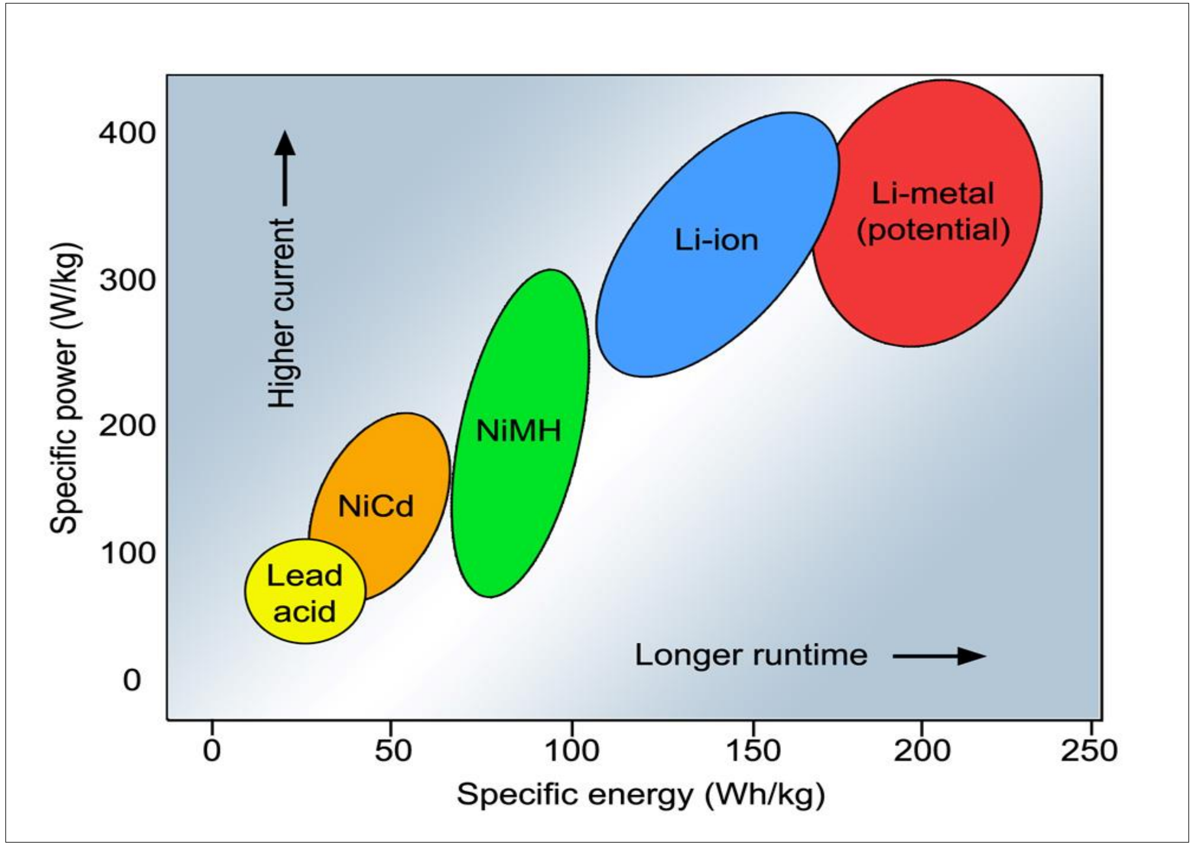
BATTERY BASICS

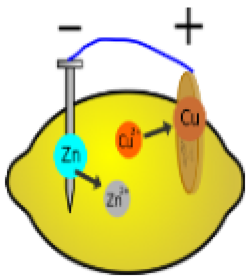
Outline

1. Battery chemistries
2. Packaging and Configurations
3. Charging, Discharging, Storing
4. How to prolong Battery Life
5. Summary

Relationship between Power and Energy

Power



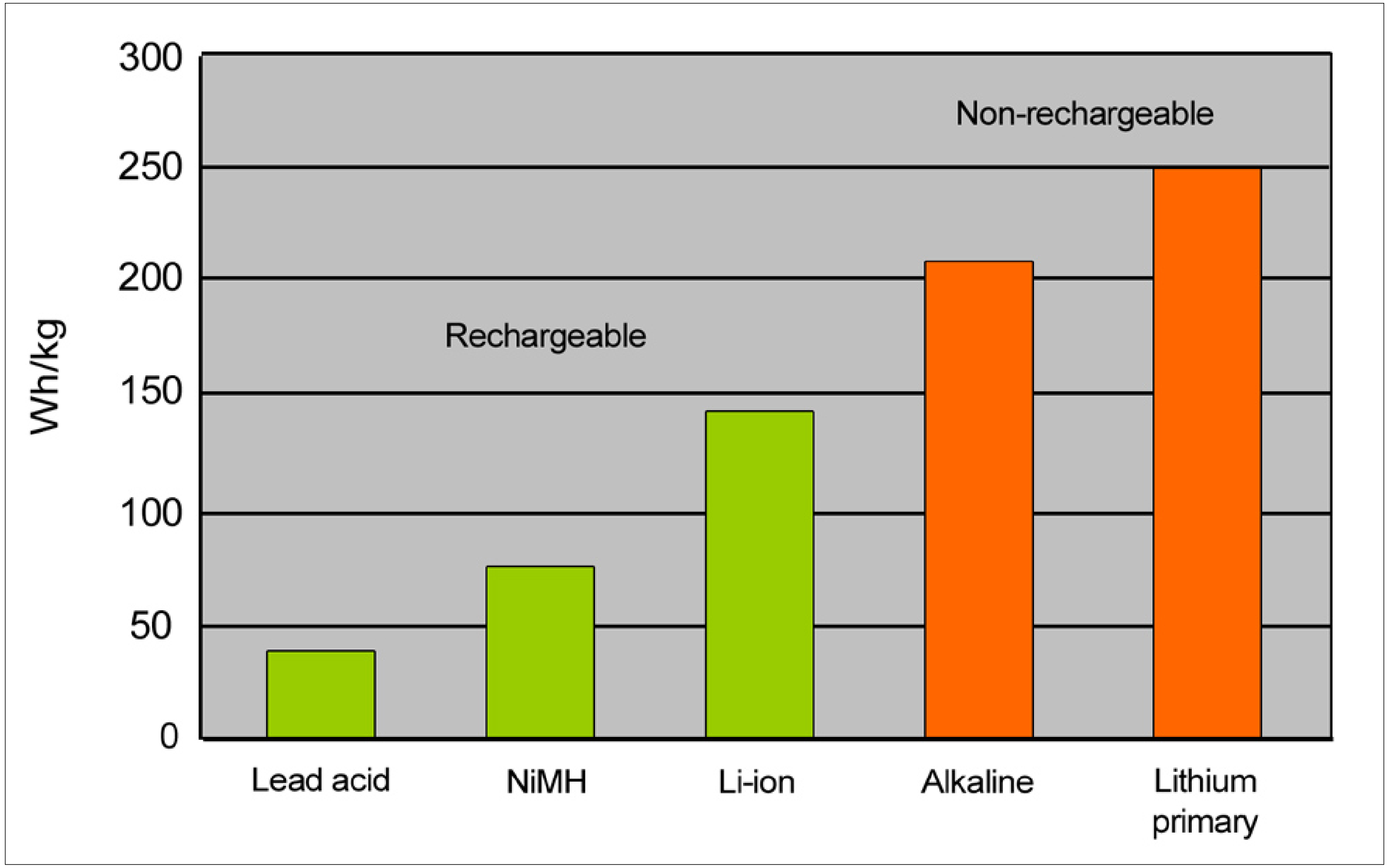


Energy

Specific energy: Capacity a battery can hold (Wh/kg)

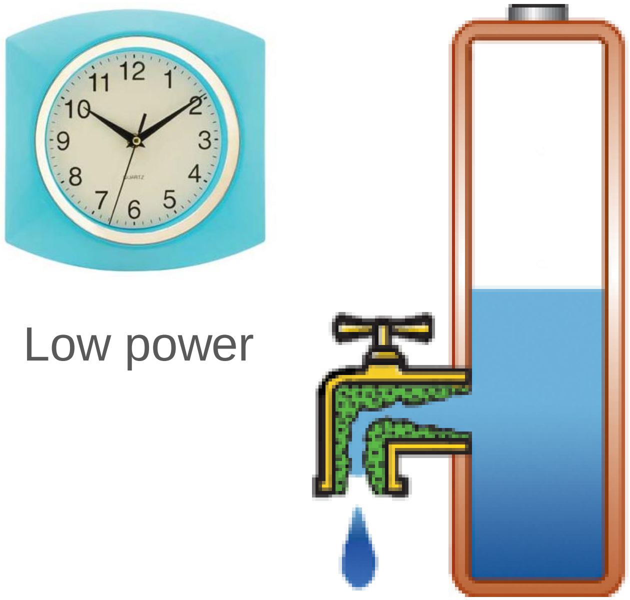
Specific power: Ability to deliver power (W/kg)

Energy storage capacity



Non-rechargeable batteries hold more energy than rechargeables but cannot deliver high load currents

Ability to deliver current

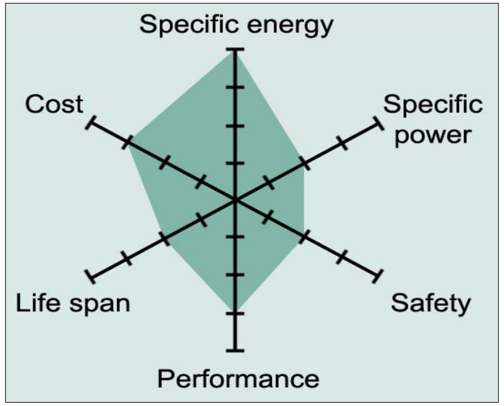


Power tool draws
up to 50 amperes

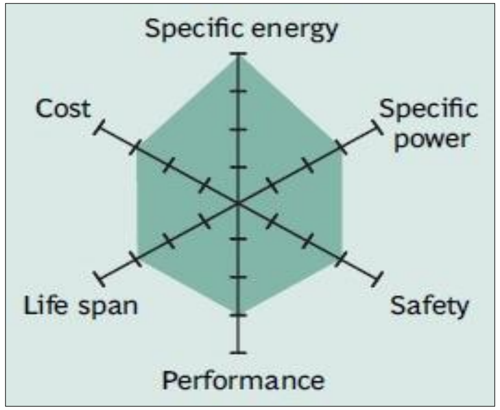
Kitchen clock runs
on a few milliamps

Li-ion Systems

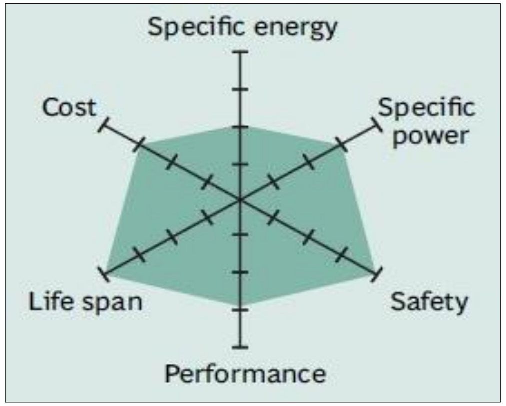
Li-cobalt (LiCoO2)
Available since 1991, replaces NiCd and NiMH. Lighter, longer runtimes.



NMC (nickel-manganese-cobalt)
High specific energy. Power tools, medical instruments, e-bikes, EVs.



Li-phosphate (LiFePO4)
Long cycle life, enhanced safety but has lower specific energy. UPS, EVs



Lithium-polymer Hype

- **Lithium-polymer** (1970s) uses a solid electrolyte. Requires 50–60°C operating temperature to attain conductivity.
- Modern Li-polymer includes gelled electrolyte; can be built on Li-cobalt, NMC, Li-phosphate and Li-manganese platforms.
- Li-polymer is not a unique chemistry but a different architecture. Characteristics are the same as other Li-ion chemistries.

***Polymer** serves as marketing catchword in consumer products*

Confusion with Nominal Voltages

Lead acid: 2V/cell nominal (OCV is 2.10V/cell)

NiCd, NiMH: 1.20V/cell (official rating is 1.25V/cell)

Li-ion: 3.60V/cell (Some are 3.70V, 3.80V*)

* Cathode material affect OCV. Manganese raises voltage.
Higher voltage is used for marketing reasons.

Official Li-ion Ratings

Li-ion	3.60V/cell
Li-phosphate	3.30V/cell

Safety concerns with Li-ion

- Microscopic metal particles can puncture the separator, leading to an electrical short circuit. (Quote by Sony, 2006)
- Modern cells with ultra-thin separators are more susceptible to impurities than the older designs with lower Ah ratings.
- External protection circuits cannot stop a thermal runaway.

In case of overheating battery

- Move device to non-combustible surface.
- Cool surrounding area with water
- Use chemicals to douse fire, or allow battery to burn out.
- Ventilate room.

2. Packaging and Configurations

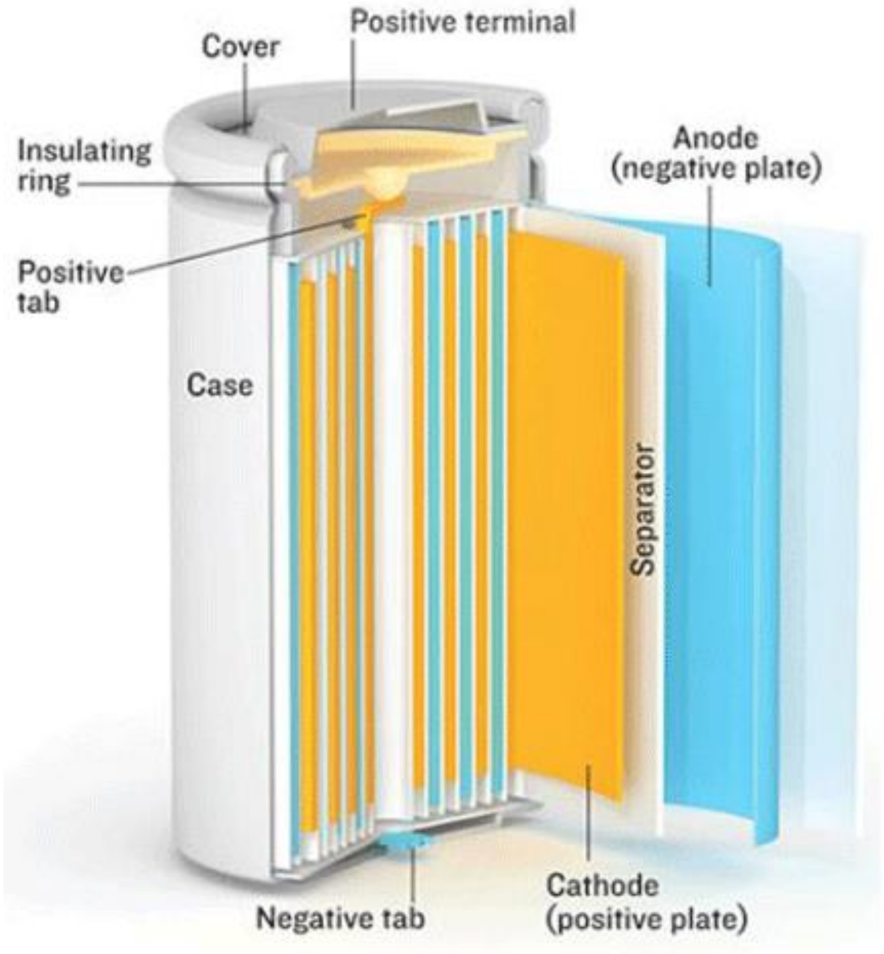
In ca. 1917, the National Institute of Standards and Technology established the alphabet nomenclature.

Battery formats

Type	Size (mm)	History
F	33x90	1896 for lantern, later for radios, NiCd only
E	N/A	1905 for lantern and hobby, discontinued 1980
D	34x61	1898 for flashlight, later radios
C	25.5x50	1900 as above for smaller form factor
B	N/A	1900 for portable lighting, discontinued 2001
A	17x50	NiCd only, also in half-sizes
AA	14.5x50	1907 for WWI; made standard in 1947
AAA	10.5x44.5	1954 for Kodak, Polaroid to reduce size
AAAA	8.3x42.5	1990 for laser pointers, flashlights, PC stylus
4.5V	85x61x17.5	Flat pack for flashlight, common in Europe
9V	48.5x26.5x17.5	1956 for transistor radios
18650	18x65	Early 1990s for Li-ion
26650	26x65	Larger size for Li-ion

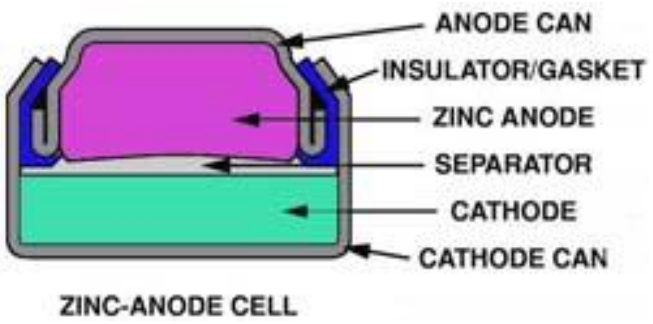
Cylindrical cell

- Classic packaging for primary & secondary cells
- High mechanical stability, economical, long life
- Holds internal pressure without deforming case
- Inefficient use of space
- Metal housing adds to weight



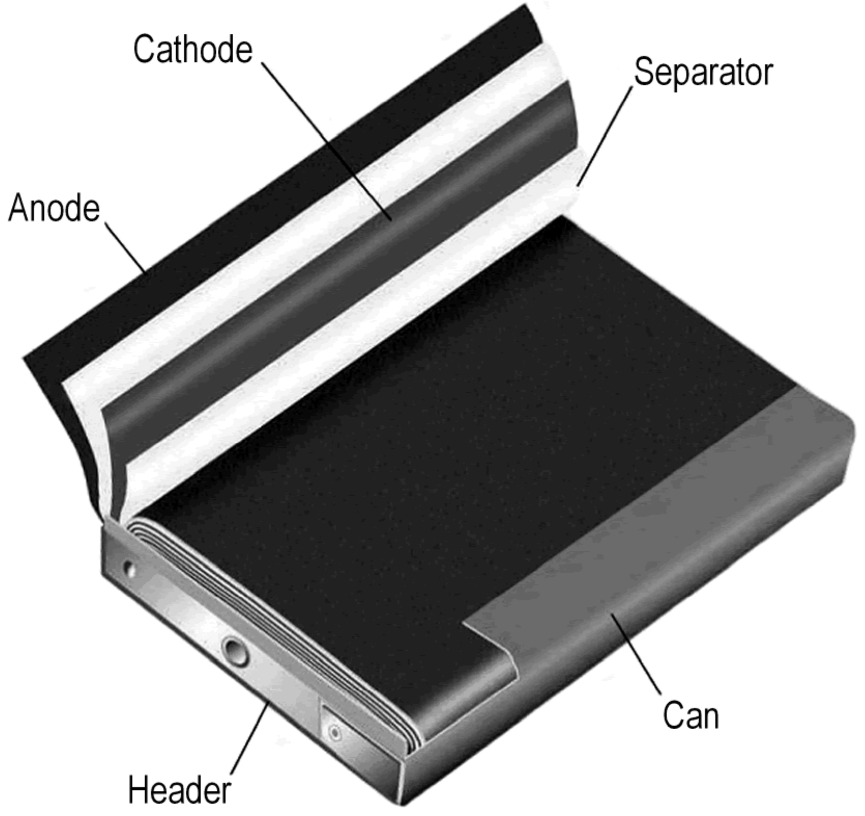
Button cell

- Also known as coin cells; small size, easy to stack
- Mainly reserved as primary batteries in watches, gauges
- Rechargeable button cells do not allow fast charging
- Limited new developments
- Must be kept away from children, harmful if swallowed (voltage)



Prismatic cell

- ➢ Best usage of space
- ➢ Allows flexible design
- ➢ Higher manufacturing cost
- ➢ Less efficient thermal management
- ➢ Shorter life



Pouch cell

- Light and cost-effective to manufacture
- Simple, flexible and lightweight solutions
- Exposure to humidity, hot temperature shorten life
- Loss of stack pressure; swelling due to gassing
- Design must include allowance for 8-10% swelling

Some cells may bloat

Best Cell Design

Cylindrical cell has good cycling ability, long life, economical to manufacture. No expansions during charge and discharge.

Heavy; creates air gaps on multi-cell packs. Not suitable for slim designs.

Prismatic cell allows compact design; mostly used for single-cell packs.

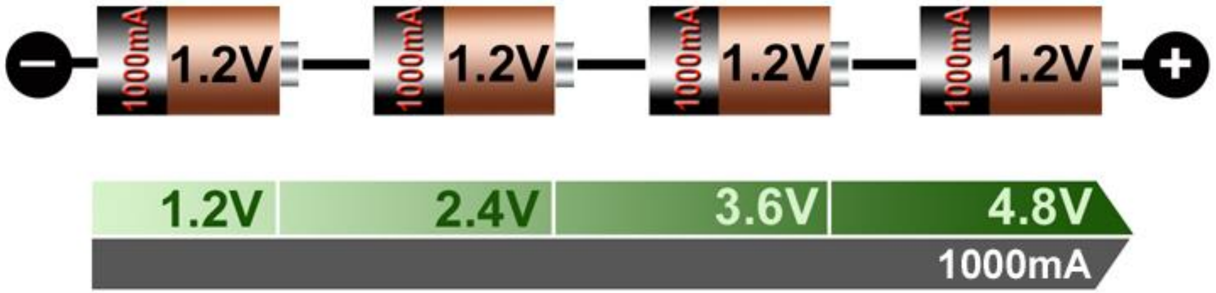
Less efficient in thermal management; possible shorter cycle life; can be more expensive to make.

Pouch pack is light and cost-effective to manufacture.

Exposure to humidity and heat shorten service life; 8–10% swelling over 500 cycles.

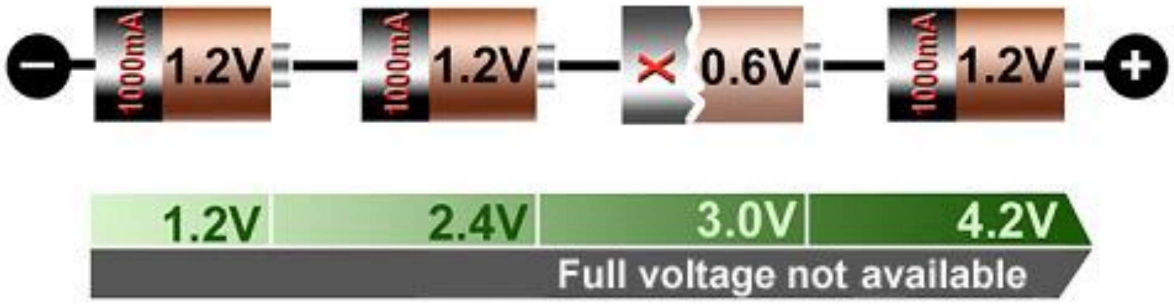
Serial connection

Good string



- Adding cells in a string increases voltage; same current

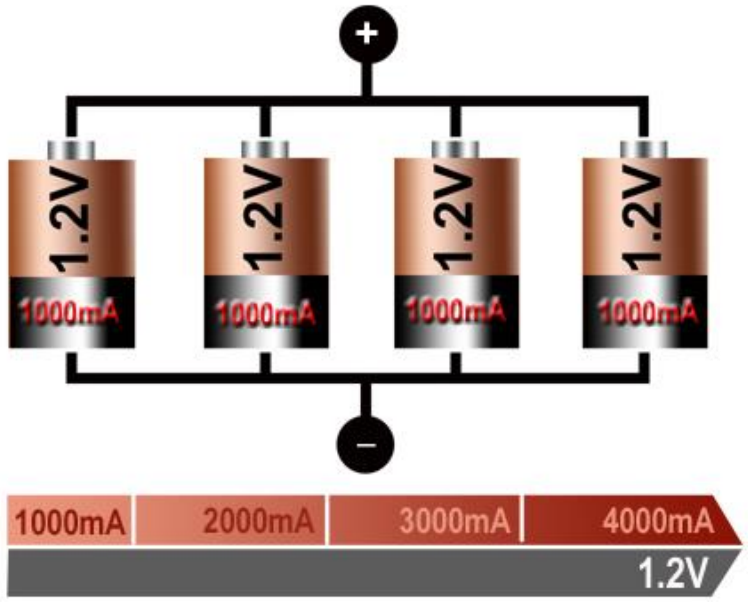
Faulty string



- Faulty cell lowers overall voltage, causing early cut-off
- Weakest cell is stressed most; stack deteriorates quickly

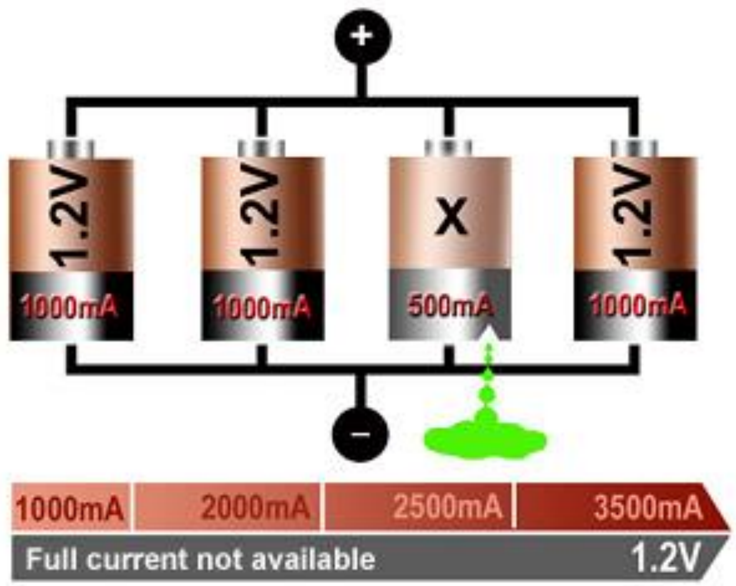
Parallel connection

Good parallel pack



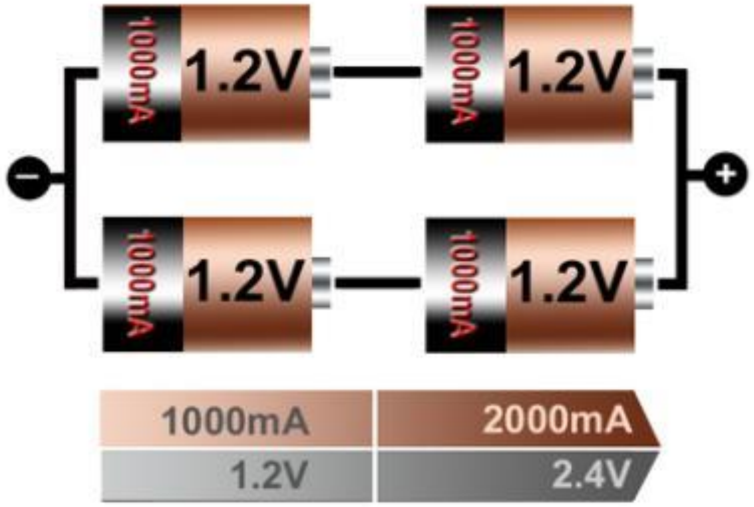
Allows high current;
same voltage

Faulty parallel pack



Weak cell reduces current,
poses a hazard if shorted

Serial-parallel connection



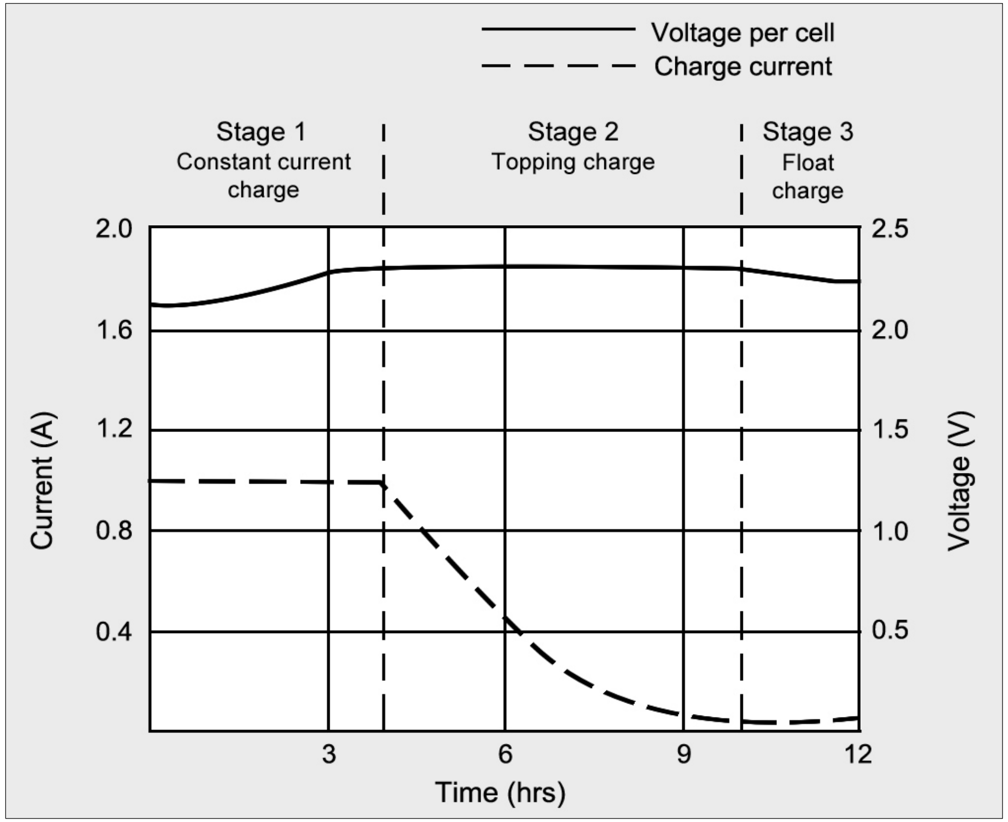
2S2P means:
2 cells in series
2 cells in parallel

- Most battery packs have serial-parallel configurations
- Cells must be matched

3. Charging, Discharging, Storing

A battery behaves like humans; it likes moderate temperatures and light duty.

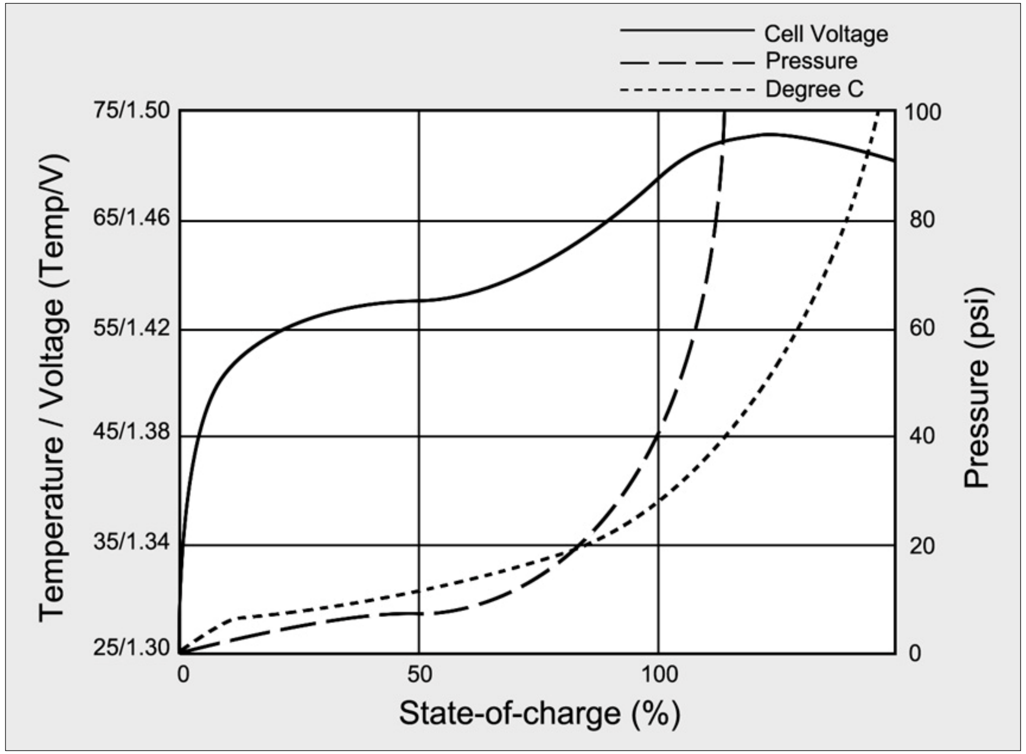
The right way to charge lead acid



- Charge to 2.40V/cell, then apply topping charge
- 2.25V/cell float charge compensates for self-discharge
- Over-charging causes corrosion, short life

- Charges in ~8h. Topping charge a must
- Current tapers off when reaching voltage limit
- Voltage must drop when ready on float charge

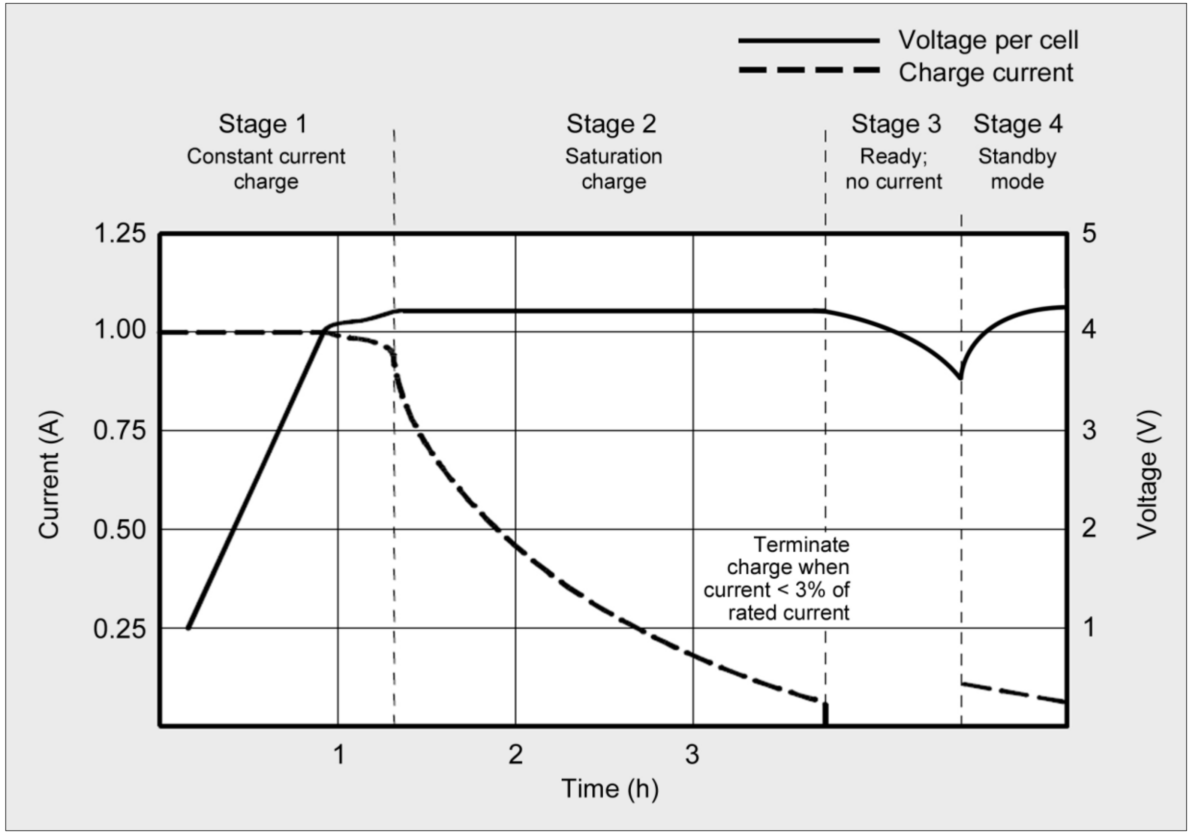
The right way to charge NiMH



- Charge to 70% efficient, then battery gets warm
- Full-charge detection difficult if battery faulty, mismatched
- Redundant full charge detection required
- Temperature sensing is required for safety

- NiCd & NiMH charge in 1-3 hours; floating voltage
- Voltage signature determines full charge
- Trickle charge on NiMH limited to 0.05C; NiCd less critical

The right way to charge Li-ion

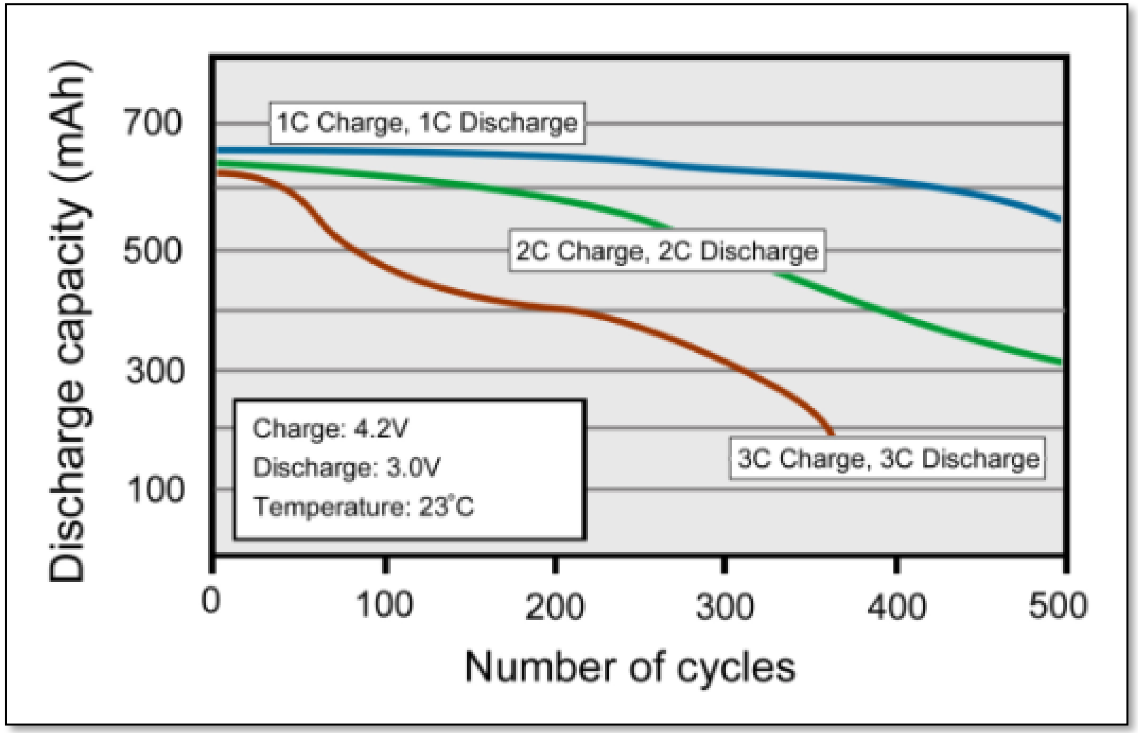


- Charge to 4.20V/cell
- Absolutely no trickle charge; cells must relax after charge
- Occasional topping charge allowed

- Li-ion charges in 1-3 hours (2/3 of time is for topping charge)
- Full charge occurs when current drops to a set level
- No trickle charge! (Li-ion cannot absorb overcharge)

What batteries like and dislike

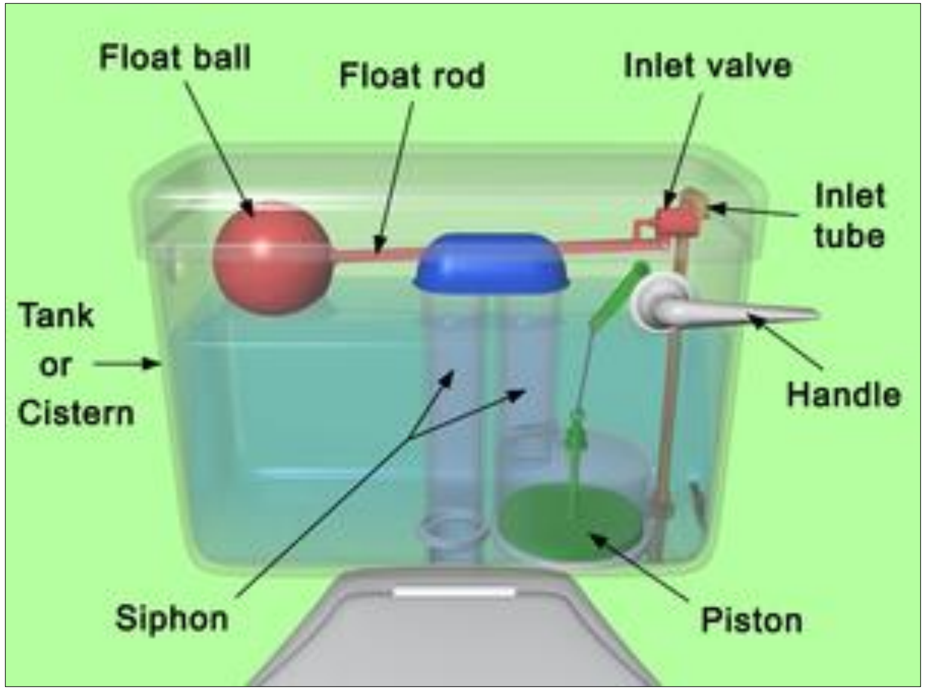
- Lead acid needs an occasional 14h saturation charge.
- Lead acid cannot be fast-charged. (A fast charge is 8h).
- Charging/discharging faster than 1h (1C-rate) causes stress.



Charging and discharging Li-ion above 1C reduces service life

Charging / Discharging

- Chargers must safely charge even a faulty battery
- Chargers fill a battery, then halt the charge
- Overcharge hints to a faulty charger
- Discharge must be directed to a proper load



Analogy

Water-flow stops when the tank is full. A faulty mechanism can cause flooding.

Placing a brick in the tank reduces capacity.

Ultra-fast charging *Use moderate charge if possible*

Some batteries can be charged in less than 30 minutes, but

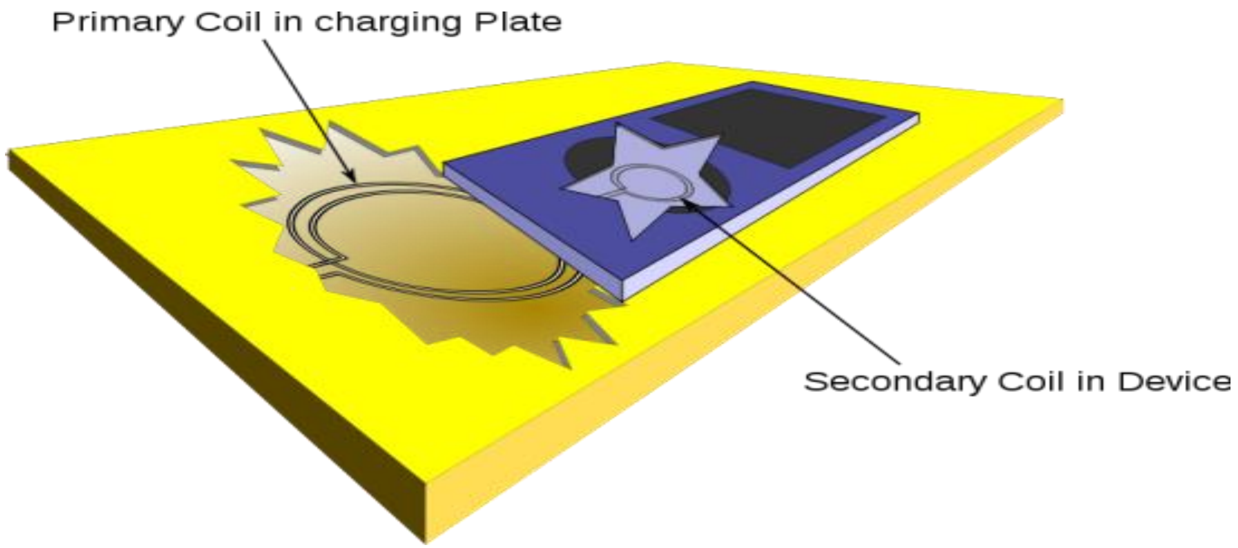
- Ultra-fast charging only works with a perfect pack
- Fast-charging causes undue stress, shortens life
- For best results, charge at 0.5–1C-rate (1–2h rate)

Chinese high-speed train

As a high-speed train can only go as fast as the tracks allow. Likewise, a battery must be in good condition to accept fast charge.

Charging without wires

- Inductive charging resembles a transmitter and receiver
- Received magnetic signals are rectified and regulated
- Transmitter and receiver command power needs
- Inductive charging is 70% efficient; produces heat



Advantages

- Convenience, no contact wear
- Helps in cleaning, sterilization
- No exposed metals, no corrosion
- No shock and spark hazard

Disadvantages

- Power limit prolongs charge times
- Generated heat stresses battery
- Concerns regarding radiation
- Complex, 25% more expensive
- Incompatible standards (Qi, PMA, A4WP)

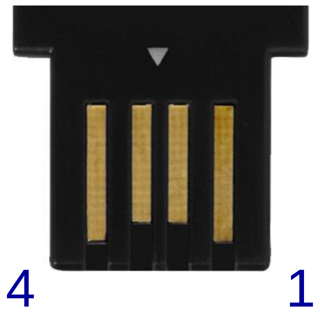
Charging at high and low temperatures

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, less below freezing. Lower V-limit by 3mV/°C >30°C
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 and 0°C Charge at 0.3C between 0°C and 5°C
Li-ion	0°C to 45°C (32°F to 113°F)	–20°C to 60°C (–4°F to 140°F)	No charge below freezing. Good charge/discharge performance at higher temperature but shorter life

Important: Charging has a reduced temperature range than discharging.

Charging from a USB Port

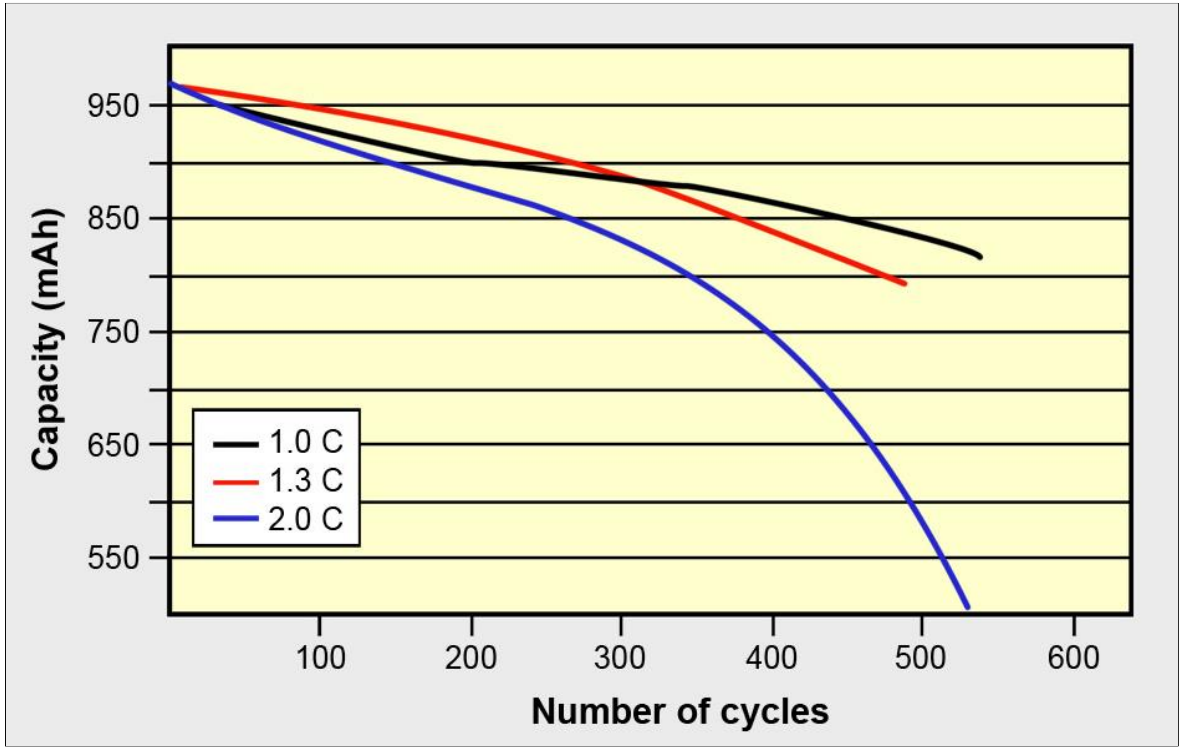
- The Universal Serial Bus (USB) introduced in 1996 is a bi-directional data port that also provides 5V at 500mA
- Charges small single-cell Li-ion
- Full charge may not be possible on larger packs
- Overloading may cause host (laptop) to disconnect



Type A USB plug

Pin 1 provides +5VDC
Pins 2 & 3 carry data
Pin 4 is ground.

Discharge methods



Source: Choi et al (2002)

- Higher loads and pulses increase stress on a battery
- Weak cells in a chain suffer most on load, fast charge
- Cells must be matched for high current discharge

Storing

Lead acid: Fully charge before storing

- Partial charge causes sulfation
- Self-discharge increases with heat
- Topping-charge every 6 months

NiCd, NiMH: No preparation needed

- Can be stored charged or empty
- Needs exercise after long storage

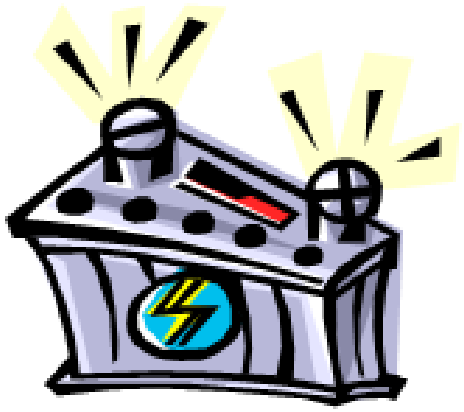
Li-ion: Store at 30-60% SoC

- Charge empty Li-ion to 3.85V/cell
- Discharge full Li-ion to 3.75V/cell (3.80V/cell relates to ~50% SoC)

Do not purchase batteries for long storage. Like milk, batteries spoil.

Health concerns with lead

- Lead can enter the body by inhalation of lead dust or touching the mouth with contaminated hands.
- Children and pregnant women are most vulnerable to lead exposure.
- Lead affects a child's growth, causes brain damage, harms kidneys, impairs hearing and induces behavioral problems.
- Lead can cause memory loss, impair concentration and harm the reproductive system.
- Lead causes high blood pressure, nerve disorders, muscle and joint pain.



Health concerns with cadmium

- Workers at a NiCd manufacturing plant in Japan exhibited heath problems from cadmium exposure
- Governments banned the disposal of nickel-cadmium batteries in landfills
- Cadmium can be absorbed through the skin by touching a spilled battery; causes kidney damage.
- Exercise caution when working with damaged batteries

Transporting Li-ion

- Estimated Li-ion failure is 1 per 10 million pack
  (1 in 200,000 failure triggered a 6 million recall in 2006)
- Most failures occur by improper packaging and handling at airports and in cargo hubs.
- Li-ion is not the only problem battery. Primary lithium, lead, nickel and alkaline can also cause fires.
- Battery failures have gone down since 2006.

Maximum lithium or equivalent lithium content (ELC) **shipped under Section II**

- **2g lithium in a lithium-metal battery** (primary)
- **8g ELC in a single Li-ion pack** (up to 100Wh)
- **25g ELC if in several packs** (up to 300Wh)

To calculate ELC, multiply Ah times 0.3.

Spare batteries must be carried, not checked in.

*Shipment exceeding Section II by land, sea and air must be expedited under **“Class 9 miscellaneous hazardous material.”***

FAQ on charging and discharging

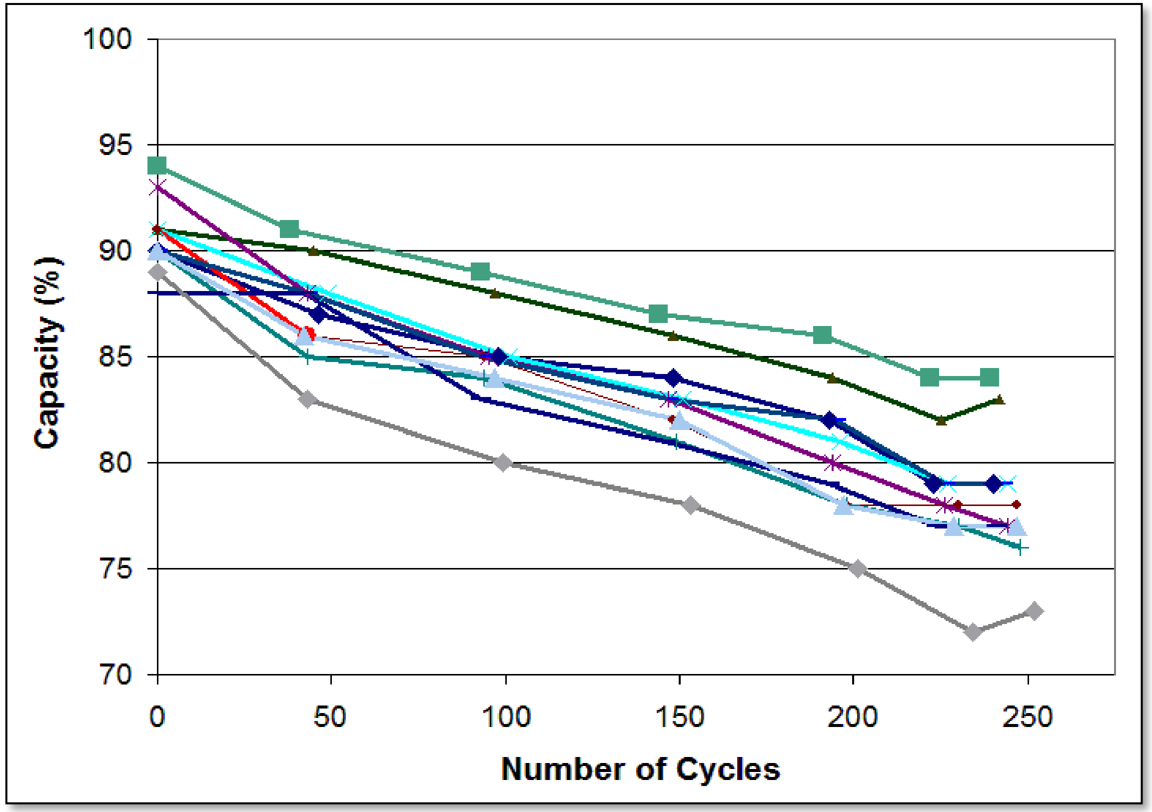
FAQ	Lead acid	Nickel-based	Li-ion
Can I harm battery by incorrect use?	Yes, do not store partially charged	Do not overheat, do not overcharge	Keep cool, store ate partial charge
Is a partial charge fine?	Charge fully to prevent sulfation	Charge NiCd and NiMH fully	Partial charge fine
Do I need to use up all charge before charging?	No, deep dis-charge harms the battery	Apply scheduled discharges only to prevent “memory”	Partial discharge is better, charge more often instead
Will the battery get warm on charge?	Slight temperature raise is normal	Gets warm; must stay cool on ready	Must always remain cool
Can I charge when cold?	Slow charge only (0.1) at 0–45°C Fast charge (0.5–1C) at 5–45°C		Do not charge below 0°C
Can I charge at hot temperature?	Lower V threshold when above 25°C	Will not fully charge when hot	Do not charge above 50°C
How should I store my battery?	Keep voltage above 2.05V/cell	Can be stored totally discharged	Store cool and at a partial charge

4. How to prolong Battery Life

Batteries are sometimes replaced too soon, but mostly too late.

Battery fade cannot be stopped, but slowed

- Li-ion provides 300-500 full discharge cycles
- Capacity is the leading health indicator of a battery
- A capacity-drop to 80 or 70% marks end of life

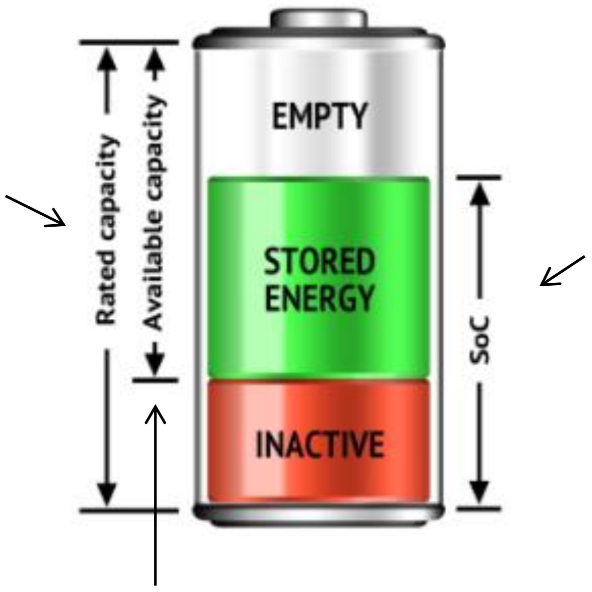


Capacity loss of 11 Li-ion batteries for mobile phones when fully cycled at 1C

Knowing the difference between Capacity and SoC

Capacity *and* ***SoC*** *determine the runtime but the siblings are not related*

Rated Capacity (Ah) includes the *Empty, Stored Energy* and *Inactive* part



SoC includes *Stored Energy* and *Inactive* part

Available Capacity represents the actual playfield

Avoid deep discharges

Cycle life as a function of depth-of-discharge (DoD)

Depth of discharge	Number of discharge cycles of Li-ion, NiMH
100% DoD	300 - 500
50% DoD	1,200 - 1,500
25% DoD	2,000 - 2,400
10% DoD	3,750 - 4,700

← Satellites

- Prevent deep discharges; charge more often
- Only apply a deliberate full discharge for calibration
- NiCd & NiMH benefit from periodic cycling (memory)

Keep battery cool

Function of SoC and temperature

Capacity of Li-ion after 1 year

Temperature	40% charge	100% charge
0°C	98%	94%
25°C	96%	80%
40°C	85%	65%
60°C	75%	60% (after 3 months)

← Laptop

Heat in combination of full-charge hastens aging

Retain moderate charge voltage

Longevity as a function of charge voltage

Charge level V/cell of Li-ion	**Number of full discharge cycles**	**Capacity at full charge**
(4.30)	(150 – 250)	(110%)
4.20	300 – 500	100%
4.10	600 – 1,000	90%
4.00	1,200 – 2,000	70%
3.90	2,400 – 4,000	50%

Every 0.10V below 4.20V/cell doubles cycle life; lower charge voltages reduce capacity

Table of Battery Dos and Don’ts

Battery care	Lead acid	Nickel-based	Li-ion
Best way to charge	Apply occasional full 14h charge to prevent sulfation; charge every 6 month	Avoid leaving battery in charger on Ready for days (memory).	Partial charge fine; lower cell voltages preferred; keep cool.
Discharge	Do not cycle starter batteries; avoid full discharges; always charge after use.	Do not over-discharge at high load; cell reversal causes short.	Keep protection circuit alive by applying some charge after a full discharge.
Disposal	do not dispose; recycle instead. Lead is a toxic.	Do not dispose NiCd. NiMH can be disposed at low volume.	Environmentally friendly. Can be disposed at low volume.

How far can the Battery go?

- EV sets the upper boundary on battery feasibility.
- Price and longevity dictate how far the battery can go.
- Powering trains, ships and airplanes makes little sense.
- Competing against oil with a 100x higher net calorific value that is tough to meet, but . . .
- Petroleum cannot touch the battery that is clean, quiet, small, and provides an immediate start-up.

Net Calorific Values

Fuel	Energy by mass (Wh/kg)
Diesel	12,700
Gasoline	12,200
Body fat	10,500
Ethanol	7,800
Black coal (solid)	6,600
Wood (average)	2,300
Li-ion battery	150
Flywheel	120
NiMH battery	90
Lead acid battery	40
Compressed air	34
Supercapacitor	5

Complied from various sources. Values are approximate