB cannot satisfy both. Connecting a high-speed disk drive requires more than 500mA and this can create a power issue with the original USB port.

In 2008, USB 3.0 relieved the power shortage by upping the current to

In 2000, USB 3.0 relieved the power shortage by upping the current to 900mA. This current ceiling was chosen to prevent the thin ground wire from interfering with high-speed data transfer when drawing a full load.

With the need for more power, the USB Implementers Forum released the

Battery Charging Specification in 2007 that enables a faster way to charge off a USB host. This led to the *dedicated charger port (DCP)* serving as a USB charger, delivering currents of 1,500mA and higher by connecting the DCP to an AC outlet or a vehicle. To activate the DCP, the D- and D+ pins are internally connected by a resistor of 200 ohms or less. This distinguishes the DCP from the original USB ports that carry data. Some Apple products limit the charge current by connecting different resistor values to the D+ and D- pins.

To support charging and data communication when using the DCP, a Y-shaped cable is offered that connects to the original USB port for data streaming and to the DCP port to satisfy charging needs. This appears like a logical solution but the USB compliance specification states that the “use of a Y-cable is prohibited on any USB peripheral,” meaning that “if a USB peripheral requires more power than allowed by the USB specification to which it is designed, then it must be self-powered.” The Y-cables and the so-called *accessory charging adapters (ACA)* are being used without apparent difficulties.

The question is asked: “Can I cause damage by plugging my device into a USB charger that delivers more current than 500mA and 900mA?” The answer is *no*. The device only draws what it requires and no more. An analogy is plugging in a lamp or a toaster into an AC wall plug. The lamp requires little current while the toaster goes to the maximum. More power from the USB charger will shorten the charge time.

Sleep-and-charge Mode

In most cases, turning the computer off also shuts down the USB. Some PCs feature the *sleep-and-charge* USB port that remains powered on and can be used to charge electronic devices when the computer is off. Sleep-and-charge USB ports might be colored in red or yellow, but no standard exists. Dell adds a lightning bolt icon and calls it the “PowerShare” while Toshiba uses the term

“USB Sleep-and-Charge.” The sleep-and-charge USB ports may also be marked with the acronym USB over the drawing of a battery.

USB 3.1 and Type-C Connector

As with most other successful technologies, USB has spawned several versions of connectors and cables over the years. USB chargers do not always work as advertised and charge times are slow. Incompatibilities between competitive systems exist, willingly or by oversight.

Companies overseeing USB standards are aware of the shortcomings and brought out the *type-C* connector and cable based on the USB 3.1 standard. Rather than using four-pins as in the classic type-A and type-B, the type-C connector has 24 pins and is reversible, meaning it can be plugged in either way. It supports 900mA and, on command, delivers 1.5A and 3.0A over a 5V power bus while streaming data. This results in 7.5 and 15 watt power consumption respectively, as opposed to 2.5W using the original USB (current times voltage = wattage). The type-C can go up to 5A at 12V or 20V, providing 60W and 100W respectively.

New devices come with the USB-C connector and USB 3.1, but consumers beg for two or three regular USB 3.0 ports on their gadgets to support what worked so well in the past. USB 3.1 is backward compatible with USB 2.0 and USB 3.0 and the classic type-A and type-B connectors. While in transition to the type-C, adaptors are available to convert, but expect lower data transfer speeds with adapters than what USB 3.1 offers.

Charging Without Wires

Wireless charging may one day replace plugs and wires, similar to how Bluetooth and Wi-Fi have modernized personal communication. The concept rests on inductive coupling using an electromagnetic field that transfers energy from the transmitter to the receiver.

Wireless transfer of power is not new. In 1831, Michael Faraday discovered induction by sending electromagnetic force through space. In the late 1800s and

the early 1900s, Nicola Tesla demonstrated wireless broadcasting and power transmission. The experiments in Colorado Springs in 1899 lead to the Wardenclyffe Tower in New York. Tesla wanted to prove that electrical power could be transmitted without wires, but lack of funding halted the project.

It was not until the 1920s that public broadcasting began. Europe built massive transmitters that covered many countries. The station at Beromünster in Switzerland could have transmitted radio signals at 600kW, but legislation on electro-smog and protests from the local population limited the power to 180kW. Smaller FM stations have since replaced these large national transmitters; cellular repeaters and Wi-Fi stations transmit at a fraction of this power and many are in single watt digits.

Wireless charging shares similarities with radio transmission. It sends signals in a *near field* condition in which the primary coil produces a magnetic field that is picked up by the secondary coil in close proximity. The radio transmitter, on the other hand, works on the *far field* principle by sending waves that travel through space. While the receiving coil of the wireless charger captures most of the energy generated, the receiving antenna of the radio only needs a few microvolt (one millionth of a volt) to recover a signal that becomes intelligent when amplified.

Types of Wireless Charging

Wireless charging is classified as inductive charging, radio charging and resonance charging. Most of today's wireless chargers use inductive charging with transmit and receive coils in close proximity. Electric toothbrushes were one of the first consumer goods to adopt this method.

Radio charging serves low-power devices operating within a 10-meter (30-foot) radius from the transmitter to charge batteries in medical implants, hearing aids, watches, entertainment devices and RFID (radio frequency identification) chips. The transmitter sends a low-wattage radio wave and the receiver converts the signal to energy. Radio charging resembles radio transmission the most; it offers high flexibility but has a low power capture and exposes people to electro-

smog. Radio charging is not in common use.

Larger batteries for the electric vehicle use resonance charging by making a coil “ring.” The oscillating magnetic field works within a 1-meter (3-foot) radius. To stay in the power field, the distance between transmit and receive coil

must be within a quarter wavelength (915Mhz has a wavelength of 0.328 meters or 1 foot).

Resonance charging is not limited to high-wattage wireless chargers; it is used at all power levels. While a 3kW system for EV charging achieves a reported efficiency of 93–95 percent with a 20cm (8 inch) air gap, a 100W system is better than 90 percent efficient; however the low-power 5W systems remain in the 75–80 percent efficiency range. Resonance charging is still in the experimental stages and is not widely used.

Wireless charging needed a global standard and the Wireless Power Consortium (WPC) accomplished this in 2008 by introducing the Qi norm. This opened the door for device manufacturers to offer chargers for Qi-compatible devices with 5 watts of power.

Powermat, a Qi participant, sprung loose over a disagreement and in 2012 started PMA as a new competitive norm. PMA is similar to Qi but runs at a different frequency. Also in 2012, A4WP announced resonance charging that allows freedom of movement while simultaneously charging several devices. A4WP has not yet been approved as a standard.

While the A4WP format may not be available soon in a charging station, a war is being fought over Qi and PMA. To accommodate both systems, some manufacturers offer chargers and mobile devices that serve both standards. This is a repeat of when Columbia Records released the 33 rpm LP (Long Play) in 1948 and RCA Victor promoted the 45 rpm record featuring a large hole. Dual-speed gramophones and an insert solved the problem. Table 4-18 summarizes the three norms.

Modern wireless charging follows a complex handshake to identify the device to be charged. When placing a device onto a charge mat, the change in

capacitance or resonance senses its presence. The mat then transmits a burst signal; the qualified device awakens and responds by providing identification and signal strength status. The signal quality is often also used to improve the positioning of the receiver or enhance magnetic coupling between mat and

receiver.

	WPC or Qi (Wireless Power Consortium)	PMA (Power Matters Alliance)	A4WP (Alliance for Wireless Power)
Established	2008, Qi was first wireless charging standard	2012, Procter & Gamble and Powermat	2012 by Samsung and Qualcomm
Technology	Inductive charging, 100–205kHz; coil distance 5mm;	Inductive charging, 277–357kHz; similar to Qi	Resonant charging, loosely coupled; serious emission issues remain.
Markets	Qi has widest global use; Over 500 products, more than 60 mobile phones	Tight competition with Qi, gaining ground, 100,000 Powermats at Starbucks,	A4WP and PWA merged, no product available
Members & companies	Samsung, LG, HTC, TI, Panasonic, Sony, Nokia, Motorola, Philips, Verizon, BMW, Audi, Daimler, VW, Porsche, Toyota, Jeep	Powermat, Samsung, LG, TDK, TI, AT&T, Duracell, WiTricity, Starbucks, Teavana, Huawei, FCC, Energy Star, Flextronics	Qualcomm, TediaTek, Intel, LG, HTC, Samsung, Deutsche Telecom. No commercial products.

Table 4-18: Recognized standards for wireless charging. Qi and PMA are in completion while A4WP has no standard and no commercial products. Emission issues must be solved first.

The charge mat only transmits power when a valid object is recognized, which occurs when the receiver fulfills the protocol as defined by one of the interoperability standards. During charging, the receiver sends control error signals to adjust the power level. Upon full charge or when removing the load, the mat switches to standby.

Transmit and receive coils are shielded to obtain good coupling and to reduce stray radiation. Some charge mats use a free moving transmit coil that seeks the object placed for best coupling, others systems feature multiple transmit coils and engage those in close proximity with the object.

WPC calls the transmitter the TX Controller, or Base Station, and the receiver on the mobile device the RX Controller, or Power Receiver. There is a resemblance to a transformer with a primary and secondary coil. Figure 4-19

resemblance to a transformer with a primary and secondary coil. Figure 4-19 illustrates an overview of a Qi wireless charging system.

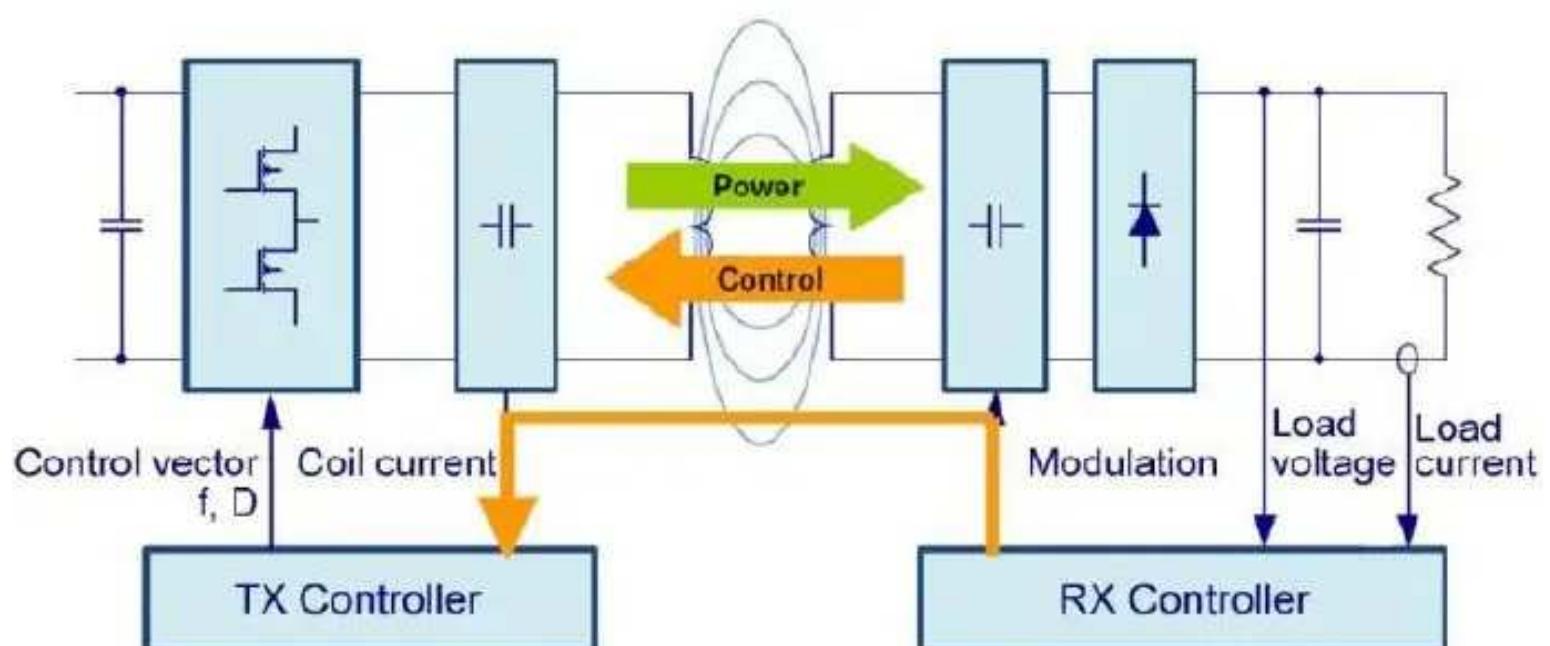


Figure 4-19: Overview of Qi wireless charging system.

Several systems are competing that may not be compatible. The three most common are Qi, PMA, A4WP.



Qi logo, Chinese word meaning “natural energy”

Pros and Cons of Wireless Charging

Wireless charging offers the ultimate convenience for consumers and enables safe charging in a hazardous environment where an electrical spark could cause an explosion. It further permits charging where grease, dust or corrosion would prevent a good electrical contact. Eliminating electrical contacts also helps doctors in sterilizing surgical tools. Wireless charging is durable and does not wear out the contacts on multiple insertions.

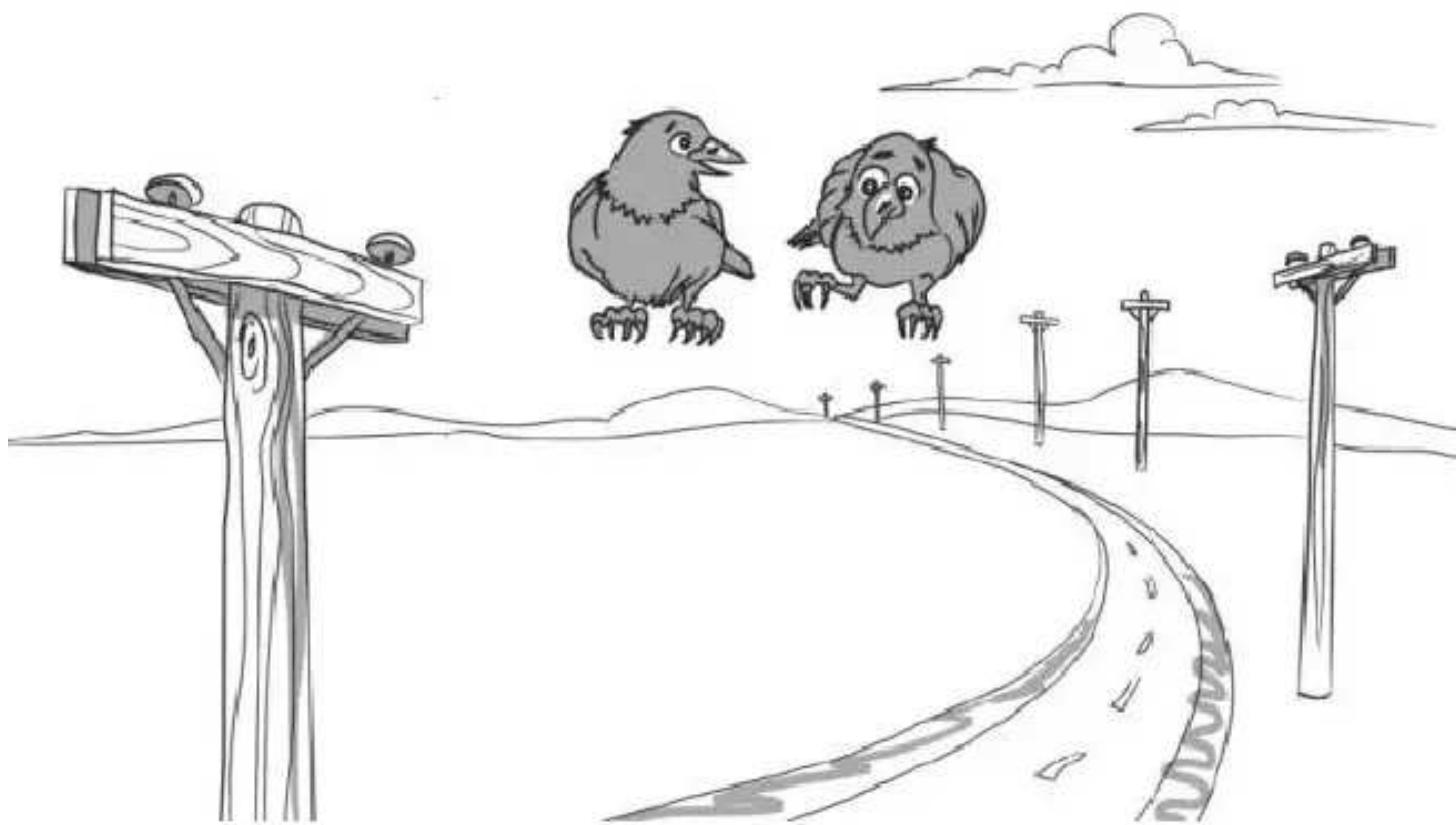
Makers of electric vehicles seek convenience in charging, and this is elegantly solved by parking the vehicle over a transmit coil. Engineers talk about embedding charging coils into highways for continuous charging while driving or when waiting at a traffic light. This is technically feasible, but high cost, low efficiency and field emission when transmitting high power remain

insurmountable challenges.

For household and business use, the California Energy Commission (CEC), Level V, mandates that AC adapters must meet a minimum efficiency of 85

percent; Energy Star Level V requires 87 percent (European CE uses CEC as a base). Adding the losses of the AC adapter to wireless charging brings the overall efficiency down further as the inductive transfer efficiency of inductive charging is only 75–80 percent. Such a loss adds up when considering that an estimated one billion mobile phone chargers are plugged into AC outlets worldwide. To improve efficiency and comply with the Energy Star requirements, WPC combines the power needs into a single power conversion.

Lost energy turns into heat, and a wireless charger can get quite warm during charging. This causes stress on the device's battery sitting on the mat. It should be noted that the heat buildup only occurs during charging; the charging pad cools down once the battery is fully charged.



"TELL ME AGAIN THE BENEFITS OF WIRELESS."

Figure 4-20: Pros and cons of wireless charging.

Wireless charging provides convenience but wires still offer a practical alternative, which the birds will support.

Anonymous source

WPC was very careful when releasing Qi; the first version has a power

limit of 5 watts. A medium-power version of up to 120 watts is in the works, but this norm must meet stringent radiation standards before release. Radiation prompts health concerns and these are raised by folks living next to mobile phone towers and Wi-Fi stations.

Electromagnetic energy from radio towers, mobile phones, Wi-Fi and now wireless charging are categorized as non-ionizing radiation and are said to be harmless. Ionizing rays from x-rays, on the other hand, can cause cancer. As the number of non-ionizing devices grows, folks begin to question the safety of this form of radiation as well. Regulatory authorities are observing possible health risks and will impose restrictions if harm can be proven.

Health problems caused by electromagnetic waves are inconclusive; however, carrying a mobile phone close to the body is a concern. In standby mode the device is constantly seeking contact with a tower by transmitting signal bursts. The transmit power is adjusted to the proximity of the tower and is higher in remote areas.

Going wireless demands a 25 percent cost premium on the charging station, a burden that also affects the receiver. For consumers who don't want to pay the price, charging by wires remains a workable alternative and birds looking for the missing wires appreciate this move.

Charging with Solar, Turbine

Folks concerned about the environment gravitate towards using renewable energy. The sun provides peak power of about 1,000 watts per square meter (93W/sq ft) and a solar panel transforms this power into roughly 130W per square meter (12W/sq ft). This energy harvest corresponds to a clear day with the solar panel facing the sun. Surface dust on the solar panels and high heat reduce the overall efficiency.

Generating electricity by sunlight goes back to 1839 when Edmond Becquerel (1820–1891) first discovered the photovoltaic effect. It took another century before researchers understood the process on an atomic level, which

works similar to a solid-state device with n-type and p-type silicon bonded together.

Commercial photovoltaic (PV) systems are 10 to 20 percent efficient. Of these, the flexible panels are only in the 10 percent range and the solid panels are about 20 percent efficient. Multi-junction cell technologies are being tested that achieve efficiencies of 40 percent and higher.

At 25°C (77°F), a high quality monocrystalline silicon solar panel produces about 0.60V open circuit (OCV). Like batteries, solar cells can be connected in series and parallel to get higher voltages and currents. The surface temperature in full sunlight will likely rise to 45°C (113°F) and higher, reducing the open circuit voltage to 0.55 V per cell due to lower efficiency. Solar cells become more efficient at low temperatures, but caution is necessary when charging batteries below freezing temperatures. The internal resistance of a solar cell is relatively high: with a commercial cell the series resistance is about 1 ohm per square centimeter ($1\Omega\text{cm}^2$).

A solar charging system is not complete without a charge controller. The charge controller takes the energy from the solar panels or wind turbine and converts the voltage so it's suitable for battery charging. The supply voltage for a 12V battery bank is about 16V. This allows charging lead acid to 14.40V (6 x 2.40V/cell) and Li-ion to 12.60 (3 x 4.20V/cell). Note that 2.40V/cell for lead acid and 4.20V/cell for lithium-ion are the full-charge voltage thresholds.

Charge controllers are also available for lithium-ion to charge 10.8V packs (3 cells in series). When acquiring a charge controller, observe the voltage requirements. The standard Li-ion family has a nominal voltage of 3.6V/cell; lithium iron phosphate is 3.30V/cell. Only connect the correct batteries for which the charge controller is designed. Do not connect a lead acid battery to a charge controller designed for Li-ion and vice versa. This could compromise the

charge controller designed for Li-ion and vice-versa. This could compromise the safety and longevity of the batteries as the charge algorithms and voltage settings are different.

A lower-cost charge controller only produces an output voltage when

sufficient light is available. With a diminishing light source, the charge controller simply turns off and resumes when sufficient levels of light are restored. Most of these devices cannot utilize fringe power present at dawn and dusk and this limits them to applications with ideal lighting conditions.

An advanced charge controller tracks power by measuring the voltage and adjusting the current to get maximum power transfer with prevailing light conditions. This is made possible with *maximum power point tracking (MPPT)*. Figure 4-21 illustrates the voltage and current source from a solar cell with varying sunlight. Optimal power is available at the voltage knee where the dropping voltage line meets the vertical power line. MPPT determines this point.

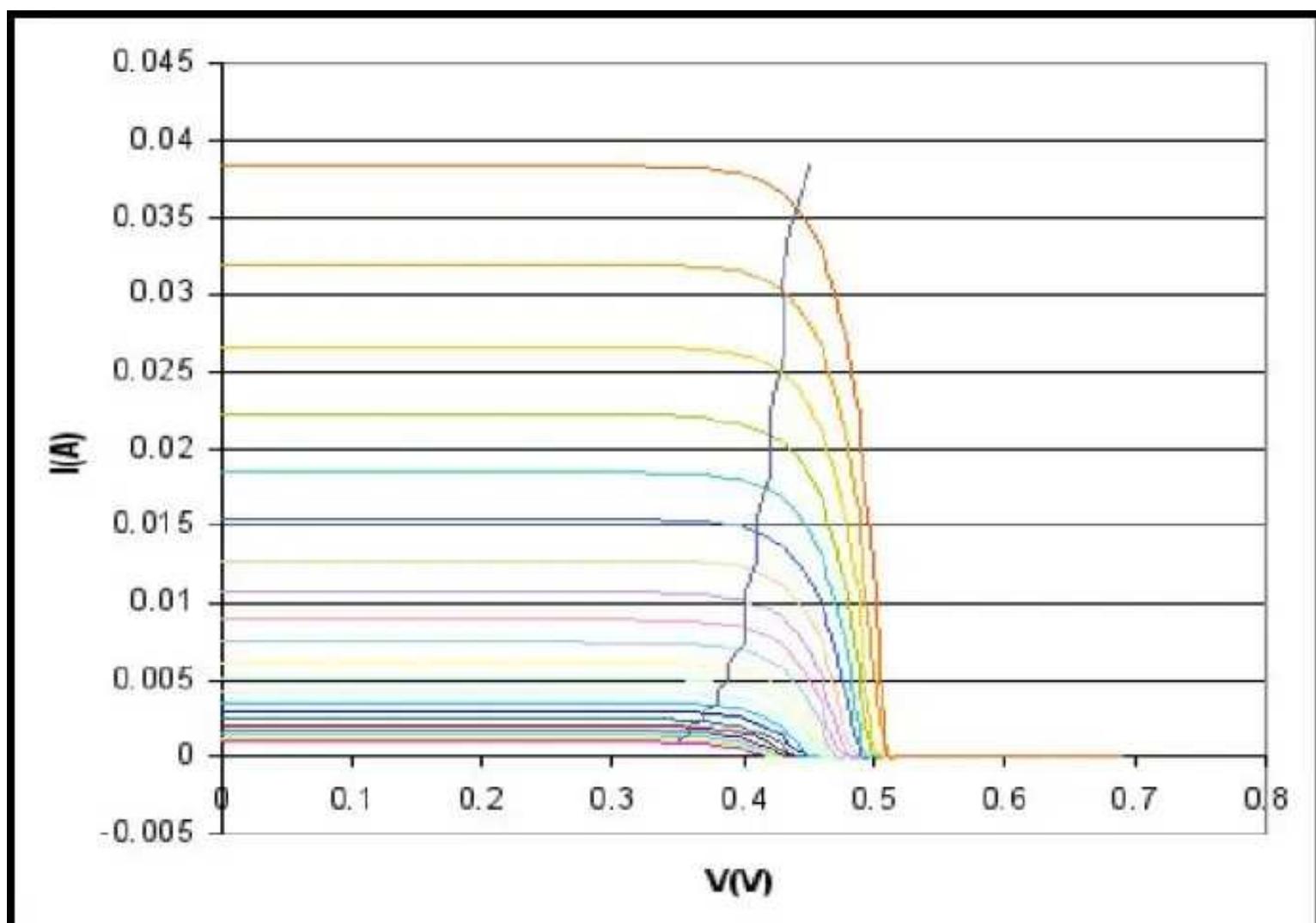


Figure 4-21: Voltage and current from a solar cell at varying sunlight levels.

MPPT finds the best power point which is at the crossing point of the vertical power line. ($V \times A = W$). The top horizontal line gets the most light.

Wind turbines have a lower internal resistance than PV and the MPPT differs.

It should be noted that not all MPPT circuits function equally well. Some are coarse and do not respond immediately to light changes, causing the output to fall or turn off if a shadow falls on the panel. Other systems drop off too early and do not fully utilize low light conditions.

A common MPPT method is *perturb and observe (P&O)*. The circuit increases the voltage by a small amount and measures power. If the power increases by the equal amount, further voltage increases are applied until the optimal setting is reached. P&O achieves good efficiency but it can be sluggish and result in oscillations.

Another method is incremental conductance that computes the maximum power point by comparing current and voltage deltas. This requires more computation but has an improved tracking ability over P&O. *Current sweep* is a method that observes the current and voltage characteristics of the PV array to calculate the maximum power point.

Solar panels are normally connected in series, each providing about 20V on a sunny day. The controller reads the overall string voltage but if one panel gets shaded, the MPPT loses effectiveness. Advanced systems process each panel or group of panels individually. This allows voltage tracking of shaded panels down to 5V. The negative is higher system costs.

You may ask, “Why can I not simply plug a 12V solar panel directly into my laptop or mobile phone?” This should work in principle but is not recommended. The charge controller transforms the incoming DC voltage from the solar panel or wind turbine to the correct voltage range. In bright sunlight, the voltage of a 12V solar panel can go up to 40V, and this could damage your device.

From 1998 to 2011, the price of commercial photovoltaic systems dropped

by 5–7 percent annually and analysis suggests that the price-drop will continue.

It now costs between US\$4 and \$5 per watt for a typical residential solar installation capable of delivering 5kW. Larger installations cost \$3 to \$4 per watt with further reductions for megawatt systems.

Maintenance Charger

A maintenance charger is usually powered by a small solar cell that provides a trickle charge to a battery on a sunny day. These devices help prevent sulfation of a lead acid battery when stored. Even a small float charge will keep the battery at full charge.

Choose a maintenance charger that switches to a controlled float charge when the battery is fully charged. A prolonged charge, even at a low current, could overcharge the battery and promote internal corrosion. A float charge that is correctly adjusted only replenishes what the battery loses through self-discharge.

How to Store Renewable Energy in a Battery

Economists predict rapid growth in micro-grid technology using batteries. Environmentally conscious Germany, Japan and other countries have made use of solar panels for many years to reduce energy costs. In parts of Africa where the AC grid is not sufficiently developed to support all household activities, solar panels with battery backup are mandatory.

Personal energy production is moving to the US Sunbelt; cheaper solar panels and longer-lasting batteries make this attractive. Batteries store energy during peak production when output is in over-supply to bridge the gap when free energy goes to rest at night or when the wind stops. Batteries will moderate peak consumption when the AC grid is stressed to the breaking point.

Renewable energy makes economic sense, but it is expensive. Most of the Western World is served with cheap and reliable electricity from the AC grid with a per kilowatt-hour cost as low as US \$0.06 in parts of Canada, to \$0.15 in many cities and up to \$0.40 in some European countries. Electricity produced by a solar panel comes in at about \$0.20 per kWh. When including peripheral

a solar panel comes in at about \$0.20 per kWh. When including peripheral expenses, solar power in most parts of the world is more expensive than buying electricity from the utilities, and as a rough guideline, stored energy doubles the price.

In spite of the apparent higher cost, putting solar panels on houses is becoming fashionable. Hardware prices are falling and so is the installation. The most common photovoltaic solar cells are the crystalline silicon type with an efficiency of about 20 percent. Flexible panels for portable use, in comparison, have an efficiency of only about 10 percent. The hardware cost to generate 1 watt of electricity with solid panels is \$2.00–2.50, with costs trending lower.

In solar-rich countries where electricity is expensive, energy from solar panels is being fed back to the AC grid. This causes the electrical meter to spin backwards, offsetting previously consumed energy, but it can also induce a problem. The amount of power generated cannot exceed consumption. Dumping more energy into the grid than consumed makes the system unstable, resulting in voltage fluctuations that can overload the circuit and lead to brownouts.

Renewable energy has friends and foes in high places. On one side, governments hand out subsidies to install renewable energy systems, while on the other side utilities try desperately to stem the move of home electricity generation by reducing incentives and adding fees. The utilities argue that spurious energy production by homeowners complicates control and cuts into the revenue stream. They see it as creating glut and famine by means of excess supply during times of plenty and famine when demand is high but renewable contributions are not available.

The conflict is understandable because utility companies are responsible for providing stable energy at all times while independent producers are unable to reduce the concern of pending failure caused by an aging grid that moans during peak demand. Right or wrong, producing clean energy from a renewable resource should never be curtailed, especially if the resource can be stored, and solar companies are fighting back through regulators, lawmakers and the courts.

Storage batteries have mostly been lead acid, and users complain about their short life span. This is in part caused by excessive cycling as the battery charges during the day and discharges at night. Lead acid has a limited cycle count and suffers from sulfation when not periodically fully charged. A fully

saturated charge takes 16 hours, and no solar system can deliver energy for this long. In addition, electrical consumption tends to increase with time while the solar panels reduce their output due to dirt buildup and aging. This often leaves lead acid with insufficient charge.

The switch to Li-ion solves this in part. Li-ion is more resistant to cycling than lead acid and does not need to be fully charged; in fact a partial charge is better as it relieves stress. But Li-ion is still double or three times the cost of lead acid in terms of system purchase.

The Tesla Powerwall offers a 7kWh and a 10kWh battery, enough energy to keep a home lit for several hours. Both packs have the same number of cells; the 7kWh battery uses the robust NMC that is used in many industrial applications while the 10kWh makes use of the NCA that powers the Tesla S-models. NCA offers high energy density and short charge time, while the NMC delivers a high cycle count at a lower capacity.

Both the NCA and NMC are Energy Cells that dislike heavy loads. The power of the Powerwall is limited to 2kW. This is sufficient to run a fridge, brown toast and perhaps iron a shirt, but the wattage is too low to cook a meal on an electric stove, run an electric dryer or keep the air conditioner going; high-energy appliances consume more than 2kW. To fill the gap, the AC grid kicks in seamlessly during peak household activity. A 10kWh battery with 2kW peak power cannot disconnect a household from the grid, but it reduces the electrical bill by one third to one half.

To fully charge a 10kWh battery during 5 hours of optimal sunshine requires a solar system that delivers 5–12kW. At an estimated cost of \$2 per watt, the 10kW solar hardware comes in at \$20,000. Installation and the DC-AC inverter to convert the solar DC to compatible AC power and synchronize it with the grid should add another \$10,000 to the cost.

the grid might double the cost. The battery will be extra also.

Another hidden cost that is often overlooked is end-of-life. Solar panels have a life span of 25 years and batteries are commonly guaranteed for 10 years. At a cost-of-money of 5 percent and a 20 year amortization, a \$25,000 system

could cost the owner \$2,500 per year. The energy savings should be greater than this or else the exercise may be misconstrued. Even larger energy savings can be made by reducing personal transportation or scaling down on the size and power of such a carriage.

Charger Chips

When first introduced in the 1980s, charger chips simplified the design of NiCd and NiMH chargers as batteries with these chemistries were difficult to charge. Li-ion is simpler and most modern charging chips also include the protection circuits that are needed to safe charge Li-ion. These include current and voltage regulation, FET switches and may also contain charge status indicators and cell balancing. Added to most chips is a time-out-timer that halts charge if predictable symptoms do not occur as expected when charging a flawed battery.

Advanced chips also feature *pre-charge conditioning (boost)* to wake up an inactive battery, as well as a *sleep mode* that lowers the housekeeping current of the circuit while the battery is in storage. Some chips also initiate a charge if a parasitic load lowers the battery voltage below a preset threshold while residing in a charger.

Although charger chips are easy and economical to use, they have limitations. Most offer a fixed charge algorithm that does not permit fine-tuning for specialty uses. Chips are made for a given battery and may not accommodate different chemistries as requested by the user or read a battery code that may be embedded in a battery holder. Nor do most chips adjust to an optimal charge current when charging an aging battery with reduced charge acceptance.

Microcontrollers offer an alternative to charger chips. Although the design cost is higher because of the extra programming time needed, manufacturing costs are compatible to charger chips. It should be noted that the charge chip or

costs are compatible to charger chips. It should be noted that the charge chip or the microcontroller only form a small part of the charger circuit; the bulk of the cost lies in the peripheral components, which include solid-state switches, signal lights and the power supply. The parts cost is directly related to wattage.

Factory-configured charger modules are available that are set to the correct voltage, current and algorithm. Some have seamless DC-DC conversion to allow charging a battery with a higher voltage than the input provides. Options include SMBus, solar charging, discharge for calibration and display. Using soft-programmable charger modules resembles the ready-made AC power supplies that became popular in the 1990s as a lower-cost alternative to building one's own charger for each application.

How to Charge – When to Charge Table

Early batteries were reserved for commercial use only, such as telecommunications, signaling, portable lighting and war activities. Today, batteries have become a steady travel companion of the public at large to reach a friend; they allow working outside the confines of four walls, provide entertainment when time permits and enable personal transportation. Best of all, batteries help in missions when people are in need.

Folks are eager to learn more about this wonderful energy device and one of the most common questions asked is, “What can I do to prolong the life of my battery?” Table 4-22 addresses how to care for your batteries to meet their needs. Because of similarities within the different battery families, the table addresses the needs and wants of only the most common systems by keeping in mind that these desires extend to almost all batteries in use.

- **Keep a battery at a moderate temperature.** As food stays fresher when refrigerated, so also does cool temperature protect the battery by reducing internal corrosion, also known as parasitic reactions on the electrolyte and electrodes.
- **Avoid deep cycling.** Each cycle wears the battery down by a small amount and a partial discharge is better than a full discharge. When

amount and a partial discharge is better than a full discharge. When possible, only apply a full discharge to calibrate a smart battery and to prevent “memory” on nickel-based batteries. Li-ion is maintenance-free and the battery lasts longest when operating between 30 and 80 percent SoC.

- **Avoid abuse.** Like a machine that wears down quicker under strenuous work, so also is a battery stressed by harsh discharges and rapid charges. Use cells that are optimized for the power and energy requirements as per application and increase that pack size to minimize load-related stresses.
- **Avoid ultra-fast charge.** Charge Li-ion Energy Cells at less than 1C (below rated Ah); Power Cells are more rugged and can be charged and discharged at a higher rate. NiCd is the only battery that can be fast charged up to 70 percent SoC without adverse side-effects.
- **Store Li-ion at partial charge in a cool place.** The worst combination is high voltage and elevated temperature. Store Li-ion at approximately 50 percent SoC.

Frequently asked question	Lead acid (Sealed, flooded)	Nickel-based (NiCd and NiMH)	Lithium-ion (Li-ion, polymer)
How should I prepare a new battery?	Battery comes fully charged. Apply topping charge every 6 months	Charge 14–16h. Priming may be needed to format	Apply a topping before use. No priming needed
Can I damage a battery with incorrect use?	Yes, do not store partially charged, keep fully charged	Battery is robust and the performance will improve with use	Keep partially charged. Low charge can turn off protection circuit
Do I need to apply a full charge?	Yes, partial charge causes sulfation	Partial charge is fine	Partial charge better than a full charge
Can I disrupt the charge cycle?	Yes, partial charge causes no harm	Repeat charges can cause heat buildup	Partial charge causes no harm
Should I use up all battery energy before charging?	No, deep discharge wears battery down. Charge more often	Apply scheduled discharges only to prevent memory	Deep discharge wears the battery down
Do I have to worry about "memory"?	No memory	Discharge every 1–3 months	No memory
How do I calibrate a "smart" battery?	Not applicable	Apply discharge/charge when the fuel gauge gets inaccurate. Repeat every 1–3 months	
Can I charge with the device on?	Avoid load if possible	Parasitic load can alter full-charge detection and overcharge battery or induce mini-cycles	
Do I remove the battery when full?	Charger switches to float charge	Remove after a few days in charger	Not necessary; charger turns off
How do I store my battery?	Keep cells above 2.10V; charge every 6 months	Store in cool place; can be stored fully discharged	Store in cool place partially charged
Does the battery heat up on charge?	Lukewarm towards end of charge	Warm but must cool down when ready	Must stay cool or slightly warm
How do I charge when cold?	Slow charge (0.1): 0–45°C (32–113°F) Fast charge (0.5–1C): 5–45°C (41–113°F)	Do not charge below freezing	
Can I charge at hot temperatures?	Lower threshold by 3mV/°C above 25°C	Battery will not fully charge when hot	Do not charge above 50°C (122°F)
What should I know about chargers?	Float charging at 2.25–2.30V/cell when ready	Should include temp sensor	Battery must stay cool; no trickle charge

Table 4-22: Best charging methods. Strenuous demands cannot always be prevented.

Chapter 5 | Discharge Methods

Basics About Discharging

The purpose of a battery is to store energy and release it at a desired time. This section examines discharging under different C-rates and evaluates the depth of discharge to which a battery can safely go. Chapter 5 also observes different discharge signatures and explores battery life under diverse loading patterns.

The electrochemical battery has the advantage over other energy storage devices in that the energy stays high during most of the charge and then drops rapidly as the charge depletes. The supercapacitor has a linear discharge, and compressed air and a flywheel storage device is the inverse of the battery by delivering the highest power at the beginning. Figures 5-1, 5-2 and 5-3 illustrate the simulated discharge characteristics of stored energy.

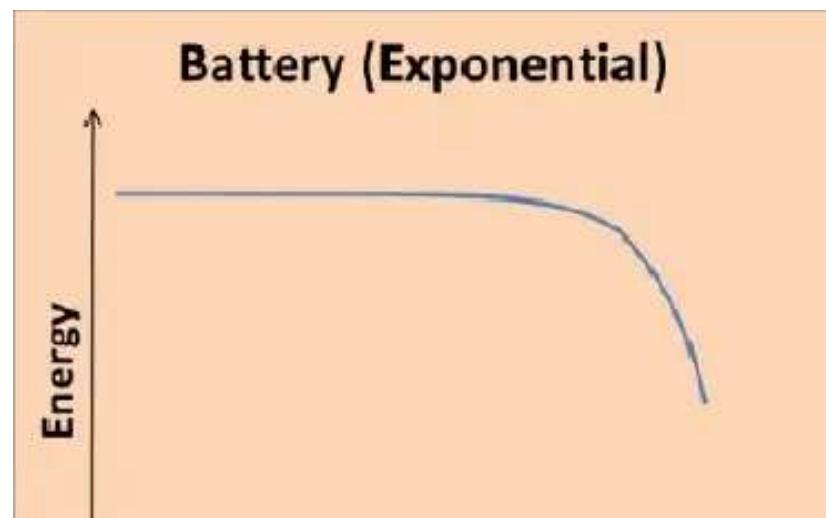




Figure 5-1: Discharge curve of battery. Energy storage stays high to the end; good utilization.

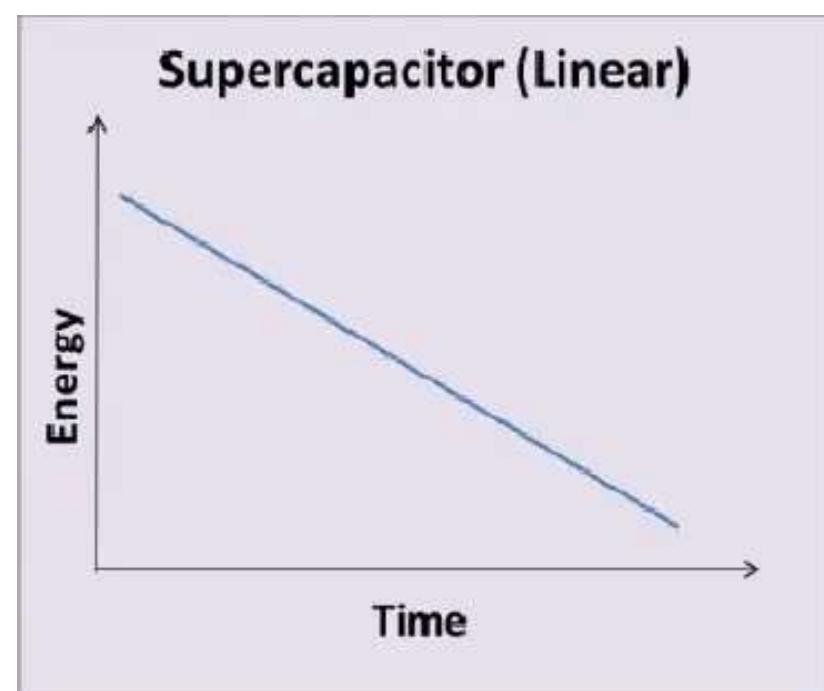


Figure 5-2: Discharge curve of supercapacitor. Linear discharge prevents the full use of energy.

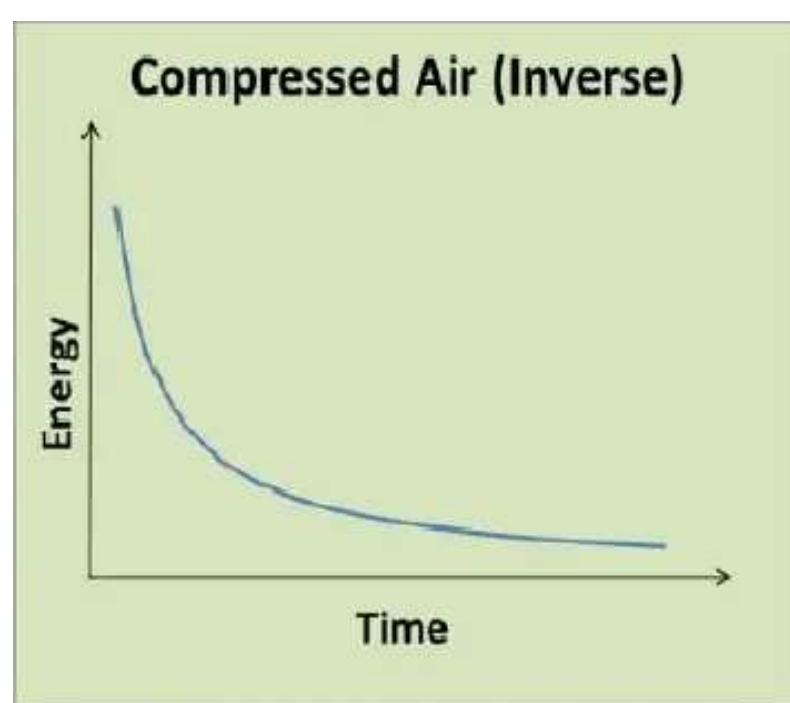


Figure 5-3: Discharge curve of compressed air. Inverse. Best performance at beginning.

Most rechargeable batteries can be overloaded briefly, but this must be kept short. Battery longevity is directly related to the level and duration of the stress inflicted, which includes charge, discharge and temperature.

Remote control (RC) hobbyists are a special breed of battery users who stretch tolerance of “frail” high-performance batteries to the maximum by discharging them at a C-rate of 30C, 30 times the rated capacity. As thrilling as an RC helicopter, race car and fast boat can be; the life expectancy of the packs

will be short. RC buffs are well aware of the compromise and are willing both to pay the price and to encounter added safety risks.

To get maximum energy per weight, drone manufacturers gravitate to cells with a high capacity and choose the Energy Cell. This is in contrast to industries requiring heavy loads and long service life. These applications go for the more robust Power Cell at a reduced capacity.

Depth of Discharge

Lead acid discharges to 1.75V/cell; nickel-based system to 1.0V/cell; and most Li-ion to 3.0V/cell. At this level, roughly 95 percent of the energy is spent, and the voltage would drop rapidly if the discharge were to continue. To protect the battery from over-discharging, most devices prevent operation beyond the specified end-of-discharge voltage.

When removing the load after discharge, the voltage of a healthy battery gradually recovers and rises towards the nominal voltage. Differences in the affinity of metals in the electrodes produce this voltage potential even when the battery is empty. A parasitic load or high self-discharge prevents voltage recovery.

A high load current, as would be the case when drilling through concrete with a power tool, lowers the battery voltage and the end-of-discharge voltage threshold is often set lower to prevent premature cutoff. The cutoff voltage should also be lowered when discharging at very cold temperatures, as the battery voltage drops and the internal battery resistance rises. Table 5-4 shows typical end-of-discharge voltages of various battery chemistries.

End-of-discharge Nominal	Li-manganese 3.2V/cell	Li-phosphate 3.2V/cell	Lead acid 2.0V/cell	NiCd/NiMH 1.2V/cell
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Nominal	3.6V/cell	3.2V/cell	2.0V/cell	1.2V/cell
Normal load	3.0–3.3V/cell	2.7V/cell	1.75V/cell	1.0V/cell
Heavy load or low temperature	2.7V/cell	2.45V/cell	1.4V/cell	0.90V/cell

Table 5-4: Nominal and recommended end-of-discharge voltages under normal and heavy load.

The lower end-of-discharge voltage on a high load compensates for the greater losses.

Over-charging a lead acid battery can produce hydrogen sulfide, a colorless, poisonous and flammable gas that smells like rotten eggs. Hydrogen sulfide also occurs during the breakdown of organic matter in swamps and sewers and is present in volcanic gases and natural gas. The gas is heavier than air and accumulates at the bottom of poorly ventilated spaces. Strong at first, the sense of smell deadens with time, and victims are unaware of the presence of the gas. (See “Health Concerns with Batteries” on page 198)

What Constitutes a Discharge Cycle?

A discharge/charge cycle is commonly understood as the full discharge of a charged battery with subsequent recharge, but this is not always the case. Batteries are seldom fully discharged, and manufacturers often use the 80 percent depth-of-discharge (DoD) formula to rate a battery. This means that only 80 percent of the available energy is delivered and 20 percent remains in reserve. Cycling a battery at less than full discharge increases service life, and manufacturers argue that this is closer to a field representation than a full cycle because batteries are commonly recharged with some spare capacity left.

There is no standard definition as to what constitutes a discharge cycle.

Some cycle counters add a full count when a battery is charged. A smart battery may require a 15 percent discharge after charge to qualify for a discharge cycle; anything less is not counted as a cycle. A battery in a satellite has a typical DoD of 30–40 percent before the batteries are recharged during the satellite day. A new EV battery may only charge to 80 percent and discharge to 30 percent. This bandwidth gradually widens as the battery fades to provide identical driving distances. Avoiding full charges and discharges reduces battery stress.

A hybrid car only uses a fraction of the capacity during acceleration before the battery is recharged. Cranking the motor of a vehicle draws less than 5 percent energy from the starter battery, and this is also called a cycle in the automotive industry. Reference to cycle count must be done in context with the respective duty.

Discharging at High and Low Temperatures

Like humans, batteries function best at room temperature. Warming a dying battery in a mobile phone or flashlight in our jeans might provide additional runtime due to improved electrochemical reaction. This is likely also the reason why manufacturers prefer to specify batteries at a toasty 27°C (80°F). Operating a battery at elevated temperatures improves performance but prolonged exposure will shorten life.

As all drivers in cold countries know, a warm battery cranks the car engine better than a cold one. Cold temperature increases the internal resistance and lowers the capacity. A battery that provides 100 percent capacity at 27°C (80°F) will typically deliver only 50 percent at –18°C (0°F). The momentary capacity-decrease differs with battery chemistry.

The dry solid polymer battery requires a temperature of 60–100°C (140–212°F) to promote ion flow and become conductive. This type of battery has found a niche market for stationary power applications in hot climates where heat serves as a catalyst rather than a disadvantage. Built-in heating elements keep the battery operational at all times. High battery cost and safety concerns have limited the application of this system. The more common lithium-polymer uses gelled electrolyte to enhance conductivity.

All batteries achieve optimum service life if used at 20°C (68°F) or slightly below. If, for example, a battery operates at 30°C (86°F) instead of a more moderate lower room temperature, the cycle life is reduced by 20 percent. At 40°C (104°F), the loss jumps to a whopping 40 percent, and if charged and discharged at 45°C (113°F), the cycle life is only half of what can be expected if

used at 20°C (68°F). (See “How to Prolong Lithium-based Batteries” on page 249.)

The performance of all batteries drops drastically at low temperatures; however, the elevated internal resistance will cause some warming effect

because of efficiency loss during use. At –20°C (–4°F) most batteries stop functioning. Although NiCd can go down to –40°C (–40°F), the permissible discharge is only 0.2C (5-hour rate). Specialty Li-ion can operate to a temperature of –40°C but only at a reduced discharge rate; charging at this temperature is out of the question. With lead acid there is the danger of the electrolyte freezing, which can crack the enclosure. Lead acid freezes quicker with a low charge when the specific gravity is more like water than when fully charged.

Matched cells with identical capacities play an important role when discharging at low temperature and under heavy load. Since the cells in a battery pack can never be perfectly matched, a negative voltage potential can occur across a weaker cell in a multi-cell pack if the discharge is allowed to continue beyond a safe cutoff point. Known as cell reversal, the weak cell gets stressed to the point of developing a permanent electrical short. The larger the cell-count, the greater is the likelihood of cell-reversal under load. Over-discharge at a low temperature and heavy load is a large contributor to battery failure of cordless power tools. (See “Cell Matching and Balancing” on page 231.)

The driving range of an electric vehicle between charges is calculated at ambient temperature. EV drivers are being made aware that frigid temperature reduces the available mileage. This loss is not only caused by heating the cabin electrically but by the inherent slowing of the battery’s electrochemical reaction, which reduces the capacity while cold.

Discharge Characteristics of Li-ion

The early Li-ion battery was considered fragile and unsuitable for high loads. This has changed, and today lithium-based systems stand shoulder to shoulder with very robust nickel and lead chemistries. Two basic types of Li-ion have

with very robust nickel and lead chemistries. Two basic types of Li-ion have emerged: The Energy Cell and the Power Cell.

Energy Cell

The Li-ion Energy Cell is made for maximum capacity to provide long runtimes. The Panasonic NCR18650B Energy Cell (Figure 5-5) has high capacity but is

less enduring when discharged at 2C. At the discharge cutoff of 3.0V/cell, the 2C discharge produces only about 2.3Ah rather than the specified 3.2Ah. This cell is ideal for portable computing and similar light duties.

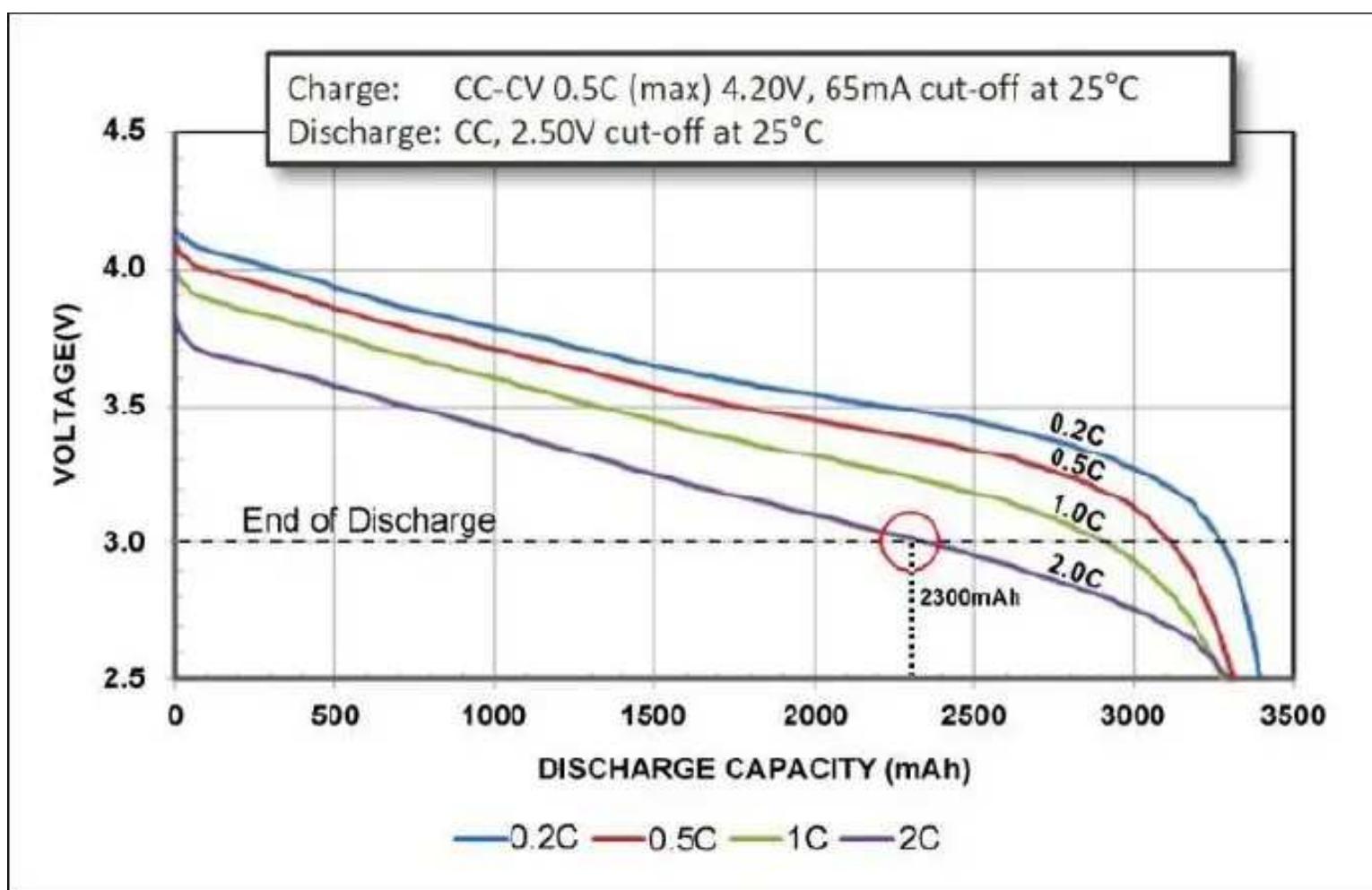


Figure 5-5: Discharge characteristics of NCR18650B Energy Cell by Panasonic.

The 3.200mAh Energy Cell is discharged at 0.2C, 0.5C, 1C and 2C. The circle at the 3.0V/cell line marks the end-of-discharge point at 2C.

Cold temperature losses:

25°C (77°F) = 100%

0°C (32°F) = ~83%

-10°C (14°F) = ~66%

-20°C (4°F) = ~53%

Source: Panasonic

Power Cell

The Panasonic UR18650RX Power Cell (Figure 5-6) has a moderate capacity but excellent load capabilities. A 10A (5C) discharge has minimal capacity loss at the 3.0V cutoff voltage. This cell works well for applications requiring heavy load current, such as power tools.

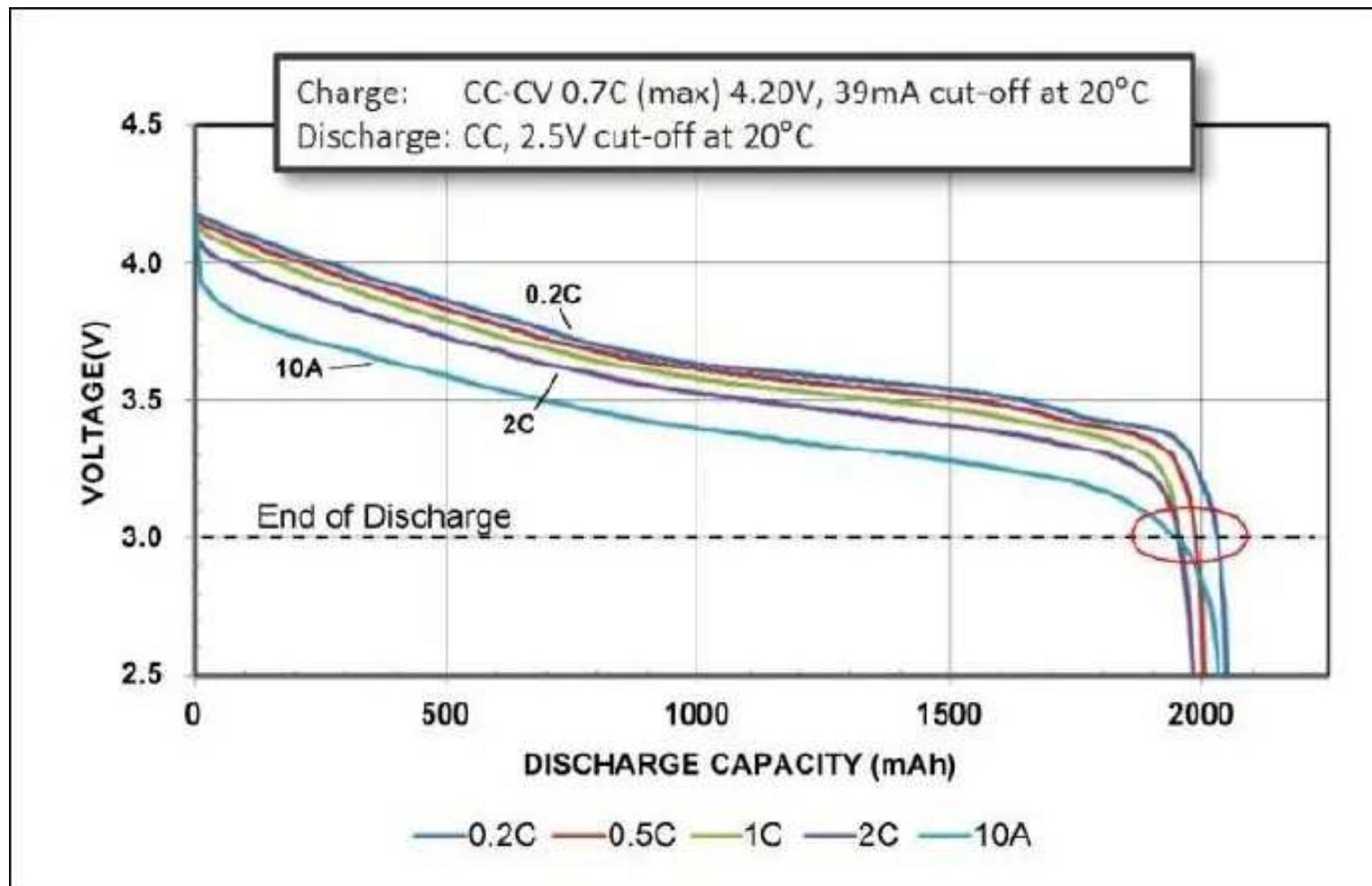


Figure 5-6: Discharge characteristics of UR18650RX Power Cell by Panasonic.

The 1950mAh Power Cell is discharged at 0.2C, 0.5C, 1C and 2C and 10A. All reach the 3.0V/cell cut-off line at about 2000mAh. The Power Cell has a moderate capacity but delivers high current.

Cold temperature losses:

25°C (77°F) = 100%

0°C (32°F) = ~92%

-10°C (14°F) = ~85%

-20°C (4°F) = ~80%

Source: Panasonic

The Power Cell permits a continuous discharge of 10C. This means that an 18650 cell rated at 2,000mAh can provide a continuous load of 20A (30A with Li-phosphate). The superior performance is achieved in part by lowering the internal resistance and by optimizing the surface area of active cell materials.

Low resistance enables high current flow with minimal temperature rise. Running at the maximum permissible discharge current, the Li-ion Power Cell heats to about 50°C (122°F); the temperature is limited to 60°C (140°F).

To meet the loading requirements, the pack designer can either use a Power

Cell to meet the discharge C-rate requirement or go for the Energy Cell and oversize the pack. The Energy Cell holds about 50 percent more capacity than the Power Cell, but the loading must be reduced. This can be done by oversizing the pack, a method the Tesla EVs use. The battery achieves exceptional runtime but it gets expensive and heavy.

Discharge Signature

One of the unique qualities of nickel- and lithium-based batteries is the ability to deliver continuous high power until the battery is exhausted; a fast electrochemical recovery makes it possible. Lead acid is slower and this can be compared to a drying felt pen that works for short markings on paper and then needs rest to replenish the ink. While the recovery is relatively fast on discharge, and this can be seen when cranking the engine, the slow chemical reaction becomes obvious when charging. This only gets worse with age.

A battery may discharge at a steady load of, say, 0.2C as in a flashlight, but many applications demand momentary loads at double and triple the battery's C-rating. GSM (Global System for Mobile Communications) for a mobile phone is such an example (Figure 5-7). GSM loads the battery with up to 2A at a pulse rate of 577 micro-seconds (μ s). This places a large demand on a small battery; however, with a high frequency, the battery begins to behave more like a large capacitor and the battery characteristics change.

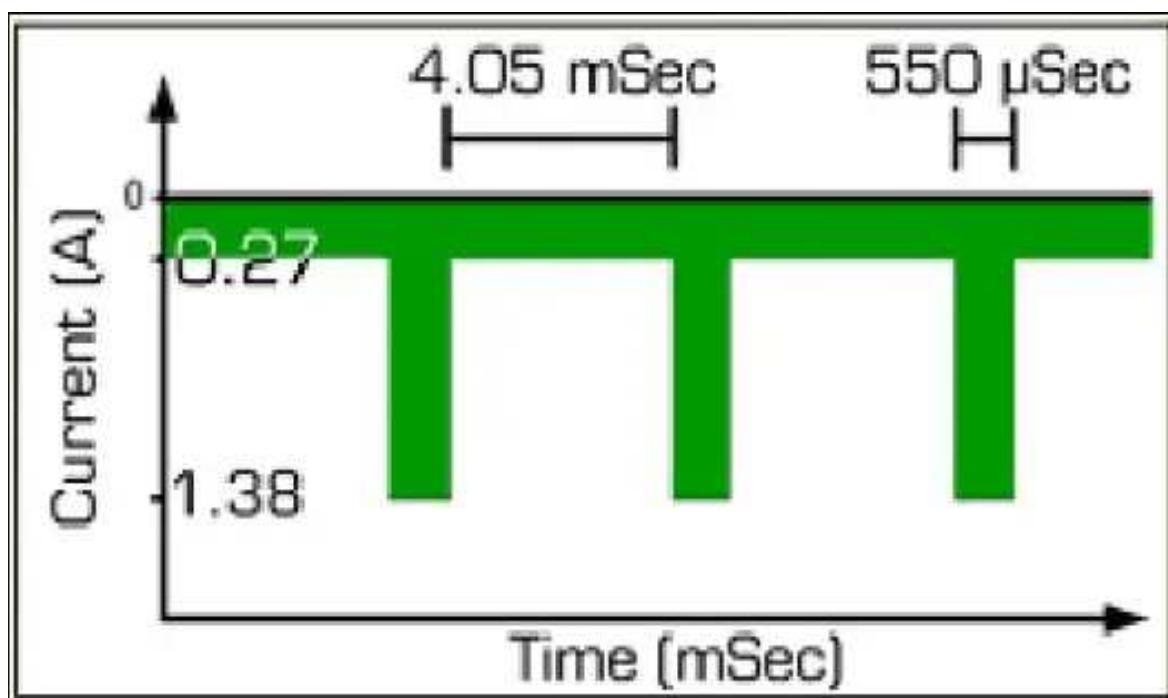


Figure 5-7: GSM discharge pulses of a cellular phone.

The 577 microsecond pulses drawn from the battery adjust to field strength and can reach 2 amperes.
Courtesy of Cadex

In terms of longevity, a battery prefers moderate current at a constant discharge rather than a pulsed or momentary high load. Figure 5-8 demonstrates the decreasing capacity of a NiMH battery at different load conditions from a gentle 0.2C DC discharge, an analog discharge to a pulsed discharge. Most batteries follow a similar pattern in terms of load conditions, including Li-ion.

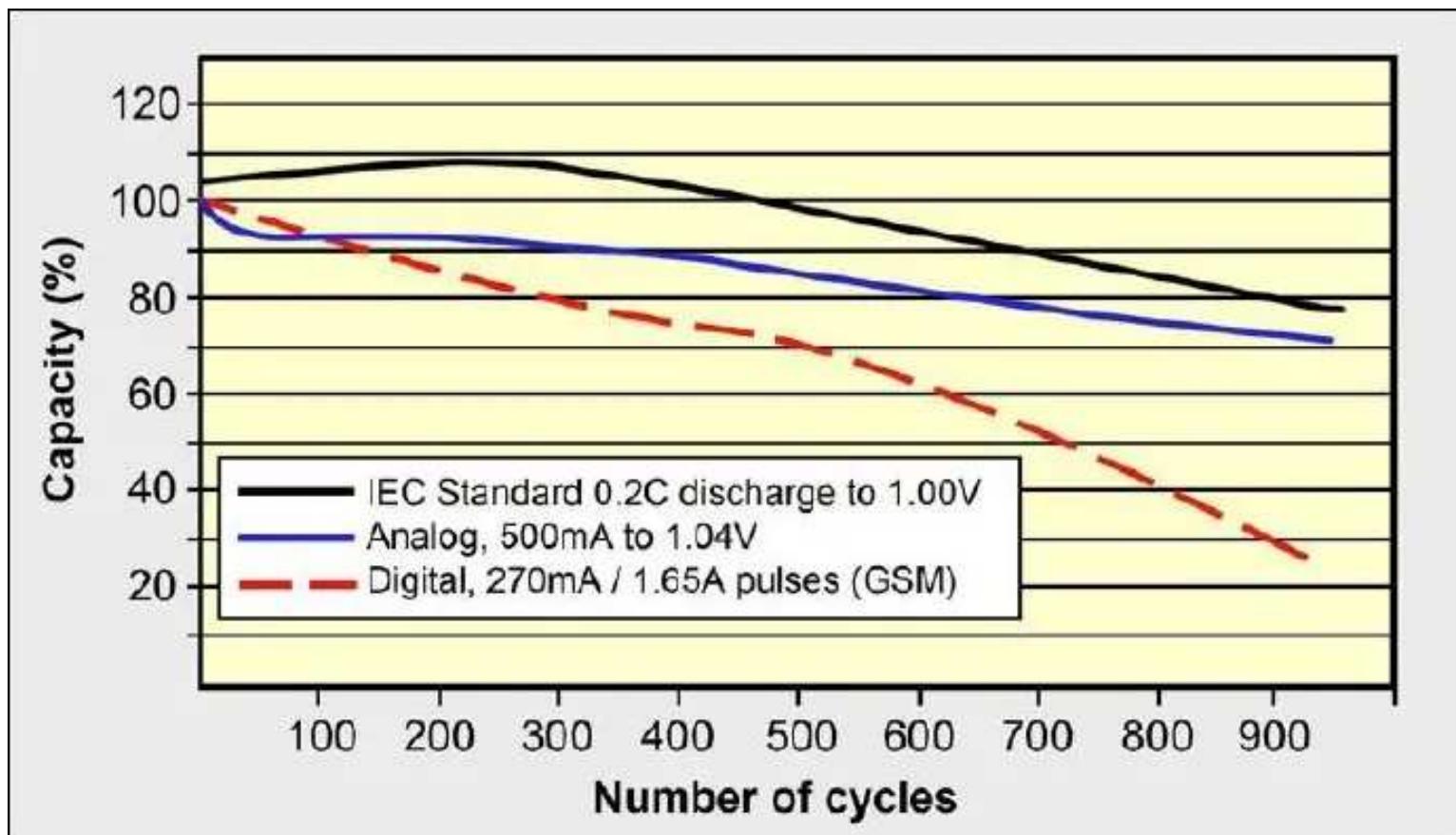


Figure 5-8: Cycle life of NiMH under different load conditions.

NiMH performs best with DC and analog loads; digital loads lower the cycle life. Li-ion behaves similarly.

Source: Zhang (1998)

Figure 5-9 examines the number of full cycles a Li-ion Energy Cell can endure when discharged at different C-rates. At a 2C discharge, the battery exhibits far higher stress than at 1C, limiting the cycle count to about 450 before the capacity drops to half the level.

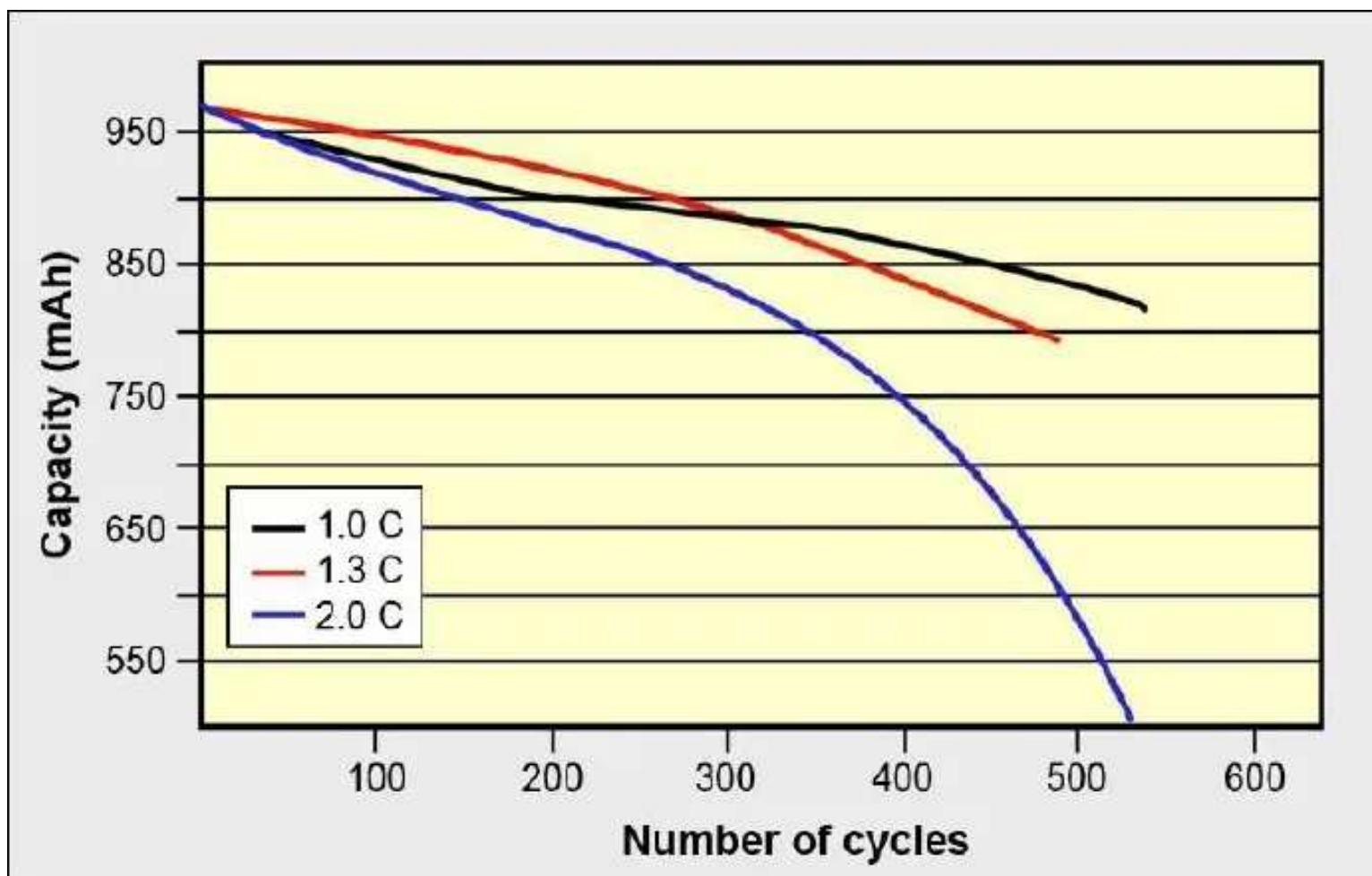


Figure 5-9: Cycle life of Li-ion Energy Cell at varying discharge levels.

The wear and tear of all batteries increases with higher loads. Power Cells are more robust than Energy Cells.

Source: Choi et al (2002)

How to Calculate Battery Runtime

If the battery was a perfect power source and behaved linearly, charge and discharge times could be calculated according to in-and-out flowing currents, also known as coulombic efficiency. (See “Coulombic Efficiency” on page 255.) What is put in should be available as output in the same amount; a 1-hour charge at 5A should deliver a 1-hour discharge at 5A, or a 5-hour discharge at 1A. This is not possible because of intrinsic losses and the coulombic efficiency is always less than 100 percent. The losses escalate with increasing load, as high discharge

currents make the battery less efficient.

Peukert Law

The *Peukert Law* expresses the efficiency factor of a battery on discharge. W. Peukert, a German scientist (1855–1932), was aware that the available capacity

of a battery decreases with increasing discharge rate and he devised a formula to calculate the losses in numbers. The law is applied mostly to lead acid to help estimate the runtime under different discharge loads.

The Peukert Law takes into account the internal resistance and recovery rate of a battery. A value close to one (1) indicates a well-performing battery with good efficiency and minimal loss; a higher number reflects a less efficient battery. Peukert's law is exponential; the readings for lead acid are between 1.3 and 1.5 and increase with age. Temperature also affects the readings. Figure 5-10 illustrates the available capacity as a function of amperes drawn with different Peukert ratings.

As an example, a 100Ah lead acid battery discharged at 15A should theoretically last 6.6 hours (100Ah divided by 15A) but the actual time is less. With a Peukert number of 1.3, the discharge hours are about 4.8 hours.

The lead acid battery prefers intermittent loads to a continuous heavy discharge. The rest periods allow the battery to recompose the chemical reaction and prevent exhaustion. This is why lead acid performs well in a starter application with brief 300A cranking loads and plenty of time to recharge in between. All batteries require recovery, and most other systems provide a faster electrochemical reaction than lead acid.

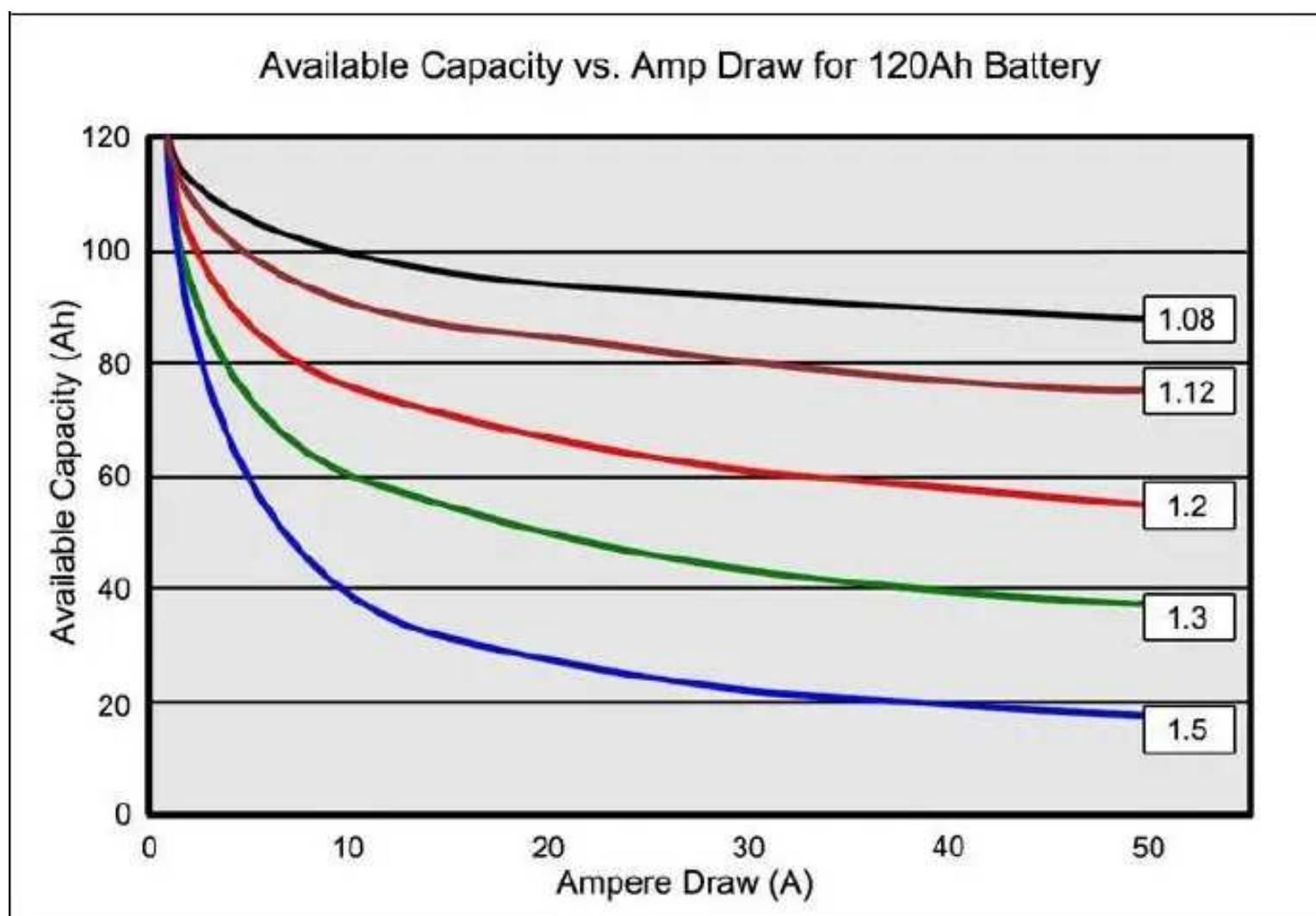


Figure 5-10: Available capacity of a lead acid battery at Peukert numbers of 1.08–1.50.

A value close to 1 has the smallest losses; higher numbers deliver lower capacities.

Peukert values change with battery type age and temperature:

AGM: 1.05–1.15

Gel: 1.10–1.25

Flooded: 1.20–1.60

Source: Von Wentzel (2008)

Ragone Plot

Lithium- and nickel-based batteries are more commonly evaluated by the Ragone plot. The Ragone plot looks at the battery's capacity in watt-hours (Wh) and discharge power in watts (W). The big advantage of the Ragone plot over the Peukert-based graphs is that it can show the performance of different batteries in a single plot.

the Peukert Law is the ability to read the runtime in minutes and hours presented on the diagonal lines on the Ragone graph.

Figure 5-11 illustrates the Ragone plot of four lithium-ion systems using 18650 cells. The horizontal axis displays energy in watt-hours (Wh) and the

vertical axis is power in watts (W). The diagonal lines across the field reveal the length of time the battery cells can deliver energy at given loading conditions. The scale is logarithmic to allow a wide selection of battery sizes. The battery chemistries featured in the chart include lithium-iron phosphate (LFP), lithium-manganese oxide (LMO), and nickel manganese cobalt (NMC).

The Sanyo UR18650F [4] Energy Cell has the highest specific energy and can run a laptop or e-bike for many hours at a moderate load. The Sanyo UR18650W [3] Power Cell, in comparison, has a lower specific energy but can supply a current of 20A. The A123 [1] in LFP has the lowest specific energy but offers the highest power capability by delivering 30A of continuous current. Specific energy defines the battery capacity in weight (Wh/kg); energy density is given in volume (Wh/l).

The Ragone plot helps in the selection of the optimal Li-ion system to satisfy discharge power while retaining the required runtime. If an application calls for a very high discharge current, the 3.3 minute diagonal line on the chart points to the A123 (Battery 1); it can deliver up to 40 watts of power for 3.3 minutes. The Sanyo F (Battery 4) is slightly lower and delivers about 36 watts. By focusing on discharge time and following the 33 minute discharge line further down, Battery 1 (A123) only delivers 5.8 watts for 33 minutes before the energy is depleted. The higher capacity Battery 4 (Sanyo F) can provide roughly 17 watts for the same time; its limitation is lower power.

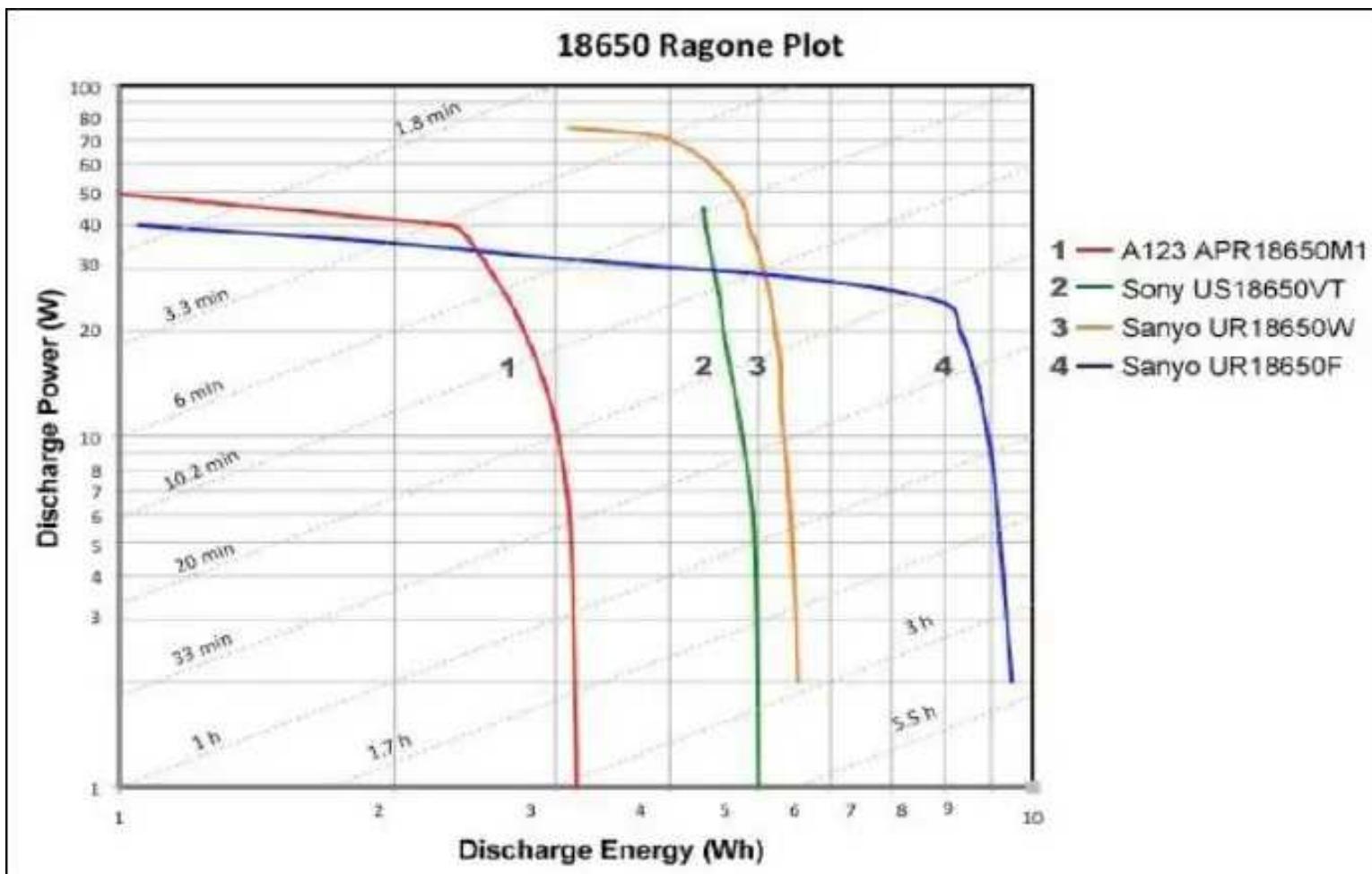


Figure 5-11: Ragone plot reflects Li-ion 18650 cells.

Four Li-ion systems are compared for discharge power and energy as a function of time. Not all curves are fully drawn out.

Source: Exponent Inc.

Legend: The A123 APR18650M1 is a lithium iron phosphate (LiFePO₄) Power Cell rated at 1,100mAh, delivering a continuous discharge current of 30A. The Sony US18650VT and Sanyo UR18650W are manganese based Li-ion Power Cells of 1,500mAh each, delivering a continuous discharge of 20A. The Sanyo UR18650F is a 2,600mAh Energy Cell for a moderate 5A discharge. This cell provides the highest discharge energy but has the lowest discharge power.

A design engineer should note that the Ragone snapshot taken by the battery manufacturers represents a new cell, a condition that is temporary. When calculating power and energy needs, engineers must take into account battery fade caused by cycling and aging. Battery-operated systems must still function

with a battery that will eventually drop to 70 or 80 percent capacity. A further consideration is low temperature as a battery momentarily loses power when cold. The Ragone plot does not take these decreased performance conditions into account.

The design engineer should further develop a battery pack that is durable and does not get stressed during regular use. Stretching load and capacity boundaries to the limit shortens battery life. If repetitive high discharge currents are needed, the pack should be made larger and with the correct choice of cells. An analogy is a truck that is equipped with a large diesel engine instead of a souped-up engine intended for a sports car.

The Ragone plot can also calculate the power requirements of capacitors, flywheels, flow batteries and fuel cells. A conflict develops with the internal combustion engine or the fuel cell that draws fuel from a tank as on-board re-fueling cheats the system. Similar plots are used to find the optimal loading ratio of renewable power sources, such as solar cells and wind turbines.

How to Verify Sufficient Battery Capacity

A battery performs well when new but the capacity soon begins to fade with use and time. To assure reliable service during the life span of the battery, design engineers oversize the pack to include some spare capacity. This is similar to an airplane carrying extra fuel to enable a waiting pattern before landing or to attempt a second landing approach when so required.

New batteries operate (should operate) at a capacity of 100 percent; replacement occurs when the packs fade to about 80 percent. All batteries must include a secure level of spare capacity to cover worst-case scenarios.

In addition to normal capacity fade as part of usage and aging, cold temperature lowers the capacity, especially Li-ion. The capacity loss of a Li-ion Energy Cell is about 17 percent at 0°C (32°F), 34 percent at -10°C (14°F) and 47 percent at -20°C (-4°F). Power Cells perform better at cold temperature; they suffer less cold-related capacity losses than Energy Cells.

Lack of spare capacity is a common cause of system failures. This often happens during heavier than normal traffic or in an emergency. During routine operations, marginal batteries can hide comfortably among their peers but, they will fail when put to the test. A battery maintenance program as part of quality

control assures that all batteries in the fleet are within the required performance range.

Figure 5-12 illustrates the breakdown of a battery that includes capacity fade and spare capacity. Adding 20 percent for fade and 20 percent for spare as a safety net leaves only 60 percent for the actual capacity. Such a generous allowance may not be practical in all cases.



Figure 5-12: Calculating spare battery capacity.

Spare capacity must be calculated for a worst-case scenario. The allowable capacity range is 80–100%; a spare capacity of 20% is recommended for critical use. Allow more capacity reserve when operating at cold temperature.

Courtesy of Cadex

To verify sufficient spare capacity in a battery fleet, identify batteries that are close to retirement and spot-check their capacities after a busy day with a battery analyzer. The Cadex battery analyzer provides this function on the “Prime” program by applying a discharge before charge. The first reading on the display reflects the spare capacity and the second represents the full capacity.

display reflects the spare capacity and the second represents the full capacity after a charge.

If packs with fringe capacity levels come back from a full-day shift with less than 10 percent of spare capacity, raise the pass/fail target capacity from 80 to 85 percent to gain five extra points. If, on the other hand, these old-timers

come back with 30 percent before charging, keep them longer by lowering the target capacity to, say, 70 percent. Knowing the energy needs for each application during a typical shift increases battery transparency. This improves reliability and creates a sweet spot between risk management and economics.

While most batteries are replaced when the capacity fades to 80 percent, scanners in some warehouses can be kept longer because they may not require all available capacity during an 8-hour shift. If this is the case, the target capacity can safely be set to 70 percent while maintaining ample spare capacity. A starter battery in a vehicle still cranks the motor with a capacity of 40 percent. The discharge is short and the battery recharges right away. Allowing the capacity to drop much further might prevent the battery from turning the engine on a cold morning, stranding the driver.

Simple Guidelines for Charging and Discharging Batteries

- Heat increases battery performance but shortens life by a factor of two for every 10°C increase above 25–30°C (18°F above 77–86°F). Always keep the battery cool.
- Operating a battery at cold temperatures does not automatically permit charging under these conditions. Only charge at moderate temperatures.
- Some batteries accept charge below freezing but this must be done at a much-reduced charge current. Check the manufacturer's specifications.
- Use heating blankets if batteries need rapid charging and discharging at cold temperatures.
- Prevent over-discharging. Cell reversal can cause an electrical short.
- On high load and repetitive full discharges, reduce stress by using a larger battery.

- A moderate DC discharge is better for a battery than pulse and heavy momentary loads.
- A battery exhibits capacitor-like characteristics when discharging at high frequency. This allows higher peak currents than is possible with a DC load.

- Nickel-and lithium-based batteries have a fast chemical reaction; lead acid is sluggish and requires a few seconds to recover between heavy loads.
- All batteries suffer stress when stretched to maximum permissible tolerances.

CAUTION In case of rupture, leaking electrolyte or any other cause of exposure to the electrolyte, flush with water immediately. If eye exposure occurs, flush with water for 15 minutes and consult a physician immediately.

Chapter 6 | Smart Battery

Inner Workings of a Smart Battery

A speaker at a battery conference once said, “The battery is a wild animal and artificial intelligence domesticates it.” A battery is illusive and does not exhibit visible changes as part of usage; it looks the same when fully charged or empty, new or old and in need of replacement. A car tire, in comparison, distorts when low on air and indicates end-of-life when the treads are worn.

The shortcomings of a battery can be summarized by these three concerns: [1] The user does not know how much runtime the pack has left; [2] the host is uncertain if the battery can satisfy the power demand; and [3] the charger must be tailored to each battery size and chemistry. The solutions are complex and the “smart” battery promises to lessen some of these deficiencies.

Battery users imagine a battery pack as being an energy storage device that resembles a fuel tank dispensing liquid fuel. For simplicity reasons, a battery can be seen as such; however, measuring stored energy from an electrochemical device is far more complex.

While an ordinary fuel gauge measures in-and-out-flowing liquid from a tank of a known size with minimal losses, a battery fuel gauge has unconfirmed definitions and only reveals the open circuit voltage (OCV), which is a fickle reflection of state of charge (SoC). To compound the problem, a battery is a

reflection of state-of-charge (SoC). To compound the problem, a battery is a leaky and shrinking vessel that loses energy and takes less content with each charge. As the capacity fades, the specified Ah (ampere-hours) rating no longer holds true. Nor can the fuel gauge assess the capacity by itself; the reading always shows full after recharge even if the capacity has dropped to half the

specified Ah.

The simplest method to measure state-of-charge is reading voltage, but this can be inaccurate as load currents pull the voltage down during discharge. The largest challenge is the flat discharge voltage curve on most lithium and nickel-based batteries. Temperature also plays a role; heat raises the voltage and a cold temperature lowers it. Agitation by a previous charge or discharge causes further errors and the battery needs a few hours rest to neutralize.

Most batteries for medical, military and computing devices are “smart.” This means that some level of communication occurs between the battery, the equipment and the user. The definitions of “smart” vary among manufacturers and regulatory authorities, and the most basic smart battery may contain nothing more than a chip that sets the charger to the correct charge algorithm. In the eyes of the Smart Battery System (SBS) forum, these batteries cannot be called smart. The SBS forum states that a smart battery must provide SoC indications.

Safety is a key design objective and the concept behind SBS is to place system intelligence inside the battery pack. The SBS battery thus communicates with the charge management chip in a closed loop. In spite of this digital supervision, most SBS chargers also rely on analog signals from the chemical battery to terminate the charge when the battery is full. Furthermore, redundant temperature sensing is added for safety reasons.

Benchmarq was the first company to offer fuel-gauge technology in 1990. Today, many manufacturers offer integrated circuit (IC) chips in *single-wire* and *two-wire* systems, also known as System Management Bus (SMBus).

State-of-charge estimations in a smart battery commonly include coulomb counting, a theory that goes back 250 years when Charles-Augustin de Coulomb

first established the “Coulomb Rule.” Figure 6-1 illustrates the principle of coulomb counting, measuring in-and-out flowing energy. One coulomb (1C) per second is one ampere (1A). Discharging a battery at 1A for one hour equates to 3,600C. (Not to be confused with C-rate.)

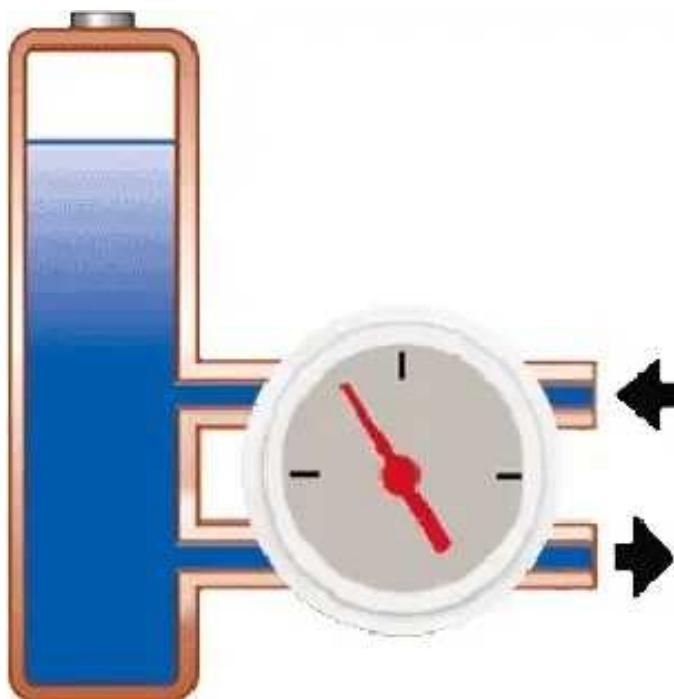


Figure 6-1: Principle of a fuel gauge based on coulomb counting.

A circuit measures the in-and-out flowing energy; the stored energy represents state-of-charge. One coulomb per second is one ampere (1A).

Courtesy of Cadex

Coulomb counting should be flawless but it is not perfect. If, for example, a battery was charged for 1 hour at 1 ampere, the same amount of energy should be available on discharge. No battery can do this. Inefficiencies in charge acceptance, especially towards the end of charge, and particularly if fast-charged, reduces energy efficiency. Losses also occur in storage and during discharge. The available energy is always less than what has been fed into the battery.

Single-wire Bus

The single-wire system, also known as 1-Wire, communicates through one wire at low speed. Designed by Dallas Semiconductor Corp., the 1-Wire combines data and clock into one line for transmission; the Manchester code, also known

as phase coding, separates the data at the receiving end. For safety reasons, most batteries also run a separate wire for temperature sensing. Figure 6-2 shows the layout of a single-wire system.

The single-wire system stores the battery code and tracks battery data that typically includes voltage, current, temperature and state-of-charge information.

Because of the relatively low hardware cost, the single-wire system is attractive for price-sensitive devices such as measuring instruments, mobile phones, two-way radios, cameras and scanners.

Most single-wire systems have their own protocol and use a customized charger. The Benchmarq single-wire solution, for example, cannot measure the current directly; state-of-health (SoH) measurement is only possible when “marrying” the host to a designated battery.

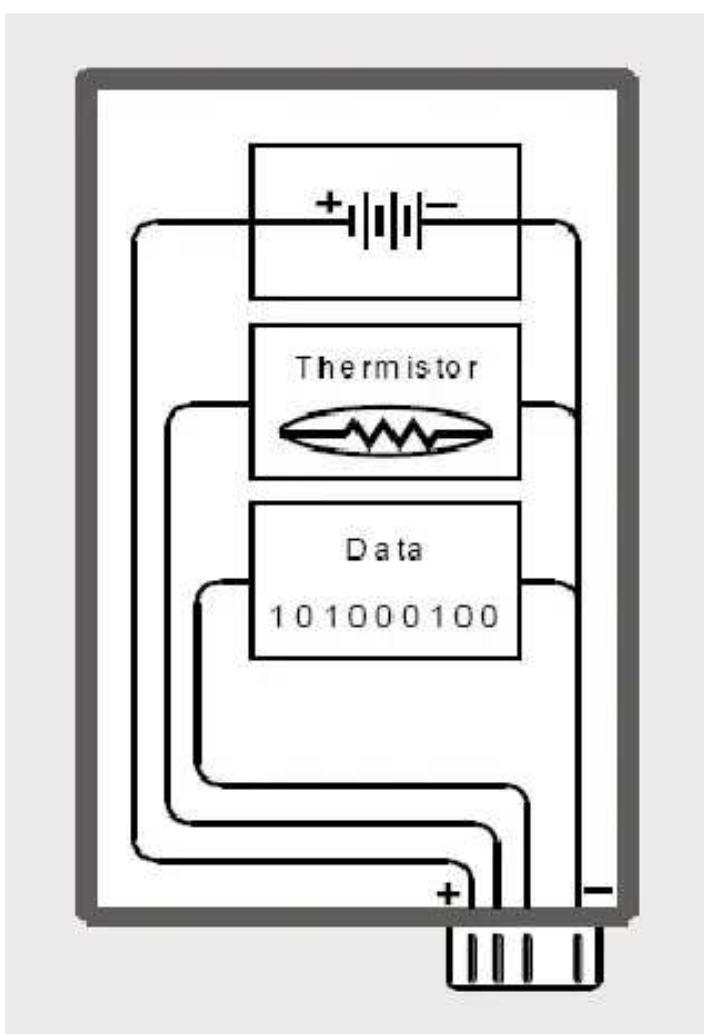


Figure 6-2: Single-wire system of a “smart” battery.

A single wire provides data communication. For safety reasons, most batteries also feature a separate wire for temperature sensing.

System Management Bus

The System Management Bus (SMBus) represents a concerted effort to agree on one communications protocol and one set of data. Derived from I2C, the

Duracell/Intel smart battery system was standardized in 1995 and consists of two separate lines for data and clock. I2C (Inter-Integrated Circuit) is a multi-master, multi-slave, single-ended, serial computer bus invented by Philips Semiconductor. Figure 6-3 shows the layout of the two-wire SMBus system.

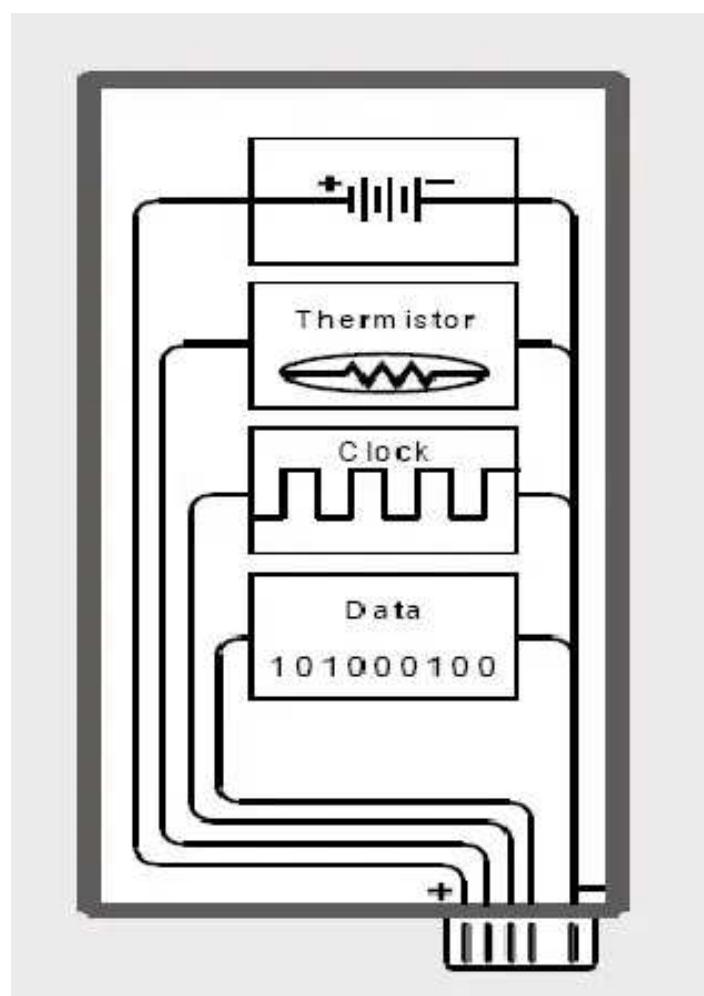


Figure 6-3: Two-wire SMBus system.

The SMBus works on a two-wire system using a standardized communications protocol. This system lends itself to standardized state-of-charge and state-of-health measurements.

Courtesy of Cadex

The philosophy behind the SMBus battery was to remove charge control from the charger and assign it to the battery. With a true SMBus system, the battery becomes the master and the charger the slave, obeying the command of

battery becomes the master and the charger the slave, obeying the command of the battery. This enables a universal charger to service present and future battery chemistries by applying correct charge algorithms.

During the 1990s, several standardized SMBus battery packs emerged, including the 35 and 202 (Figure 6-4). Manufactured by Sony, Hitachi, GP

Batteries and others, these interchangeable batteries were designed to power a broad range of portable devices, such as laptops and medical instruments. The idea was solid but standardization diverged as most manufacturers began building their own packs.

To prevent unauthorized batteries from infiltrating the market, some manufacturers add a code to exclude other pack vendors. A few manufacturers go so far as to invalidate the battery when a given cycle count is reached. To avoid surprises, most of these systems inform the user of the pending end-of-life.

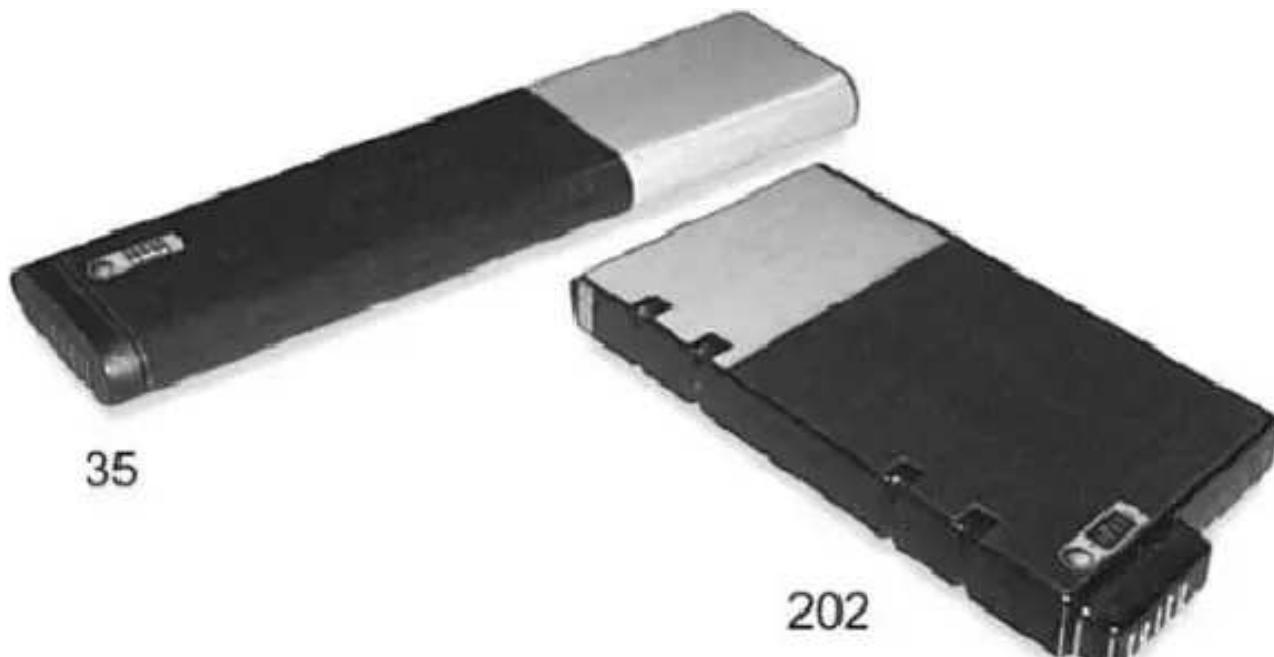


Figure 6-4: 35 and 202 series batteries featuring SMBus.

Available in nickel- and lithium-based chemistries, these batteries power laptops, biomedical instruments and survey equipment. Non-SMBus (dumb) versions with the same footprint are also available.

Courtesy of Cadex

An SMBus battery contains permanent and temporary data. The battery makers program the permanent data into the battery, which includes battery ID, battery type, manufacturer's name, serial number and date of manufacture. The

temporary data is added during use and contains cycle count, usage pattern and maintenance requirements. Some of the information is kept, while other data is renewed throughout the life of the battery. The voltage is typically measured in 1mV increments; the current resolution is 0.5mA; temperature accuracy is about $\pm 3^{\circ}\text{C}$.

Smart battery chargers are divided into Level 1, 2 and 3. Level 1 has been discontinued because it did not provide chemistry-independent charging and it only supported a single chemistry. A Level 2 charger is fully controlled by the Smart Battery and acts as an SMBus slave, responding to voltage and current commands from the Smart Battery. Level 2 also serves as in-circuit charging, a practice that is common in laptops. Another use is a battery with a built-in charging circuit. In Level 2, battery and circuit are married to each other.

A level 3 charger can interpret commands from a Smart Battery, as is done with Level 2, and also act as master. In other words, the Level 3 charger can request charging information from the Smart Battery but it can also impose its own charging algorithm by responding to the “chemical” battery. Most industrial smart chargers are based on the hybrid type Level 3.

Some lower-cost chargers have emerged that accommodate SMBus batteries, but these may not be fully SBS compliant. Manufacturers of SMBus batteries do not endorse this shortcut because of safety concerns. Applications such as biomedical instruments, data collection devices and survey equipment lean towards Level 3 chargers with full-fledged charge protocols. Table 6-5 lists the advantages and limitations of the smart battery.

Advantages Provides state-of-charge and full charge capacity, capacity estimations possible

Records battery history, including cycle count, usage pattern, maintenance requirements, max error, etc.

Configures charger to the correct algorithm

Reminds user of periodic calibration

Protects battery from unauthorized use

Limitations Adds 25% to the cost of a battery (Fuel gauge ICs are in the \$2-range)

Complicates the charger; most chargers for intelligent batteries are hybrid and also service non-intelligent batteries

Requires periodic calibration. This is reduced with learn programs

Most Smart Batteries only provide state-of-charge information although some newer fuel gauges include state-of-health estimation

Table 6-5: Advantages and limitations of the smart battery.

Simple Guidelines for Using Smart Batteries

- Calibrate a smart battery by applying a full discharge and charge every 3 months or after every 40 partial cycles. Batteries with impedance tracking provide a certain amount of self-calibration.
- A fuel gauge showing 100% SoC does not assure a good battery. The capacity may have faded to 50%, cutting the runtime in half. A fuel gauge can give a false sense of security.
 - If possible, replace the battery with the same brand to avoid incompatibility issues with the device and/or charger. Always test the battery and the charger before use.
- Exercise caution when using a smart battery that does not indicate state-of-charge correctly. This battery may be faulty or is not fully compatible with the equipment.

Fuel Gauge

The lifespan of a battery cannot be defined by the number of cycles or age alone

but to a large extent by its usage (or misusage). As the capacity fades, the runtime gets shorter. The smart battery captures this capacity fade by reading the previous energy delivered, but these vital health statistics remain mostly hidden from the user. The battery continues to be a “black box” that conceals vital performance records and masks when the battery should be replaced.

One of the main tasks of the smart battery is to establish communication between the battery, charger and user. A fuel gauge indicating state-of-charge fulfills this in part. When pressing the TEST button on a fully charged SMBus battery, all signal lights illuminate. On a partially discharged battery, half the lights illuminate, and on an empty battery all lights remain dark or a red light appears. Figure 6-6 shows a fuel gauge of a battery that is 75 percent charged with three lights glowing.

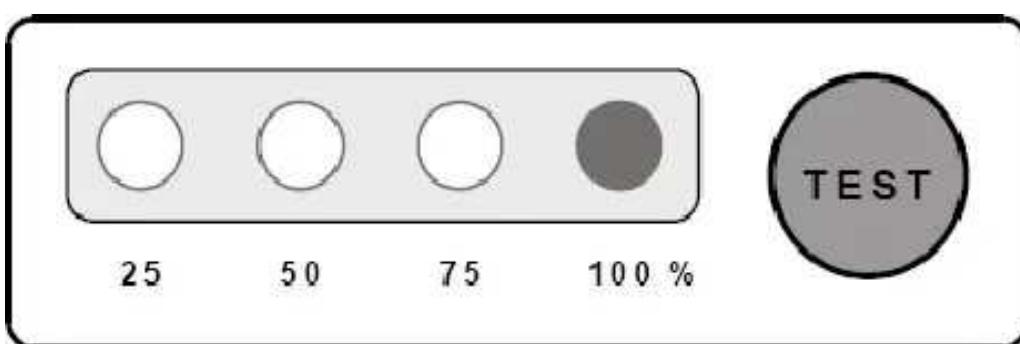


Figure 6-6: State-of-charge readout of a “smart” battery.

Signal lights indicate the battery SoC when pressing the TEST button.

Courtesy of Cadex

While the SoC information displayed on a battery or a display screen is helpful to the user, the readout does not guarantee the runtime. The fuel gauge resets to 100 percent with a full recharge regardless of how much capacity the battery can store.

A serious breach of trust occurs if an aged battery shows 100 percent SoC while the battery’s ability to hold charge has dropped to 50 percent or less. We ask, “100 percent of what?” If, for example, 100 percent of a good battery results in a 4-hour runtime, a battery holding half the capacity would run for only 2 hours. Many users are unaware that the fuel gauge only shows SoC; capacity, the leading health indicator, remains unknown.

Other than applying a controlled discharge, there is no reliable method to measure the capacity of the “chemical battery” but there is a way to read the “digital battery.” The term *chemical battery* refers to the actual capacity derived by discharging a fully charged pack, whereas the *digital battery* is a peripheral

monitoring circuit that stores the estimated capacity derived by coulomb counting when charging and discharging a battery as part of field use.

The SMBus battery stores the factory-set *design capacity* in Ah or 100 percent by default. With each full charge, the battery resets the full-charge flag and during discharge, the coulomb counter measures the energy consumed. The in-and-out-flowing coulombs can be used to estimate battery state-of-health known as *full charge capacity (FCC)*. As the battery fades with usage and time, so also does the delivered energy decrease, and the FCC number will decline. The FCC accuracy of a battery that is being deep cycled is about +/-5 percent compared to capacity readings taken by discharging. Periodic calibration will improve the FCC accuracy.

Capacity can also be estimated by coulomb counting during charging. This works best with an empty battery. A battery with a 100 percent capacity will receive the full coulomb count; one with only 50 percent capacity will only accept half before the battery reaches full charge. Not knowing the residual SoC when the coulomb count begins will affect the accuracy. SoC can be estimated by measuring the battery’s open circuit voltage (OCV), but this only gives a rough approximation as agitation after charge or discharge, as well as temperature, affects the OCV.

Tri-state Fuel Gauge

The SoC and capacity information can be shown on a linear display (Figure 6-7) using colored LEDs. The green lights (clear) indicate the usable capacity; the empty part of the battery is marked with un-lit LEDs (black); and the unusable part is shown with red LEDs (x). The results can also be shown on a digital display.

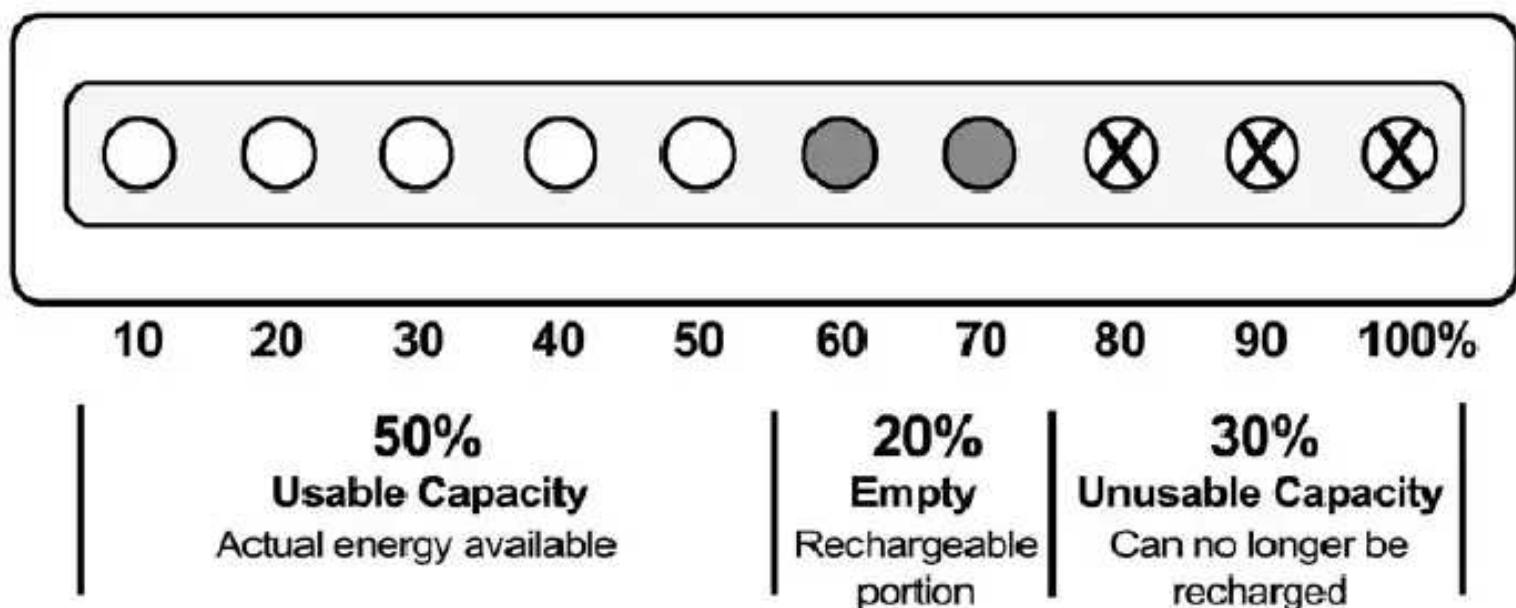


Figure 6-7: Tristate fuel gauge reads the “learned” battery information and displays it on a multi colored LED bar. The illustration shows a partially discharged battery of 50% SoC with 20% empty and 30% unusable.

Courtesy of Cadex

The tri-state fuel gauge provides state-of-function (SoF), the ultimate in battery diagnostics. Some device manufacturers are hesitant to offer this feature to consumers because this could lead to elevated warranty claims. A replacement only becomes mandatory if the battery capacity drops below 80 percent; keeping the evidence hidden is seen as the least disruptive method. SoF can always be accessed by a service code. SoF works best for industrial uses.

Vehicles with electric propulsion do not show the charge but only the remaining driving range, thus hiding the capacity. To accommodate capacity fade that would shorten the driving range, the EV battery is being oversized and does not fully charge and discharge when new. Only as the battery ages and the capacity fades does the charge range increase. Shorter driving ranges only become apparent once this reserve capacity has been consumed.

Calibration

When designing a fuel gauge, engineers commonly make a misjudgment by assuming that a battery will always stay young. As with people, batteries age and the changing characteristics must be taken into account to maintain accuracy. Fancy fuel gauges can provide a false sense of security when users believe that

the displayed battery readings are correct. For the casual user of a mobile phone or laptop, a fuel gauge error is only a mild irritant, but the problem escalates with medical and military devices, as well as drones and electric drivetrains that depend on precise range predictions.

The chemical battery representing the actual energy storage remains the master while the digital battery provides peripheral support by relying on the information obtained from charge and discharge cycles. But like all fine machines, precise settings begin to shift and need adjustment. The same happens with an SMBus battery that also requires periodic calibration. The instructions for an Apple iPad reads: “For proper reporting of SoC, be sure to go through at least one full charge/discharge cycle per month.”

Figure 6-8 demonstrates a digital battery that is drifting away from the chemical battery; calibration corrects the tracking error. The accumulating error is application related and the drift on the chart is accentuated for effect.

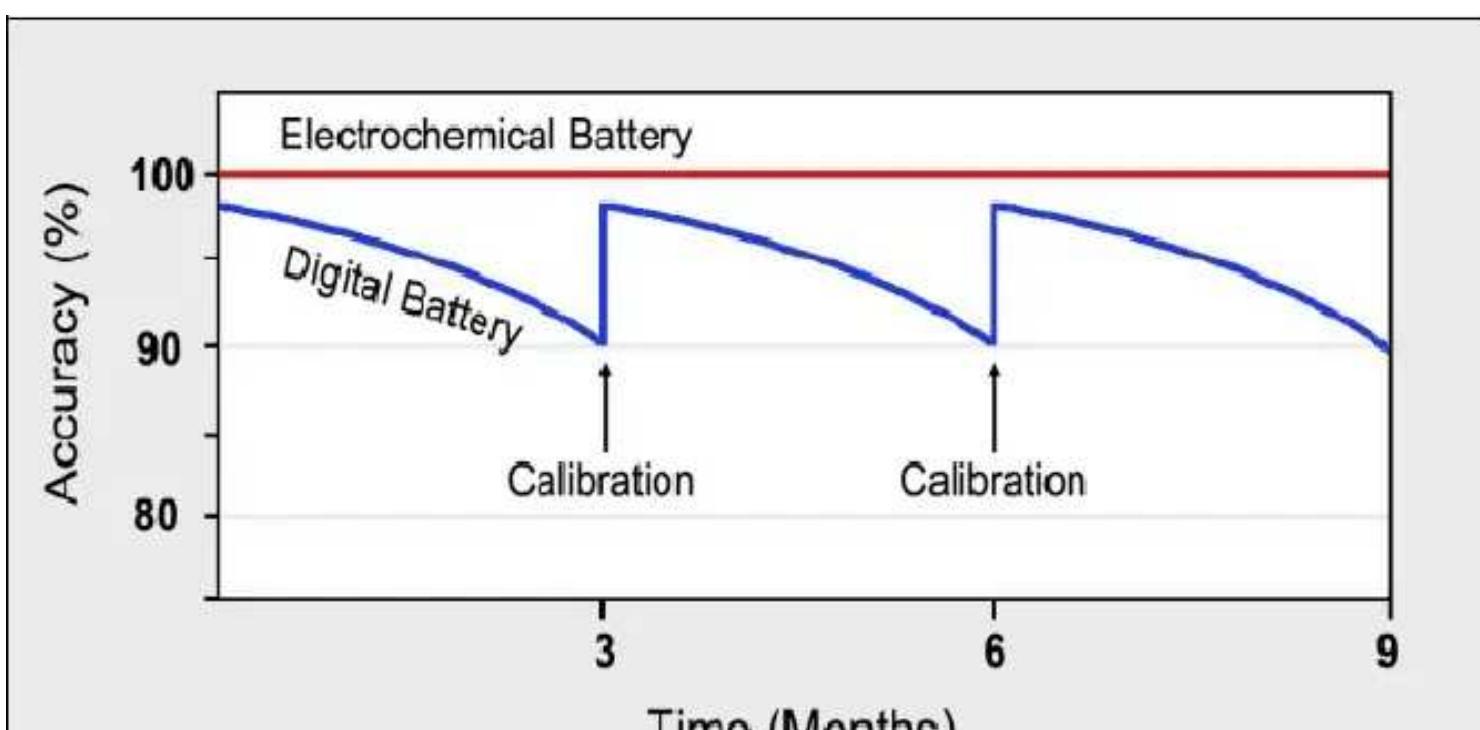


Figure 6-8: Tracking of the electrochemical and digital battery as a function of time.

With use and time the electro-chemical and digital battery drift apart; calibration corrects the error.

Note: The accumulating error is application related; the values on the chart are accentuated.

Courtesy of Cadex

A smart battery self-calibrates by taking advantage of occasional full discharges, but in real life this seldom happens. Most discharges are intermittent and go to random depth. In addition, the load signatures often consist of high frequency pulses that are difficult to capture. The partially discharged battery may be partly recharged and then stored in a warm room, causing elevated self-discharge that cannot be tracked. These anomalies add to the display error that amplifies with use and time.

To maintain accuracy, a smart battery should periodically be calibrated by running the pack down in the device until “Low Battery” appears and then applying a recharge. The full discharge sets the discharge flag and the full charge establishes the charge flag. A linear line forms between these two anchor points that allow SoC estimation. In time, this line gets blurred again and the battery requires recalibration. Figure 6-9 illustrates the full-discharge and full-charge flags.

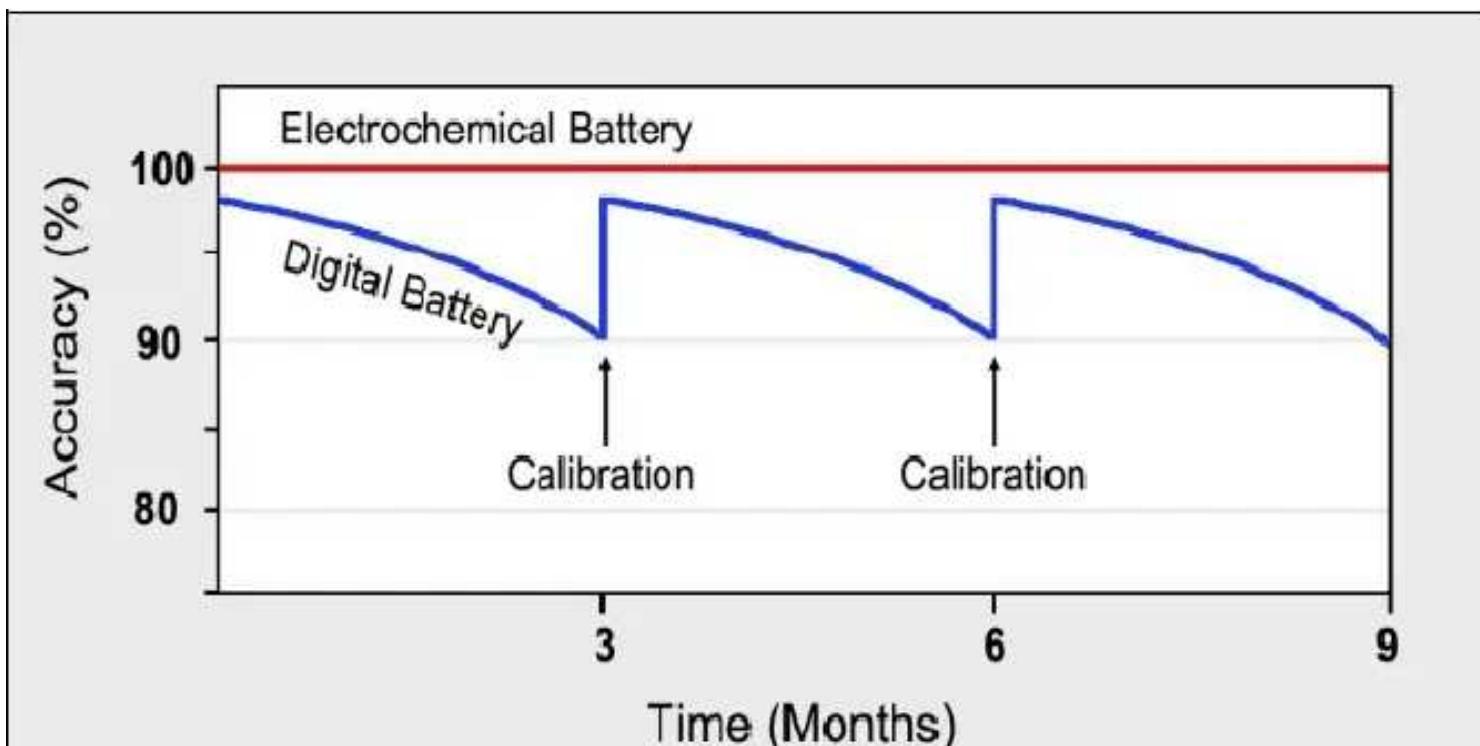


Figure 6-9: Full-discharge and full-charge flags.

Calibration occurs by applying a full charge, discharge and charge. This is done in the equipment or with a battery analyzer as part of battery a maintenance program.

Courtesy of Cadex

A battery charger with discharge function or a battery analyzer enables calibration of a smart battery. The analyzer fully charges the battery and then applies a controlled discharge that provides the all-important capacity readings of the chemical battery. This discharge measurement is a truer reading than what coulomb counting provides by capturing past discharge events of the digital battery.

How often should a battery be calibrated? The answer depends on the application. For a battery that is in continued use, a calibration should be done once every 3 months or after 40 partial cycles. If the portable device applies a periodic full deep discharge on its own accord, then no additional calibration should be needed.

What happens if the battery is not calibrated regularly? Can such a battery be used with confidence? Most smart battery chargers obey the dictates of the chemical battery rather than the digital battery and there are no safety concerns. The battery should function normally, but the digital readout may become unreliable.

Some smart batteries feature *impedance tracking*. This is a self-learning algorithm that reduces or eliminates the need to calibrate. If calibration is required, however, several cycles instead of only one may be needed to achieve the same result as with a standard system.

Max Error

The accuracy between the chemical and digital battery is measured by the Max Error. Max Error stands for “maximum error” and is presented in percentage. A low reading indicates good accuracy, and as the precision diminishes with partial cycles, the Max Error number increases steadily. This supervisory watchdog can

be compared to a medical doctor who measures a medical condition by a number.

Some manufacturers recommend calibration at a Max Error of 8 percent; readings above 12 percent may trigger an alarm and 16 could render the battery unserviceable. No unified standard exists to determine what Max Error level

requires service or what constitutes an error; every battery manufacturer follows its own recommendation.

Screen Capture

The SMBus system provides a wealth of information that includes the battery manufacturing date, battery model and serial number, capacity, temperature and estimated runtime, as well as voltages down to the cell level. It is an engineer's delight to have all this data in a table, but the fine print may confuse the user more than providing help. A busy nurse in a hospital, the policeman on duty and the soldier in combat has only one question: "Will the battery last for my mission?" Table 6-10 illustrates a screenshot of the data stored in an SMBus battery.

Of special interest in terms of battery state-of-health (SoH) is *full charge capacity (FCC)*, coulomb count that is hidden in the table among tons of other information. FCC can be used with reasonable accuracy to estimate battery SoH without applying a full discharge cycle to measure capacity. Best accuracies are achieved if the battery is being cycled with full a full charge and an occasional deep discharge. If used sporadically, a deliberate calibration involving a full discharge/charge cycle will be needed from time-to-time to maintain accuracy.

Dynamic Data					
Name	Value	Unit	Log	Scan	
Manufacturer Access	0000	hex	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Remaining Cap. Alarm	460	mAh	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Remaining Time Alarm	10	min	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Battery Mode	0001	hex	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
At Rate	0	mA	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
At Rate Time To Full	65535	min	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
At Rate Time To Empty	65535	min	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
At Rate OK	1		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Temperature	23.15	°C	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Voltage	12422	mV	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Current	0	mA	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Average Current	0	mA	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Max Error	1	%	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Relative State of Charge	97	%	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Absolute State of Charge	89	%	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Remaining Capacity	4064	mAh	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Full Charge Capacity	4220	mAh	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Run Time to Empty	65535	min	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Average Time to Empty	65535	min	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Average Time to Full	65535	min	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	
Charging Current	2400	mA	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	

Static Data					
Name	Value	Unit			
Design Capacity	4600	mAh			
Design Voltage	11100	mV			
Specification Info	09				
Manufacture Date	2015-03-02				
Serial Number	1				
Manufacturer Name	A30A30				
Device Name	SM206				
Device Chemistry	LION				

Table 6-10: Universal screenshot of SMBus battery. Data is organized in tables to assist analysis, a format that is less suited for the everyday battery user. Access is by a software tool.

Source: Texas Instruments

Processing Data from a Smart Battery

Even though smart batteries have been in service since the mid-1990s, they still do not communicate well with the outside world. Device manufacturers continue to mandate that the battery be replaced on a date stamp rather than refer to the more relevant FCC information contained in the battery. Expensive packs are thus discarded every 2–3 years instead of utilizing the typical full 5-year life

expectancy of Li-ion.

A new frontier is opening that provides easy access to battery information.

The *Battery Parser* (by Cadex) does this by establishing communications between the user and the battery by fetching intrinsic battery data to reveal state-of-function (SoF). The Fishbowl icon as shown in Figure 6-11 consists of the

Charge Ring indicating state-of-charge and the *Status Dome* with PASS, CHARGE, CHECK, and FAIL messages. The Status Dome also illustrates the energy-storage capability together with *Battery Fade* that moves towards the *Pass/Fail* line with usage and age.

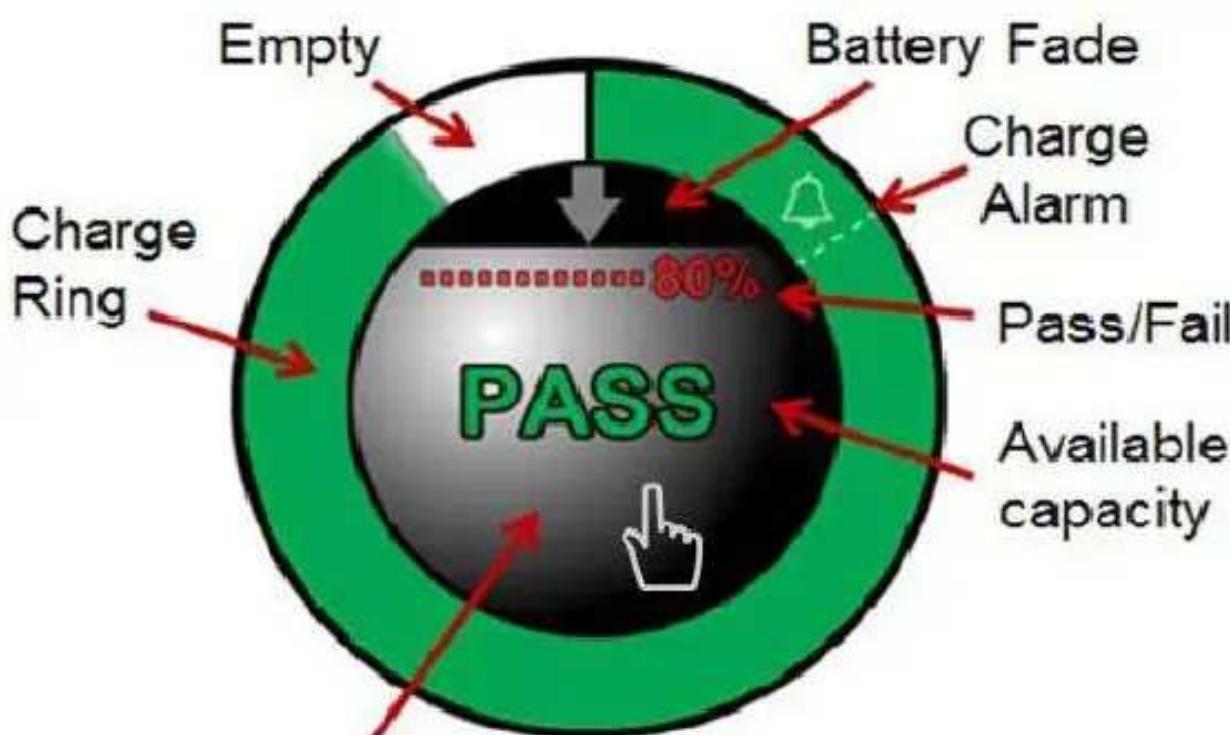


Figure 6-11: The Fishbowl icon displays battery state-of-function at a glance with these status messages:

- PASS indicates sufficient capacity and SoC
- CHARGE requires charging before use as SoC slipped below the Charge Alarm.
- CHECK includes cell imbalance, high Max Error, elevated internal resistance and more.
- FAIL hints at capacity fade, exceeding calendar date or passing beyond pre-set cycle count.

Courtesy of Cadex

Battery status indicators must separate state-of-charge and capacity and treat them as unrelated entities. While a battery with low SoC can be recharged,

treat them as unrelated entities. While a battery with low SoC can be recharged, capacity loss is permanent and predicts end-of-life. This condition is demonstrated with the encroaching black ceiling bar on top of the Fishbowl.

Pressing the Status Dome on a device featuring a touchscreen reveals possible deficiencies, as well as information relating to the battery model, specifications, serial number and manufacturing date. The Fishbowl settings can be updated by

the user.

Storing the battery test results in the cloud-based database enables an overview of the entire battery fleet in terms of location, application, performance and service requirements. This is made possible with the availability of the serial number and manufacturing date in a smart battery. To check batteries needing replacement, the operator simply calls up packs that have dropped below the 80 percent capacity or are older than, say, 5 years.

The operator can also verify SoC by listing all batteries with less than 10 percent reserve before charging. Tight reserve can lead to failure during heavy traffic or in an emergency. If consistently low, the pass/fail target capacity threshold should be set higher to boost the reserve. If, on the other hand, most batteries return with 40 percent capacity after a long mission or a full day, then the target capacity can be lowered without affecting reliability.

The Battery Parser finds a sweet spot between reliability and economy. The service life of each battery can be fully utilized and system reliability improved, reducing environmental harm and lowering operating costs. In addition, fewer devices are sent for repair because the battery becomes a controlled part.

A cost saving by using battery analysis was demonstrated in a 340-bed hospital in the USA. When the need to replace the batteries for patient monitors came to \$56,000 on the date stamp method, the supervisor objected and requested that the packs be checked with a battery analyzer. This revealed that most batteries were in good condition and the budget was reduced to \$11,000.

Military is another application where battery analysis will help. A modern soldier carries radios, GPS devices, smartphones, night vision goggles, infrared sights, flashlights and counter-IED equipment. This amounts to roughly seven

signs, hashing and counter IED equipment. This amounts to roughly seven battery types, with 10 packs needed each for a 72-hour mission at a weight of about 9kg (20 lb) per soldier. Batteries have become the second highest expense next to munitions. This can be reduced with a maintenance program, without which soldiers are soon carrying rocks instead of batteries as Figure 6-12 demonstrates.



Figure 6-12: Soldier carries rocks instead of batteries.

Maintenance keeps deadwood out of the military arsenal. The digital state-of-health of “smart” batteries can be verified within seconds or recorded during each charge.

Courtesy of Cadex

Other uses for the Battery Parser are drones and robots. Drones are demanding on the battery as heavy loads result in a shorter than expected cycle life. Battery maintenance is paramount to prevent an expensive vehicle from crashing should a second landing approach be necessary.

Battery maintenance utilizing the Battery Parser is best placed into the

Battery maintenance during the Battery Fuser is best placed into the battery charger. Such a system shows the capacity with each charge. Alternatively, a quick insertion reveals the battery status before use. Knowing the performance of each battery enables planning a mission according to the available energy source, reducing unscheduled events.

Wireless connectivity to the cloud permits collective battery management in

which each charge updates the information. This provides one of the most transparent battery management systems possible without added logistics. Battery status can be shown on a PC or smartphone with the click of a finger.

Smart batteries and chargers with performance evaluation further assist to classify batteries into performance groups: A-grade batteries with a capacity of 90–100 percent can be reserved for critical missions, B-grade packs with 80–90 percent are for everyday use, and the C-grade with 70–80 percent may be kept as spares or used for shorter errands. Having full control of the battery fleet improves reliability, simplifies logistics and protects the environment as each battery can be utilized for their full service life.

“Any intelligent fool can make things bigger and more complex... It takes a touch of genius – and a lot of courage – to move in the opposite direction.”

— *Albert Einstein*

Part Two

You and the Battery

Batteries have become the lifeline of society. They are like us and deliver on the good care given but quit on their own terms.

Chapter 7 | From Birth to Retirement

Caring for the Battery

In many ways, a battery behaves like a human being. It senses the kindness given and delivers on the care given. It is as if the battery has feelings and returns on the benevolence bestowed. But there are exceptions, as any parent raising a family will know; and the generosity conferred may not always deliver the anticipated returns.

To become a good custodian, you must understand the basic needs of a battery, a subject that is not taught in school. This section teaches what to do when the battery is new, how to feed it the right “food” and what to do when putting the pack aside for a while. Chapter 7 also looks into restrictions when traveling with batteries by air and how to dispose of them when their useful life has passed.

Just as a person’s life expectancy cannot be predicted at birth, neither can we date stamp a battery. Some packs live to a great old age while others die young. Incorrect charging, harsh discharge loads and exposure to heat are the battery’s worst enemies. Although there are ways to protect a battery, the ideal situation is not always attainable. This chapter discusses how to get the most from our batteries.

How to Prime Batteries

Not all rechargeable batteries deliver the rated capacity when new, and they require formatting. While this applies to most battery systems, manufacturers of lithium-ion batteries disagree. They say that Li-ion is ready at birth and does not

need priming. Although this may be true, users have reported some capacity gains by cycling after a long storage.

“What’s the difference between formatting and priming?” people ask. Both address capacities that are not optimized and can be improved with cycling. *Formatting* completes the fabrication process that occurs naturally during use when the battery is being cycled. Typical examples are lead- and nickel-based batteries that improve with usage until fully formatted. *Priming*, on the other hand, is a conditioning cycle that is applied as a service to improve battery performance during usage or after prolonged storage. Priming relates mainly to nickel-based batteries.

Lead Acid

Formatting a lead acid battery occurs by applying a charge, followed by a discharge and recharge. This is done at the factory and is completed in the field as part of regular use. Experts advise not to strain a new battery by giving it heavy duty discharges at first but gradually working it in with moderate discharges, like an athlete trains for weight lifting or long-distance running. This, however, may not be possible with a starter battery in a vehicle and other uses. Lead acid typically reaches the full capacity potential after 50 to 100 cycles.

Deep-cycle batteries are at about 85 percent when new and will increase to 100 percent, or close to full capacity, when fully formatted. There are some outliers that are as low as 65 percent when tested with a battery analyzer. The question is asked, “Will these low-performers recover and stand up to their stronger brothers when formatted?” A seasoned battery expert said that “these batteries will improve somewhat but they are the first to fail.”

The function of a starter battery lies in delivering high load currents to

crank the engine, and this attribute is present from the beginning without the need to format and prime. To the surprise of many motorists, the capacity of a starter battery can fade to 30 percent and still crank the engine; however, a further drop may get the driver stranded one morning. (See “How to Measure Capacity” on page 275.)

Nickel-based

Manufacturers advise to trickle charge a nickel-based battery for 16–24 hours when new and after a long storage. This allows the cells to adjust to each other and to bring them to an equal charge level. A slow charge also helps to redistribute the electrolyte to eliminate dry spots on the separator that might have developed by gravitation.

Nickel-based batteries are not always fully formatted when leaving the factory. Applying several charge/discharge cycles through normal use or with a battery analyzer completes the formatting process. The number of cycles required to attain full capacity differs between cell manufacturers. Quality cells perform to specification after 5–7 cycles, while lower-cost alternatives may need 50 or more cycles to reach acceptable capacity levels.

Lack of formatting causes a problem when the user expects a new battery to work at full capacity out of the box. Organizations using batteries for mission-critical applications should verify the performance through a discharge/charge cycle as part of quality control. The “prime” program of automated battery analyzers (Cadex) applies as many cycles as needed to attain full capacity.

Cycling also restores lost capacity when a nickel-based battery has been stored for a few months. Storage time, state-of-charge and temperature under which the battery is stored govern the ease of recovery. The longer the storage and the warmer the temperature, the more cycles will be required to regain full capacity. Battery analyzers help in the priming functions and assure that the desired capacity has been achieved.

Lithium-ion

Some battery users insist that a *passivation layer* develops on the cathode of a

lithium-ion cell after storage. Also known as *interfacial protective film* (IPF), this layer is said to restrict ion flow, cause an increase in internal resistance and in the worst case, lead to lithium plating. Charging, and more effectively cycling, is known to dissolve the layer and some battery users claim to have gained extra runtime after the second or third cycle on a smartphone, albeit by a small amount.

Scientists do not fully understand the nature of this layer, and the few published resources on this subject only speculate that performance restoration with cycling is connected to the removal of the passivation layer. Some scientists outright deny the existence of the IPF, saying that the idea is highly speculative and inconsistent with existing studies. Whatever the outcome on the passivation of Li-ion may be, there is no parallel to the “memory” effect with NiCd batteries that require periodic cycling to prevent capacity loss. The symptoms may appear similar but the mechanics are different. Nor can the effect be compared to sulfation of lead acid batteries.

A well-known layer that builds up on the anode is the *solid electrolyte interface* (SEI). SEI is an electrical insulation but has sufficient ionic conductivity to allow the battery to function normally. While the SEI layer lowers the capacity, it also protects the battery. Without SEI, Li-ion would not get the longevity that it has. (See “Electrolyte” on page 116.)

The SEI layer develops as part of a formation process and manufacturers take great care to do this right, as a batched job can cause permanent capacity loss and a rise in internal resistance. The process includes several cycles, float charges at elevated temperatures and rest periods that can take many weeks to complete. This formation period also provides quality control and assists in cell matching, as well as observing self-discharge by measuring the cell voltage after a rest. High self-discharge hints to impurity as part of a potential manufacturing defect.

Electrolyte oxidation (EO) also occurs on the cathode. This causes a permanent capacity loss and increases the internal resistance. No remedy exists

permitted capacity loss and increases the internal resistance. No remedy exists to remove the layer once formed but electrolyte additives lessen the impact. Keeping Li-ion at a voltage above 4.10V/cell while at an elevated temperature promotes electrolyte oxidation. Field observation shows that the combination of heat and high voltage can stress Li-ion more than harsh cycling.

Lithium-ion is a very clean system that does not need additional priming

once it leaves the factory, nor does it require the level of maintenance that nickel-based batteries do. Additional formatting makes little difference because the maximum capacity is available right from the beginning, (the exception may be a small capacity gain after a long storage). A full discharge does not improve the capacity once the battery has faded — a low capacity signals the end of life. A discharge/charge may calibrate a “smart” battery but this does little to improve the chemical battery. Instructions recommending charging a new Li-ion for 8 hours are written off as “old school,” a left-over from the old nickel battery days.

Non-rechargeable Lithium

Primary lithium batteries, such as lithium-thionyl chloride (LTC), benefit from passivation in storage. Passivation is a thin layer that forms as part of a reaction between the electrolyte, the lithium anode and the carbon-based cathode. (Note that the anode of a primary lithium battery is lithium and the cathode is graphite, the reverse of Li-ion.)

Without this layer, most lithium batteries could not function because the lithium would cause a rapid self-discharge and degrade the battery quickly. Battery scientists even say that the battery would explode without the formation of lithium chloride layers and that the passivation layer is responsible for the battery’s existence and the ability to store for 10 years.

Temperature and state-of-charge promote the buildup of the passivation layer. A fully charged LTC is harder to depassivate after long storage than one that was kept at a low charge. While LTC should be stored at cool temperatures, depassivation works better when warm as the increased thermal conductivity and mobility of the ions helps in the process.

CAUTION Do not apply physical tension or excessive heat to the battery. Explosions due to careless handling have caused serious injuries to workers.

The passivation layer causes a voltage delay when first applying a load to the battery, and Figure 7-1 illustrates the drop and recovery with batteries affected by different passivation levels. Battery A demonstrates a minimal

voltage drop while Battery C needs time to recover.

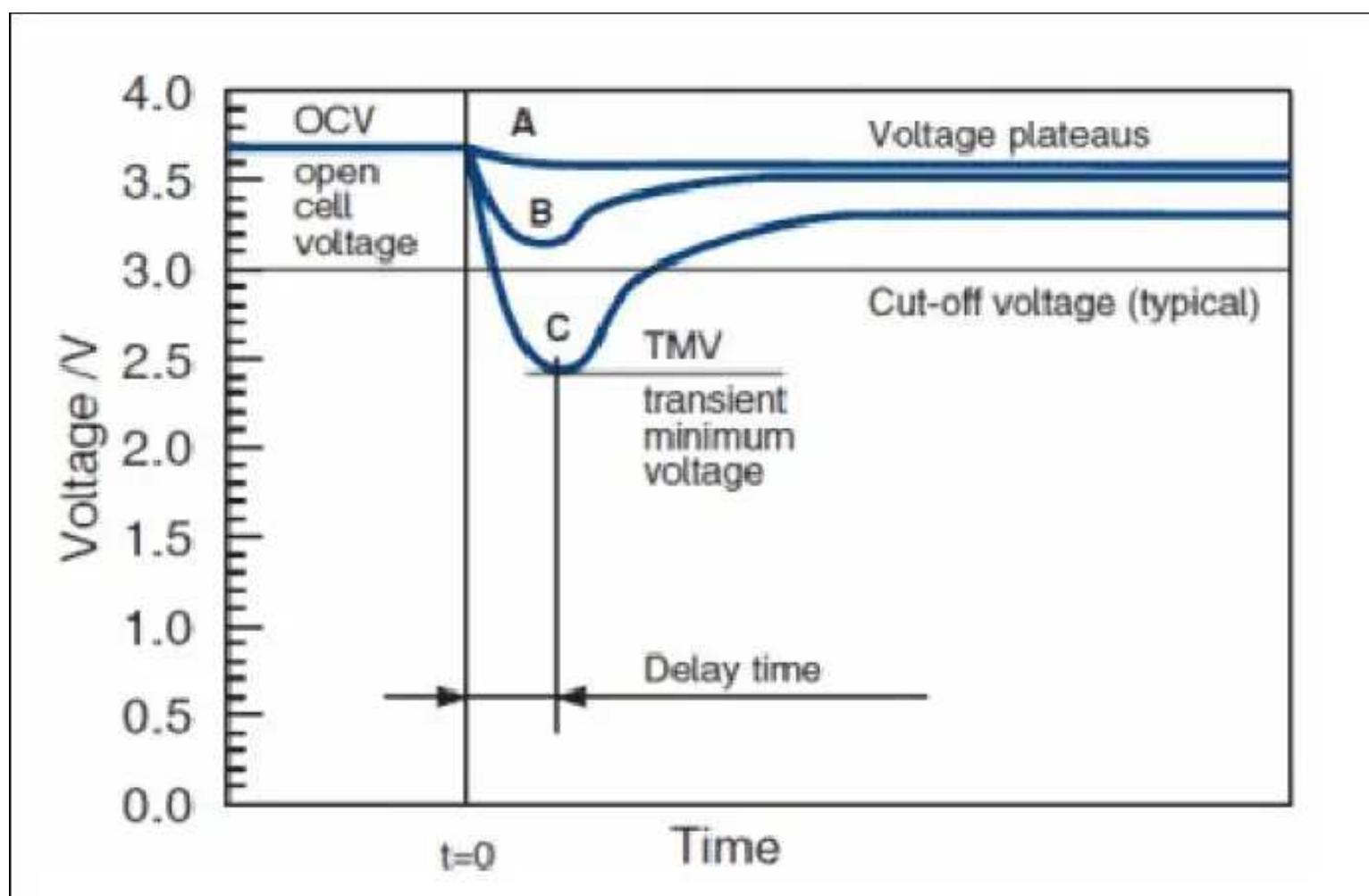


Figure 7-1: Voltage behavior when applying a load to a passivated battery.

Battery A has mild passivation, B takes longer to restore, and C is affected the most.

Source: EE Times

LTC in devices drawing very low current, such as a sensor for a road toll or metering, may develop a passivation layer that can lead to malfunction, and heat promotes such growth. This can often be solved by adding a large capacitor in parallel with the battery. The battery that has developed a high internal resistance is still capable of charging the capacitor to deliver the occasional high pulses; the standby time in bat. cap is dedicated to recharging the capacitor.

standby time in between is devoted to recharging the capacitor.

To assist in sulfation prevention during storage, some lithium batteries are shipped with a $36\text{k}\Omega$ resistor to serve as a parasitic load. The steady low discharge current prevents the layer from growing too thick, but this will reduce the storage life. After 2-year storage with the $36\text{k}\Omega$ resistor, the batteries are said to still have 90 percent capacity. Another remedy is attaching a device that

applies periodic discharge pulses during storage.

Not all primary lithium batteries recover when installed in a device and when a load is applied. The current may be too low to reverse the passivation. It is also possible that the equipment rejects a passivated battery as being low state-of-charge or defective. Many of these batteries can be prepared with a battery analyzer (Cadex) by applying a controlled load. The analyzer then verifies proper function before engaging the battery in the field.

The required discharge current for depassivation is a C-rate of 1C to 3C (1 to 3 times of the rated capacity). The cell voltage must recover to 3.2V when applying the load; the service time is typically 20 seconds. The process can be repeated but it should take no longer than 5 minutes. With a load of 1C, the voltage of a correctly functioning cell should stay above 3.0V. A drop to below 2.7V means end-of-life. (See “Primary Batteries” on page 36.)

These lithium-metal batteries have high lithium content and must follow more stringent shipping requirements than Li-ion of the same Ah. (See “Shipping Lithium-based Batteries by Air” on page 204.) Because of the high specific energy, special care must be taken in handling these cells.

CAUTION When charging an SLA with over-voltage, current limiting must be applied to protect the battery. Always set the current limit to the lowest practical setting and observe the battery voltage and temperature during charge.

In case of rupture, leaking electrolyte or any other cause of exposure to the electrolyte, flush with water immediately. If eye exposure occurs, flush with water for 15 minutes and consult a physician immediately.

Wear approved gloves when touching the electrolyte, lead and cadmium. On exposure to the skin, flush with water immediately.

How to Store Batteries

The recommended storage temperature for most batteries is 15°C (59°F); the extreme allowable temperature is –40°C to 50°C (–40°C to 122°F) for most chemistries. While lead acid must always be kept at full charge during storage, nickel- and lithium-based chemistries should be stored at around a 40 percent

state-of-charge (SoC). This minimizes age-related capacity loss while keeping the battery operational and allowing for some self-discharge.

While nickel-based batteries can be stored in a fully discharged state with no apparent side effect, Li-ion cannot dip below 2V/cell for any length of time. Copper shunts form inside the cells that can lead to elevated self-discharge or a partial electrical short. (See “Elevated Self-discharge” on page 224.) If recharged, the cells might become unstable, causing excessive heat or showing other anomalies. Li-ion batteries that have been under stress may function normally but are more sensitive to mechanical abuse. The liability for a failed battery goes to the manufacturer when a fault could have been caused by improper use and handling.

Finding the exact 40–50 percent SoC level to store Li-ion is not all that important. At 40 percent charge, most Li-ion has an OCV of 3.82V/cell measured at room temperature. To get the correct reading after a charge or discharge, rest the battery for 90 minutes before taking the reading. If this is not practical, overshoot the discharge voltage by 50mV or go 50mV higher on charge. This means discharging to 3.77V/cell or charging to 3.87V/cell at a C-rate of 1C or less. The rubber band effect will settle the voltage at roughly 3.82V. Figure 7-2 shows the typical discharge voltage of a Li-ion battery.

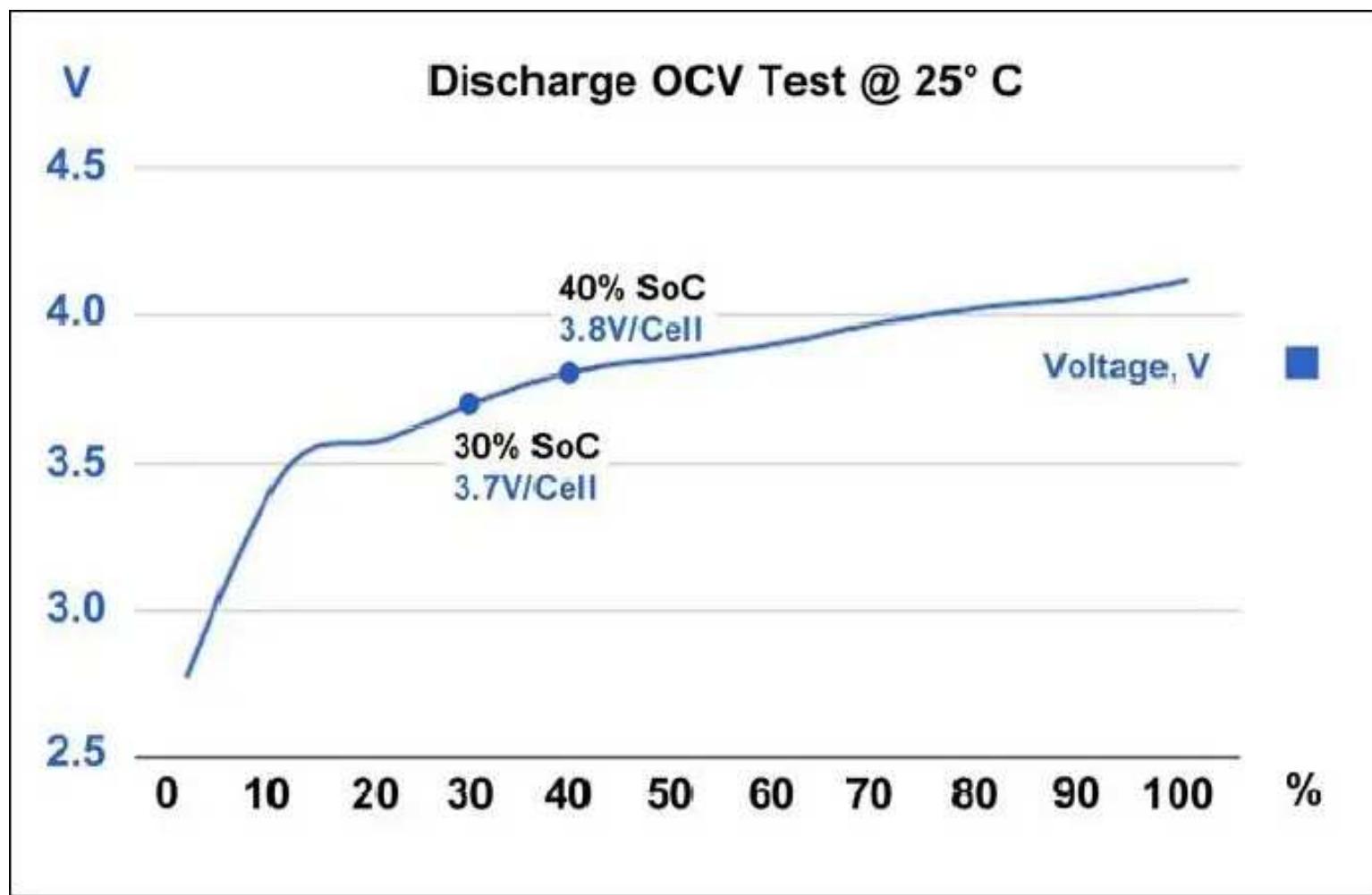


Figure 7-2: Discharge voltage as a function of state-of-charge.

Battery SoC is reflected in OCV. Lithium manganese oxide reads 3.82V at 40% SoC (25°C), and about 3.70V at 30% (shipping requirement). Temperature and previous charge and discharge activities affect the reading. Allow the battery to rest for 90 minutes before taking the reading.

Measuring SoC is especially difficult on nickel-based batteries. A flat discharge curve, agitation after charge and discharge and temperature affects the voltage. The charge level for storage is not critical for this chemistry, so simply apply some charge if the battery is empty and store it in a cool and dry place. With some charge, priming should be quicker than if stored in a totally discharged state.

Storage induces two forms of losses: Self-discharge that can be refilled with

Storage induces two forms of losses. Self-discharge that can be relieved with charging before use, and non-recoverable losses that permanently lower the capacity. Table 7-3 illustrates the remaining capacities of lithium- and nickel-based batteries after one year of storage at various temperatures. Li-ion has higher losses if stored fully charged rather than at a SoC of 40 percent.

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

Table 7-3: Estimated capacity when storing batteries for one year at various temperatures. Li-ion deteriorates faster when stored at high charge rather than partial charge.

Batteries are often exposed to unfavorable temperatures, and leaving a mobile phone or camera on the dashboard of a car or in the hot sun are such examples. Laptops get warm when in use and this increases the battery temperature. Sitting at full charge while being plugged into the mains contributes to a relatively short battery life. Elevated temperature also stresses lead- and nickel-based batteries.

Nickel-metal-hydride can be stored for 3–5 years. The capacity drop that occurs during storage is partially reversible with priming. Nickel-cadmium stores well. The US Air Force was able to deploy NiCd batteries that had been in storage for 5 years with good recovered capacities after priming. It is believed that priming becomes necessary if the voltage drops below 1V/cell. Primary alkaline and lithium batteries can be stored for up to 10 years with only moderate capacity loss.

You can store a sealed lead acid battery for up to 2 years. Since all batteries gradually self-discharge over time, it is important to check the voltage and/or specific gravity, and then apply a charge when the battery falls to 70 percent state-of-charge, which reflects 2.07V/cell open circuit or 12.42V for a 12V pack.

(The specific gravity at 70 percent charge is roughly 1.218.) Some lead acid batteries may have different readings, and it is best to check the manufacturer's instruction manual. Low charge induces sulfation, an oxidation layer on the negative plate that inhibits current flow. Topping charge and/or cycling may restore some of the capacity losses in the early stages of sulfation. (See

"Sulfation" on page 238.)

Sulfation may prevent charging small sealed lead acid cells, such as the Cyclone by Hawker, after prolonged storage. These batteries can often be reactivated by applying an elevated voltage. At first, the cell voltage under charge may go up to 5V and draw very little current. Within 2 hours or so, the charging current converts the large sulfate crystals into active material, the cell resistance drops and the charge voltage gradually normalizes. At between 2.10V and 2.40V the cell is able to accept a normal charge. To prevent damage, set the current limit to a very low level. Do not attempt to perform this service if the power supply does not have current limiting. (See "How to Charge with a Power Supply" on page 137.)

Alkaline batteries are easy to store. For best results, keep the cells at cool room temperature and at a relative humidity of about 50 percent. Do not freeze alkaline cells, or any battery, as this may change the molecular structure.

Simple Guidelines for Storing Batteries

- Primary batteries store well. Alkaline and primary lithium batteries can be stored for 10 years with moderate loss capacity.
- When storing, remove the battery from the equipment and place in a dry and cool place.
- Avoid freezing. Batteries freeze more easily if kept in discharged state.
- Charge lead acid before storing and monitor the voltage or specific gravity frequently; apply a charge if below 2.07V/cell or if SG is below 1.225 (most starter batteries).
- Nickel-based batteries can be stored for five years even at zero voltage.

Nickel based batteries can be stored for five years, even at zero voltage, prime before use.

- Lithium-ion must be stored in a charged state, ideally at 40 percent. This prevents the battery from dropping below 2.50V/cell, triggering sleep mode.
- Discard Li-ion if kept below 2.0/V/cell for more than a week. Also discard if the voltage does not recover normally after storage.

Health Concerns with Batteries

Batteries are safe, but caution is necessary when touching damaged cells and when handling lead acid systems that have access to lead and sulfuric acid. Several countries label lead acid as hazardous material, and rightly so. Lead can be a health hazards if not properly handled.

Lead

Lead is a toxic metal that can enter the body by inhalation of lead dust or ingestion when touching the mouth with lead-contaminated hands. If leaked onto the ground, the acid and lead particles contaminate the soil and become airborne when dry. Children and fetuses of pregnant women are most vulnerable to lead exposure because their bodies are developing. Excessive levels of lead can affect a child's growth, cause brain damage, harm kidneys, impair hearing and induce behavioral problems. In adults, lead can cause memory loss and lower the ability to concentrate, as well as harm the reproductive system. Lead is also known to cause high blood pressure, nerve disorders, and muscle and joint pain.

Researchers speculate that Ludwig van Beethoven became ill and died because of lead poisoning.

By 2017, members of the International Lead Association (ILA) want to keep the lead blood level of workers in mining, smelting, refining and recycling below 30 micrograms per deciliter ($30\mu\text{g}/\text{dl}$). In 2014, the average participating employee checked in at $15.6\mu\text{g}/\text{dl}$, but 4.8 percent were above $30\mu\text{g}/\text{dl}$. (Source Batteries & Energy Storage Technology, Summer 2015.)

Sulfuric Acid

The sulfuric acid in a lead acid battery is highly corrosive and is more harmful than acids used in most other battery systems. Contact with eyes can cause

than acids used in most other battery systems. Contact with eyes can cause permanent blindness; swallowing damages internal organs that can lead to death. First aid treatment calls for flushing the skin for 10–15 minutes with large amounts of water to cool the affected tissue and to prevent secondary damage. Immediately remove contaminated clothing and thoroughly wash the underlying skin. Always wear protective equipment when handling sulfuric acid.

Cadmium

Cadmium, which is used in nickel-cadmium batteries, is considered more harmful than lead if ingested. Workers at NiCd manufacturing plants in Japan have been experiencing health problems from prolonged exposure to the metal, and governments have banned disposal of nickel-cadmium batteries in landfills. The soft, whitish metal that occurs naturally in the soil can damage kidneys. Cadmium can be absorbed through the skin by touching a spilled battery. Since most NiCd batteries are sealed, there are no health risks in handling intact cells; caution is required when working with an open battery.

Nickel-metal-hydride is considered non-toxic and the only concern is the electrolyte. Although toxic to plants, nickel is not harmful to humans.

Lithium-ion is also benign — the battery contains little toxic material. Nevertheless, caution is required when working with a damaged battery. When handling a spilled battery, do not touch your mouth, nose or eyes. Wash your hands thoroughly.

Keep small batteries out of children's reach. Children younger than four are the most likely to swallow batteries, and the most common types that are ingested are button cells. Each year in the United States alone, more than 2,800 children are treated in emergency rooms for swallowing button batteries. According to a 2015 report, serious injuries and deaths from swallowing batteries have increased nine-fold in the last decade.

The battery often gets stuck in the esophagus (the tube that passes food). Water or saliva creates an electrical current that can trigger a chemical reaction producing hydroxide, a caustic ion that causes serious burns to the surrounding tissue. Doctors often misdiagnose the symptoms, which can reveal themselves as

tissue. Doctors often misdiagnose the symptoms, which can reveal themselves as fever, vomiting, poor appetite and weariness. Batteries that make it through the esophagus often move through the digestive tract with little or no lasting damage. The advice to a parent is to choose safe toys and to keep small batteries away from young children.

Safety Tips

- Keep button batteries out of children's reach. Remote controls, singing greeting cards, watches, hearing aids, thermometers, toys and electric keys may contain these batteries.
- Similar to pharmaceutical products, keep small batteries locked away from small children.
- Communicate the danger of swallowing button batteries with your children, as well as caregivers, friends, family members and babysitters.
- If you suspect your child has ingested a battery, go to the hospital immediately. Wait for a medical assessment before allowing the child to eat and drink.

Ventilation

Charging batteries in living quarters should be safe, and this also applies to lead acid. Ventilate the area regularly as you would a kitchen when cooking. Lead acid produces some hydrogen gas but the amount is minimal when charged correctly. Hydrogen gas becomes explosive at a concentration of 4 percent. This would only be achieved if large lead acid batteries were charged in a sealed room.

Over-charging a lead acid battery can produce hydrogen sulfide. The gas is colorless, very poisonous, flammable and has the odor of rotten eggs. Hydrogen sulfide also occurs naturally during the breakdown of organic matter in swamps and sewers; it is present in volcanic gases, natural gas and some well waters. Being heavier than air, the gas accumulates at the bottom of poorly ventilated spaces. Although noticeable at first, the sense of smell deadens the sensation with time and potential victims may be unaware of its presence. As a simple guideline, hydrogen sulfide becomes harmful to human life if the odor is noticeable.

CAUTION Under no circumstances should batteries be incinerated, as fire can cause an explosion. Wear approved gloves when touching electrolyte. On exposure to skin, flush with water immediately. If eye exposure occurs, flush with water for 15 minutes and consult a physician immediately.

How to Transport Batteries

Incidents in transit prompted authorities to tighten the rules for all battery shipments. The largest change involves transporting lithium-based batteries by air governed by UN 38.3. This is done to assure safety of those handling batteries and the passengers traveling with them aboard a common carrier.

Data compiled by the Federal Aviation Administration (FAA) from 1991 to 2007 states that 27 percent of all incidents occurred with lithium-based batteries, of which 68 percent failed due to short circuits, 15 percent during charging and discharging and 7 percent by unintentional activation of devices. The remaining had other malfunctions.

In another study from 1991 to 2012, the FAA recorded 132 air incidents involving batteries leading to smoke, extreme heat, fire or explosion. Examining the mishaps further puts most of the blame on inappropriate packaging or handling, of which most occurred at airports or in cargo hubs. Although lithium-ion gets the most attention regarding safety risk in transport, the FAA reports that other battery systems are experiencing a larger number of incidents. Problem batteries include primary lithium (lithium-metal), lead acid, NiMH, NiCd and alkaline. Please note that the rechargeable Li-ion and primary lithium-metal batteries are handled separately.

Lead Acid

Most countries set strict rules for transporting lead acid batteries. Failure to comply with the regulations is a civil or criminal offense that can result in stiff penalties for the carrier and/or the shipper. The rules are simple, well established and make common sense.

- The vehicle transporting batteries can carry only one type of hazardous material. Brace the batteries securely to prevent damage and short circuits in transit. Non-hazardous goods on the same vehicle must be secured to prevent damaging the batteries.
- Batteries must be stacked upright, pole side outwards, and placed on a wooden pallet. Place honeycomb cardboard between the layers and limit

the stack to three layers on a single pallet. Wrap the package several times with shrink-wrap.

- Identify hazardous material with labels marked “Corrosive” using the appropriate symbols and colors. Stickers must conform to regulatory specifications.
- Mark all packages, e.g., batteries, wet, filled with acid, identification number (UN 2794).
- Provide a bill of lading document that includes the name of the company and shipper, contents of package, description of hazardous material and shipper's certification.
- When shipping by air, restrict the weight per package to 25kg gross (55lb) ~~on passenger air carriers~~. There is no limit on the number of packages per flight.

Different rules apply when shipping damaged batteries. A lead acid battery is considered damaged if there is a possibility of leakage due to a crack or if one or more caps are missing. Transportation companies and air carriers may require that the batteries be drained of all acid prior to transport. Place damaged batteries in an acid-resistant container and add soda ash to neutralize any acid that might spill. Separate damaged from intact batteries.

Nickel-based Batteries

Nickel-based batteries have no transport limitations; however, some of the same precautions apply as for lead acid in terms of packaging to prevent electrical shorts and safeguard against fire. Regulations prohibit storing and transporting smaller battery packs in a metal box. If there is a danger of an electrical short, wrap each battery individually in a plastic bag. Do not mix batteries with coins

and house keys in your pocket.

Lithium-based Batteries

The largest changes in shipping rules occurred around lithium-based batteries, and with good reasons. Li-ion is the fastest growing battery chemistry and in 2009, 3.3 billion Li-ion batteries were transported by air. This is an ongoing concern, and an airline-pilot union has asked the FAA to ban lithium-based

batteries on passenger aircraft.

The Portable Rechargeable Battery Association (PRBA) is aware of possible hazards but opposes any revisions to transportation rules, arguing that the restrictions would cost shippers and manufacturers billions of dollars. PRBA is made up of major battery manufacturers, including Energizer, Panasonic, SAFT America, Sanyo and Varta Batteries. These manufacturers do not want to disrupt air shipments, especially batteries for critical medical and military applications. They argue that the batteries causing problems do not meet US hazardous material handling regulations and ask the FAA to enforce stricter manufacturing rule.

Battery manufacturers tell the aviation industry that, as a result of the well-publicized 2006 recall, a safer generation of Li-ion batteries has emerged. According to the US Census Bureau (2010), airfreight transports roughly 364 million cell phones, 142 million cameras and 47 million laptops as part of just-in-time delivery to stores. No deaths and only 26 injuries are attributed to shipping billions of lithium batteries every year.

The estimated failure rate of Li-ion is 1 per 10 million, or less, and newer consumer products have few surprise failures. But in spite of improved battery safety, there are restrictions with lithium-ion batteries on airplanes. Travelers are reminded how many batteries they can carry on board in portable devices and as spare packs.

Since January 2008, people can no longer pack spare lithium batteries in checked baggage, but airlines allow them as carry-on. A cabin event involving a burning battery will allow quick access to a fire extinguisher, an exercise that is

not possible in the cargo bay. In one incident, a coffee pot served as the fire extinguishing device for a flaming laptop battery on board a plane. Luckily, the battery was in the passenger department rather than in the sealed cargo bay below.

In terms of transportation, lithium-based batteries are divided into non-rechargeable lithium-metal batteries and rechargeable lithium-ion batteries found

in mobile phones and laptops. Airlines allow both types as carry-on, either installed or carried as spare packs, as long as they don't exceed the following limitation of lithium or equivalent content of:

- 2 grams for primary lithium batteries, also known as lithium-metal.
- 8 grams for a secondary lithium-ion. This amounts to a 100Wh battery.
- 25 grams for all Li-ion combined. This amounts to 300Wh worth of Li-ion batteries.

The lithium content of the lithium-metal battery is often printed on the label. Li-ion, on the other hand, has no metallic lithium and uses the equivalent lithium content (ELC) instead. To calculate the ELC, multiply the rated capacity (Ah) times 0.3. As an example, a 1Ah cell has 0.3 grams of lithium. The 8-gram ELC places the upper limit with a 100Wh battery pack.

A laptop battery commonly uses 2Ah cells containing 0.6 grams of ELC each. The battery pack may have 8 cells (4 in series; 2 in parallel), which brings the ELC to 4.8 grams, well below the 8-gram limit allowed in a single pack. To derive the watt-hour, multiply the battery voltage by the ampere-hours (Ah). The battery in question has a voltage of 14.40V (4 x 3.6V) and a rating of 4Ah (2 x 2Ah). In summary, $14.4V \times 4Ah = 57.6Wh$, or roughly 60Wh.

While regulations limit the Li-ion battery to no larger than 100Wh, each passenger and travel companion is allowed to carry spare packs of up to 25 grams of ELC, or 300Wh. The airlines recommend placing each battery in a clear plastic bag or covering the contacts with tape to prevent an electric short. Although current rules forbid passengers from carrying lithium-ion batteries in checked luggage, devices with non-removable batteries, such as the iPhone, iPad