A Bit About Batteries
Lead Acid, Lithium Ion, & Nickel Iron

VE3CZO

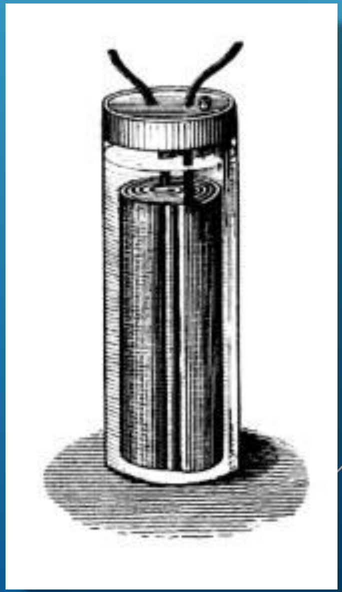
Lead Acid Battery Stuff

For every generalization there is at least one exception

- And this holds true for all the generalizations in this presentation

The first rechargeable lead acid battery…

- Invented in 1859 by French physicist Gaston Planté
- The battery consisted of two sheets of lead (assume Pb & PBO_2) held apart by two strips of tape, rolled into a cylindrical shape and immersed into a solution of 10% sulfuric acid



Battery Types & Terminology

Two Basic Lead Acid Battery Types

- 1) Wet cell
  - Two types here as well both use liquid electrolyte – Serviceable (vent caps) & maintenance free (sealed with safety valves)
- 2) VRLA Valve-regulated lead acid batteries
  - Electrolyte is immobilized by a gel or absorptive glass mat (AGM)
  - Each cell contains a one way self-releasing valve to handle overcharging
  - Structure uses oxygen recombination in immobile electrolyte to replenish water supply
  - SLA Sealed Lead Acid batteries are in this category

Battery Types & Terminology

Target applications produce different physical & electrical specs

- Starting Battery
  - Low internal resistance – very high currents for short periods of time
  - Thin plates – typically 1mm
- Deep Cycle Battery
  - Provide a lower but steady level of power for a longer period of time than starter batteries
  - Longer life cycled 30 – 60 % of capacity
  - Thicker plates typically 1.5 to 3 mm

Battery Types & Terminology

Target applications produce different physical & electrical specs

- Industrial & special purpose
  - Take deep cycle further to provide steady power over a longer period of time than deep cycle batteries
  - Usually higher capacity more cycles to end of life and longer life
  - Thicker plates 5 to 6 mm or more

Battery Types & Terminology

Some Battery Terminology

- CCA Cold Cranking Amps – spec primarily for starter motors - number of amps delivered at 0 ° F for 30 seconds with a terminal voltage greater than 7.2 volts. And no it can't be equated to amp hours – chalk and cheese.
- Capacity – is the total amount of electrical energy available from a fully charged battery. Its value depends on rate of discharge, temperature, battery condition & age and the recommended end of discharge voltage
- Ah Amp hour – this current times time unit is the amount of energy put into or taken out of a device. It is also used as measure of battery capacity - usually defined as a constant current drawn from a battery over a 20 hour discharge period (.05C)to reach the manufacturer's defined end terminal voltage.
- C rate – the rate at which a battery is discharged relative to its maximum capacity. For a 1 Ah battery 1C would represent 1 amp for 1 hour, .2C would mean 200 mA for 5 hours.

Battery Types & Terminology

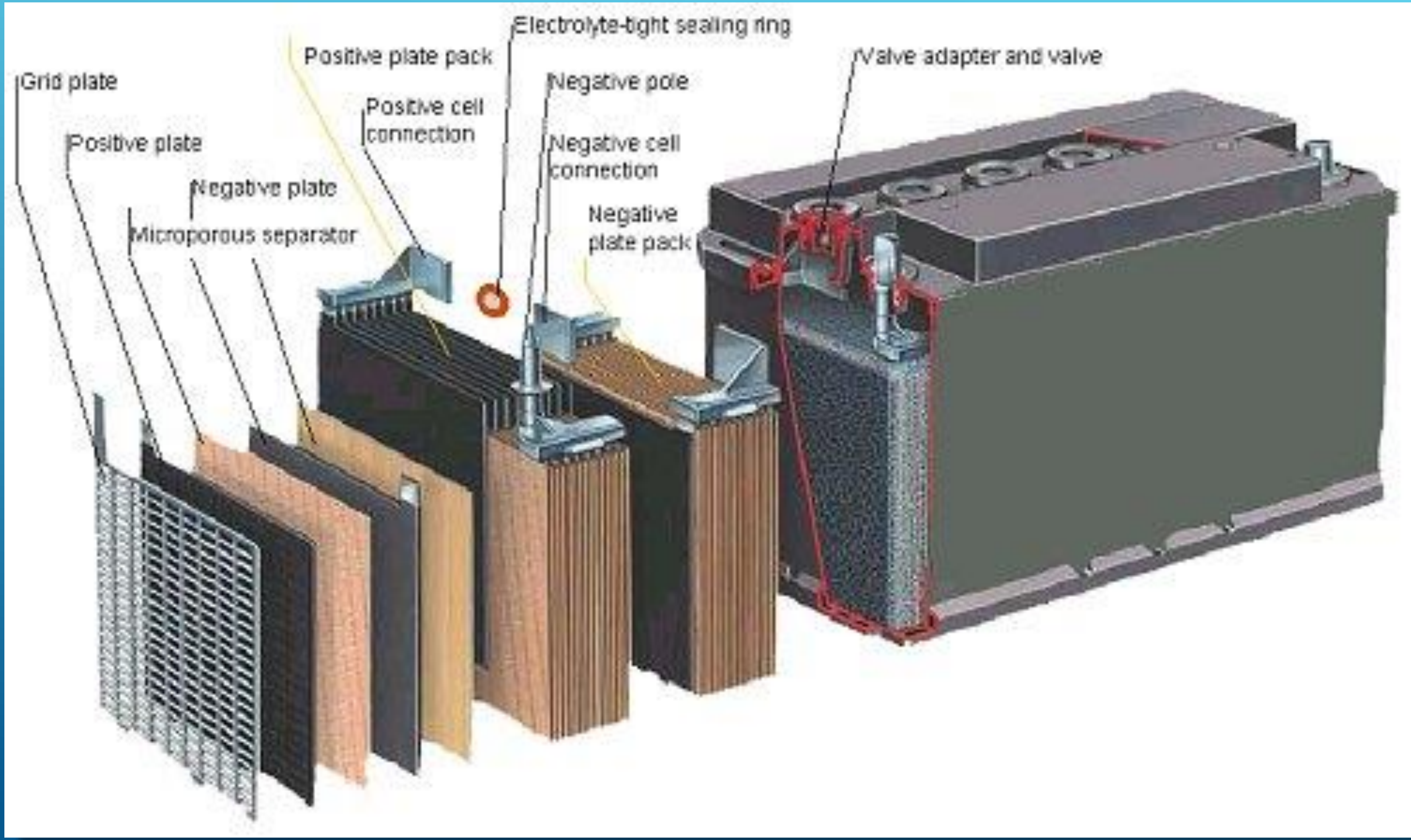
Some more Battery Terminology

- State of Charge (SoC) – Equals the remaining battery capacity in %
- Cycling – the ability to charge and discharge a battery repeatedly
- Depth of Discharge (DoD) – the amount of charge removed from a battery typically expressed as a percentage of its total capacity.
- Deep Discharge – Battery voltage under load falls below the recommended discharge cut-off voltage – significantly shortens battery life
- Self-discharge – Capacity loss during storage due to internal current leakage
- Sulfation – growth of insoluble lead sulfate crystals inhibiting ion exchange
- Float Charge – A configuration where the battery and load are permanently connected in parallel with a charging source.

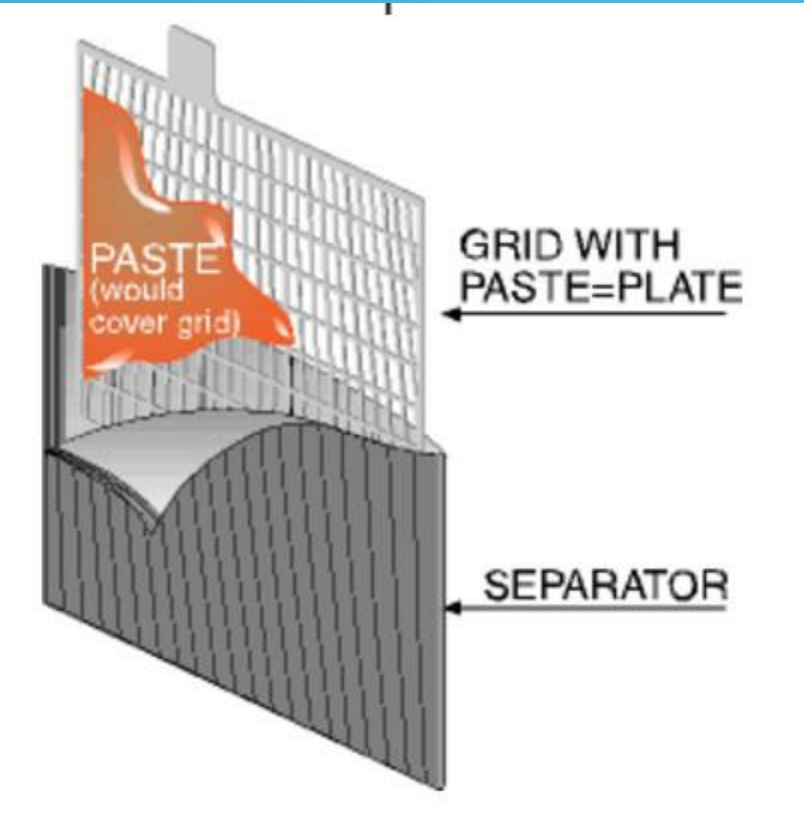
Battery Physical Structure & Chemistry

Physical Construction

- 12V battery consists of 6 cells in series
- Each cell made of positive and negative plates

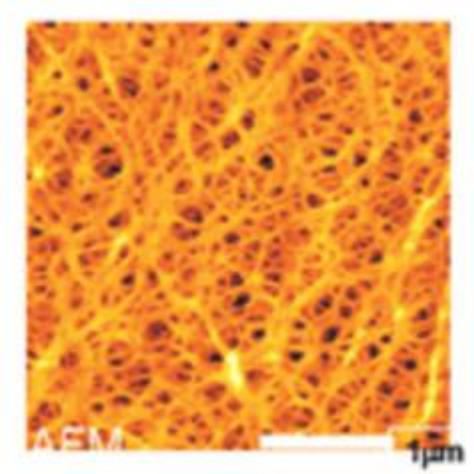


Battery Physical Structure & Chemistry



Plates & Separators

- A plate's center is a grid of lead or lead alloy
- Positive plates (anode) are formed with a lead-antimony or lead-calcium alloy with lead oxide pressed into it ($Pb0_2$)
- Negative plates (cathode) are made of porous lead
- Separators insulate plates
  - minimal thickness
  - chemically porous
  - resist penetration by burrs or dendrite growth



Battery Physical Structure & Chemistry

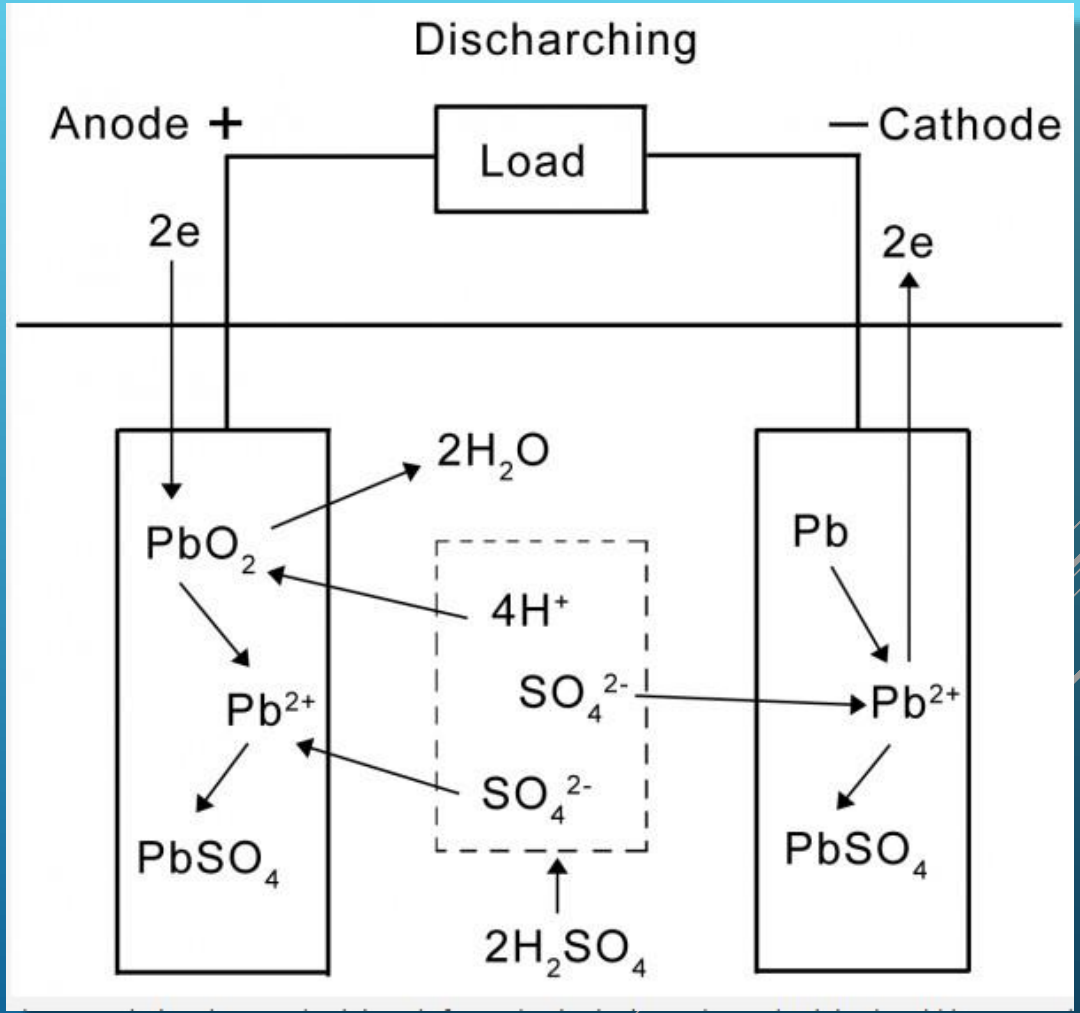
Battery Chemistry – the reversible electrochemical reaction

- While the path through an external load or charger is electrical, the path through the battery is a chemical ion exchange. For every electron that flows through the load there is an internal opposite ion flow through the electrolyte. The same amount of current flows in each path
- Electrolyte at full charge is typically 35% sulfuric acid 65% water

Battery Physical Structure & Chemistry

Battery Chemistry – Discharging

- Lead sulphate is formed at both electrodes and sulfuric acid is removed reducing electrolyte specific gravity
- Anode - Positive Plate /Terminal
  - Lead dioxide (PbO_2) is converted to lead sulphate ($PbSO_4$)
- Cathode - Negative Plate /Terminal
  - Lead (Pb) is converted to lead sulphate ($PbSO_4$)
- The reaction causes the sulfuric acid electrolyte to be consumed turning H_2SO_4 in H_2O



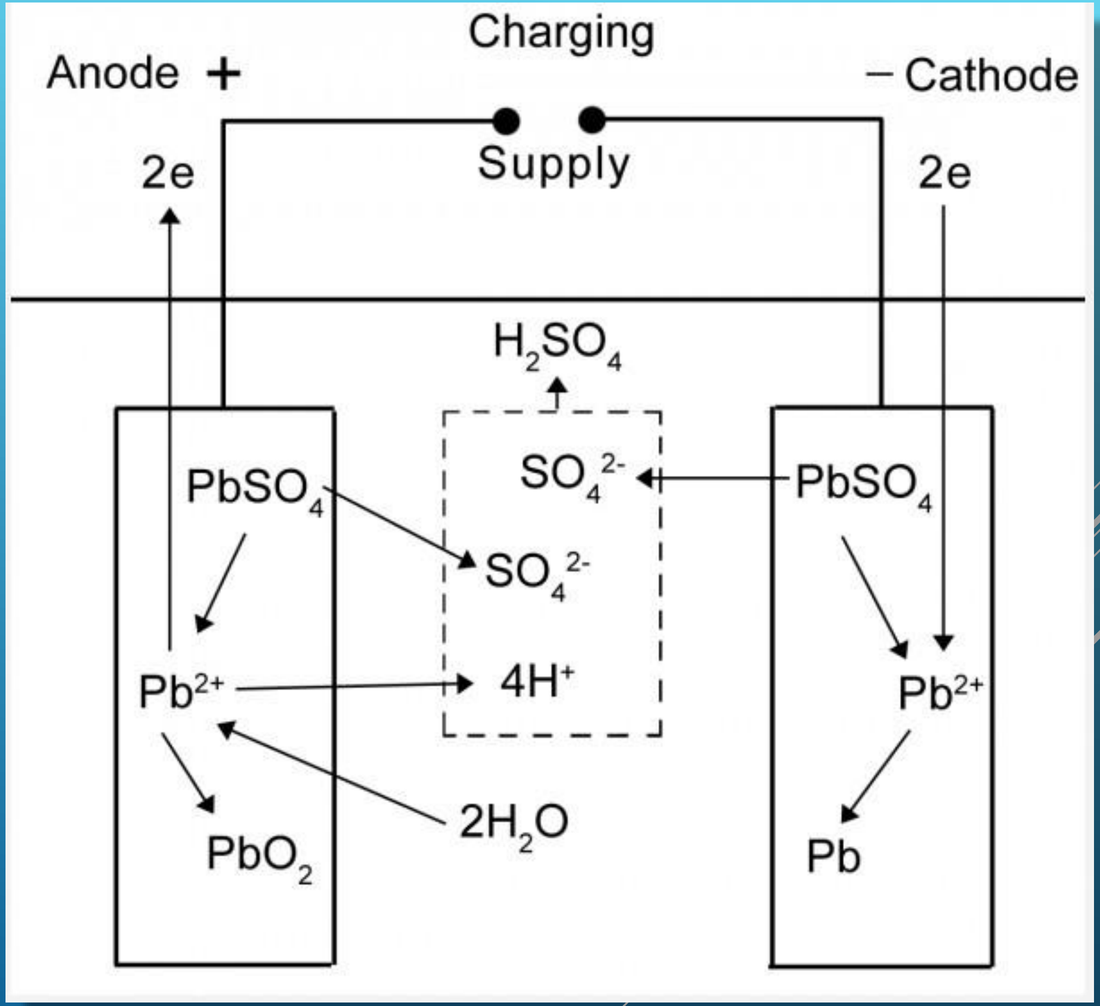
Reduction Reaction

Oxidation Reaction

Battery Physical Structure & Chemistry

Battery Chemistry – Charging

- Lead oxide is formed at the anode. Pure lead is formed at the cathode and sulfuric acid is liberated into the electrolyte causing an increase in its specific gravity
- Anode - Positive Plate / Terminal
  - Lead sulphate ($PbSO_4$) is converted to lead oxide (PbO_2)
- Cathode – Negative Plate / Terminal
  - Lead sulphate ($PbSO_4$) is converted to lead (Pb)



Battery Physical Structure & Chemistry

Maintenance free battery considerations

- Gasses generated during charging are recombined in an “oxygen cycle”
- Oxygen is generated at the positive plate and recombines with hydrogen being generated by the negative plate and forms water restoring the electrolyte volume
- If the charging rate is too high overcharging results in more oxygen being generated than can be absorbed. A safety pressure release valve opens to vent the gasses at the expense of reducing the electrolyte volume. With repeated overcharging eventually the battery loses significant electrolyte and will ‘dry out’ losing capacity

Determining State of Charge (SoC)

No method provides a precise indication all have caveats

Electrolyte specific gravity & SoC

- Hydrometer measurement is reasonably accurate but can only be used on vented batteries
  - As battery accepts charge sulfuric acid gets denser so specific gravity increases
  - As battery discharges H_2SO_4 is removed from the electrolyte & binds to the plate forming sulfate so the electrolyte density becomes lighter
- Specific gravity can vary with application
  - Deep cycle batteries use a higher H_2SO_4 concentration for a SG of 1.33 or more
  - Aviation batteries 1.285
  - Traction batteries for forklifts 1.280
  - Starter batteries for vehicles 1.265
  - Batteries for standby applications 1.225 to reduce corrosion and prolong life

Determining State of Charge (SoC)

Electrolyte specific gravity & SoC (cont'd)

- Also varies somewhat with manufacturing materials
- And varies if the fluid level is low or overfilled
- And becomes more dense as the temperature decreases
- Electrolyte stratification also causes errors
  - High acid concentration raises terminal voltage
  - Electrolyte needs to stabilize after charge or discharge

Determining State of Charge (SoC)

Electrolyte specific gravity & SoC (cont'd)

- From Trojan battery site

Percentage of Charge	Specific Gravity Corrected to 80o F	Open-Circuit Voltage 6V	8V	12V	24V
100	1.277	6.37	8.49	12.73	25.46
90	1.258	6.31	8.41	12.62	25.24
80	1.238	6.25	8.33	12.50	25.00
70	1.217	6.19	8.25	12.37	24.74
60	1.195	6.12	8.16	12.24	24.48
50	1.172	6.05	8.07	12.10	24.20
40	1.148	5.98	7.97	11.96	23.92
30	1.124	5.91	7.88	11.81	23.63
20	1.098	5.83	7.77	11.66	23.32
10	1.073	5.75	7.67	11.51	23.02

Determining State of Charge (SoC)

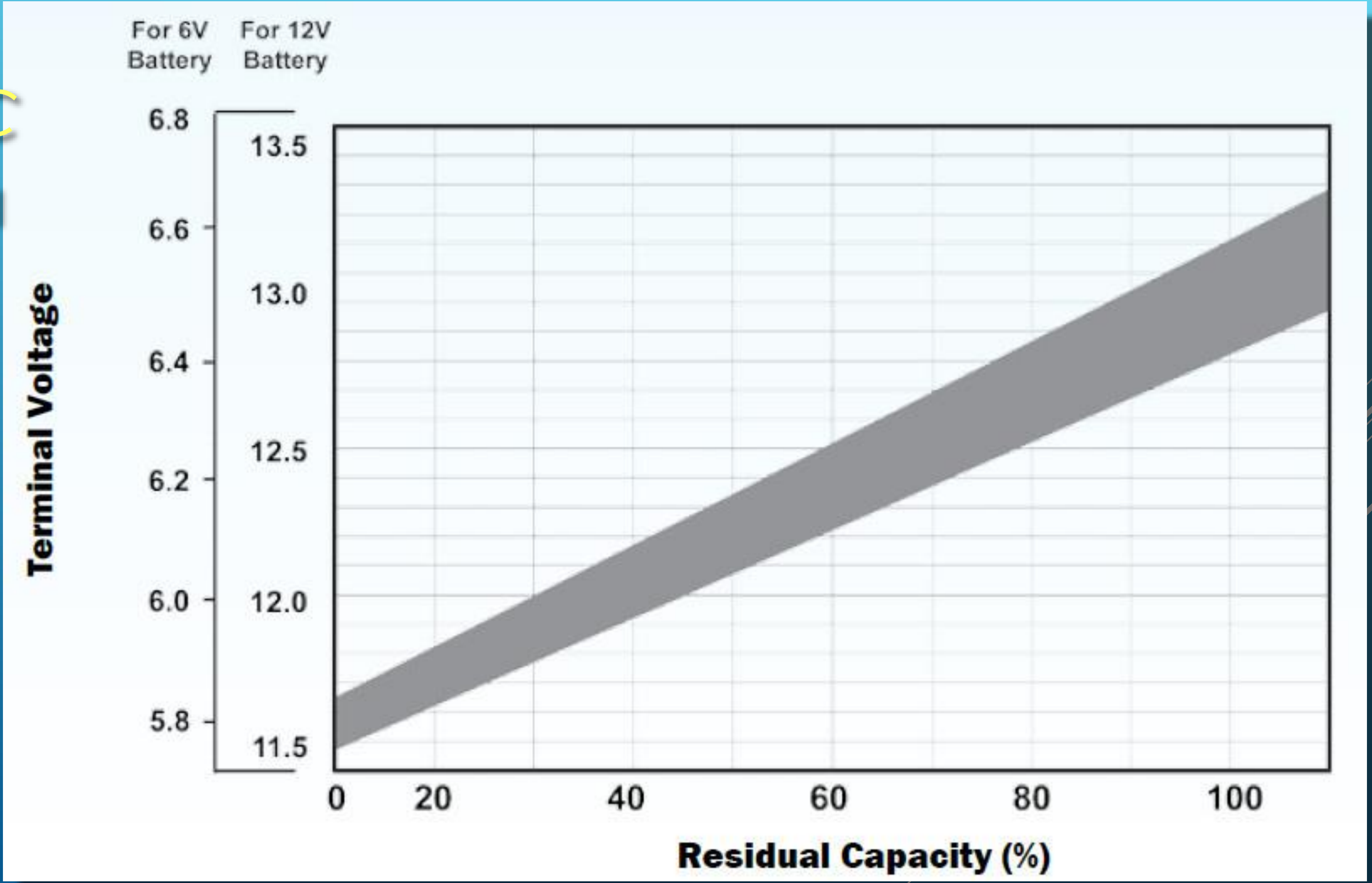
Terminal voltage measurements & SoC

- Simple but not very accurate for lead acid batteries
  - Cell materials and manufacturing techniques create significant variations
  - Charge agitation – charging or discharging distorts readings
    - Battery must be open cckt & at rest for 6 to 24 h to attain equilibrium before measuring
    - Time required to neutralize voltage polarization & the open circuit test condition makes measuring difficult for batteries in use

Determining State of Charge (SoC)

Terminal voltage measurements & SoC

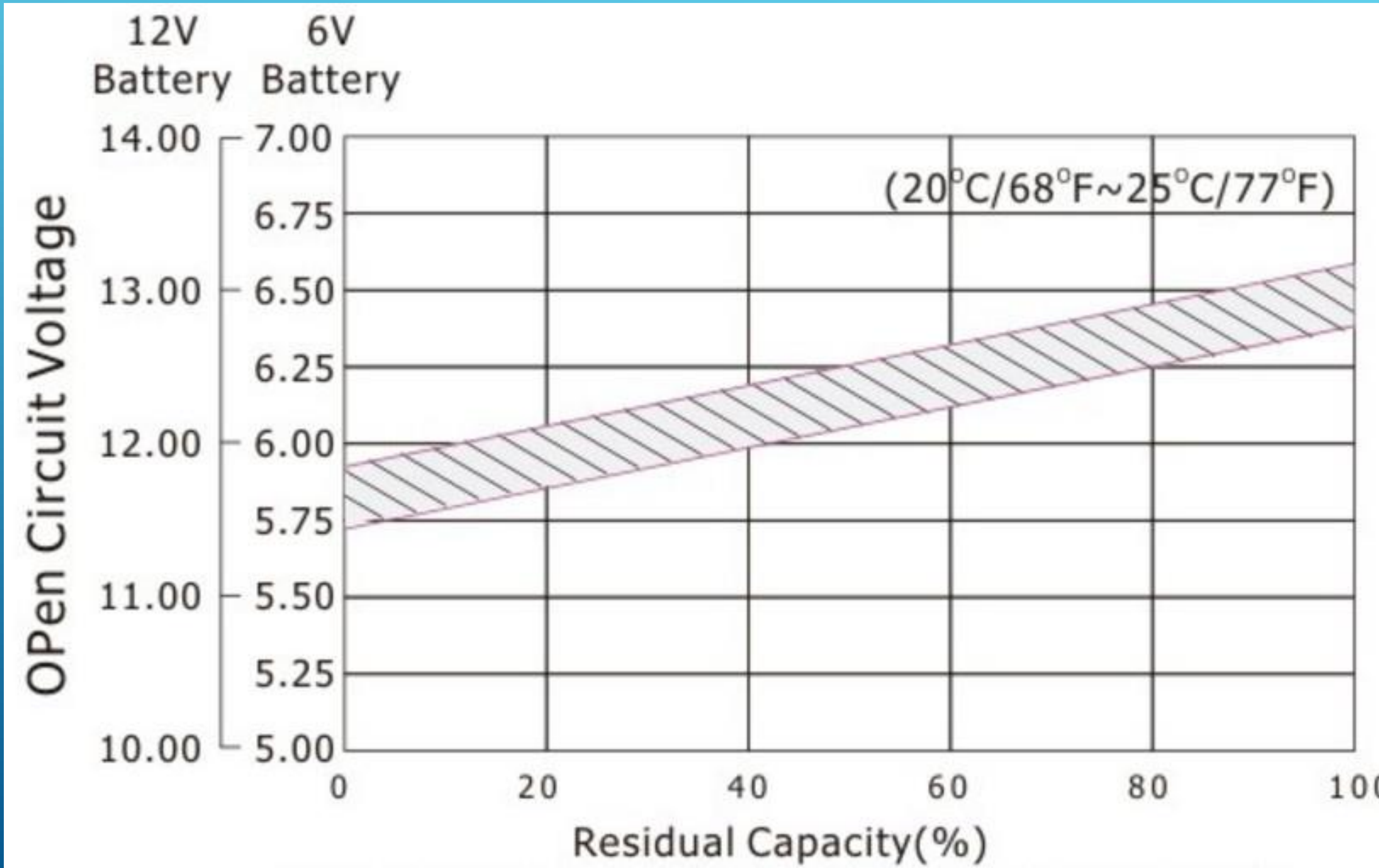
- Open circuit terminal voltage vs. SoC estimate graph after battery rest
- For example @ 12V SoC is between 30 & 45%
- And here's another graph…



Determining State of Charge (SoC)

Terminal voltage measurements & SoC

- Again for a different battery open circuit terminal voltage vs. SoC estimate graph after battery rest
- @ 12V SoC is between 10 & 45%



Self-discharge & Sulfation

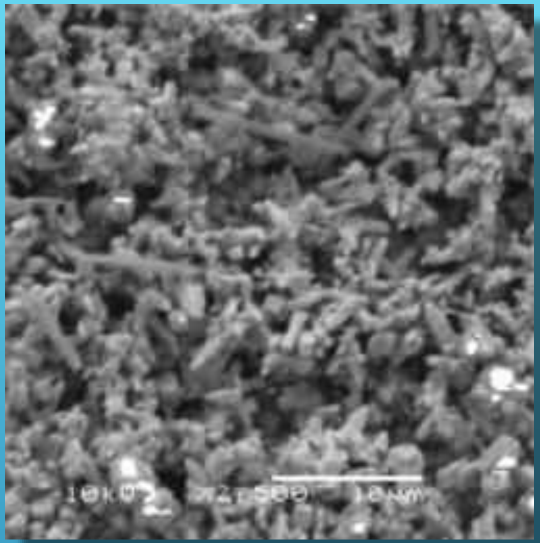
Self-discharge

- A battery's capacity loss during storage resulting from internal current leakage between positive and negative plates
- Rate depends on battery construction rages from about 2 to 5 % per month
- Rate increases with temperature doubling every 10 ° C above 25 ° C
- Rate increases with battery age
- Self-discharge mechanism
  - The discharged state is the thermodynamically stable state for a battery
  - Over time the lead and lead oxide plates react with the sulfuric acid in the electrolyte to form lead sulfate. At the same time oxygen is created at the positive electrode and hydrogen at the negative producing water that is added to the electrolyte.
  - $PbO_2+H_2SO_4 \rightarrow PbSO_4+H_20+½O_2$ and $Pb+H_2SO_4 \rightarrow PbSO_4+H_2$
  - The rate depends on battery construction, temperature, & electrolyte concentration, the lower the concentration the slower the process

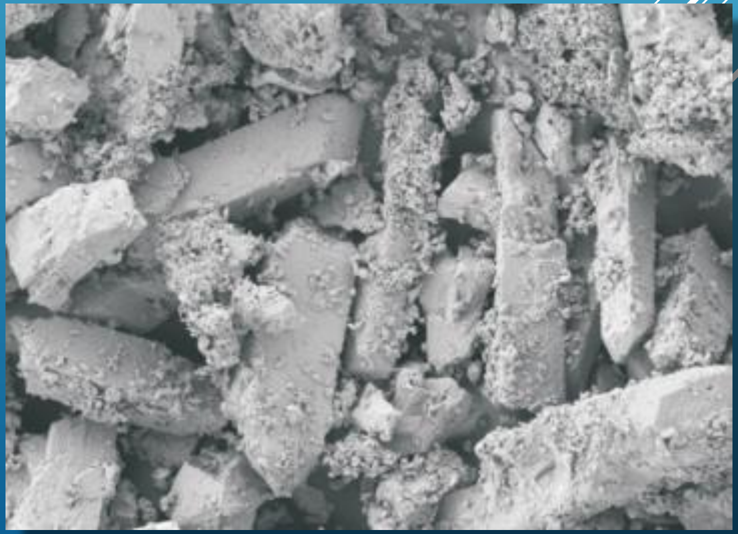
Self-discharge & Sulfation

Sulfation

- An increase in a battery's internal resistance caused by the formation of large insoluble sulphate crystals on the battery's plate which cannot be readily converted back to lead / lead oxide and sulfuric acid during recharge
- Caused by…
  - leaving or storing a battery in a partially charged state or not fully charging the battery
  - Cycling a battery in the middle of it's capacity range without fully charging
- Only a portion of the batteries rated capacity remains



New & heavily sulfated plates



Self-discharge & Sulfation

Sulfation

- Can sulfated batteries be recovered?
  - Usually the damage is irreversible
  - Sometimes at least partial recovery is possible
  - Breaking down hardened crystal sulfate and dissolving the crystals back into the electrolyte can sometimes be accomplished by charging the battery with a low current at a higher than normal charging voltage (2.5 V/cell 15V for a 12 V battery) over a long period (many days to weeks.
- Personal view on recovering sulfated battery & the great number of solutions in the market place
  - Pulsed solutions don't work very well – good place for that movie clip

Battery Life & Factors Impacting It

Battery Life factors

- Battery construction - service type – cycling - temperature

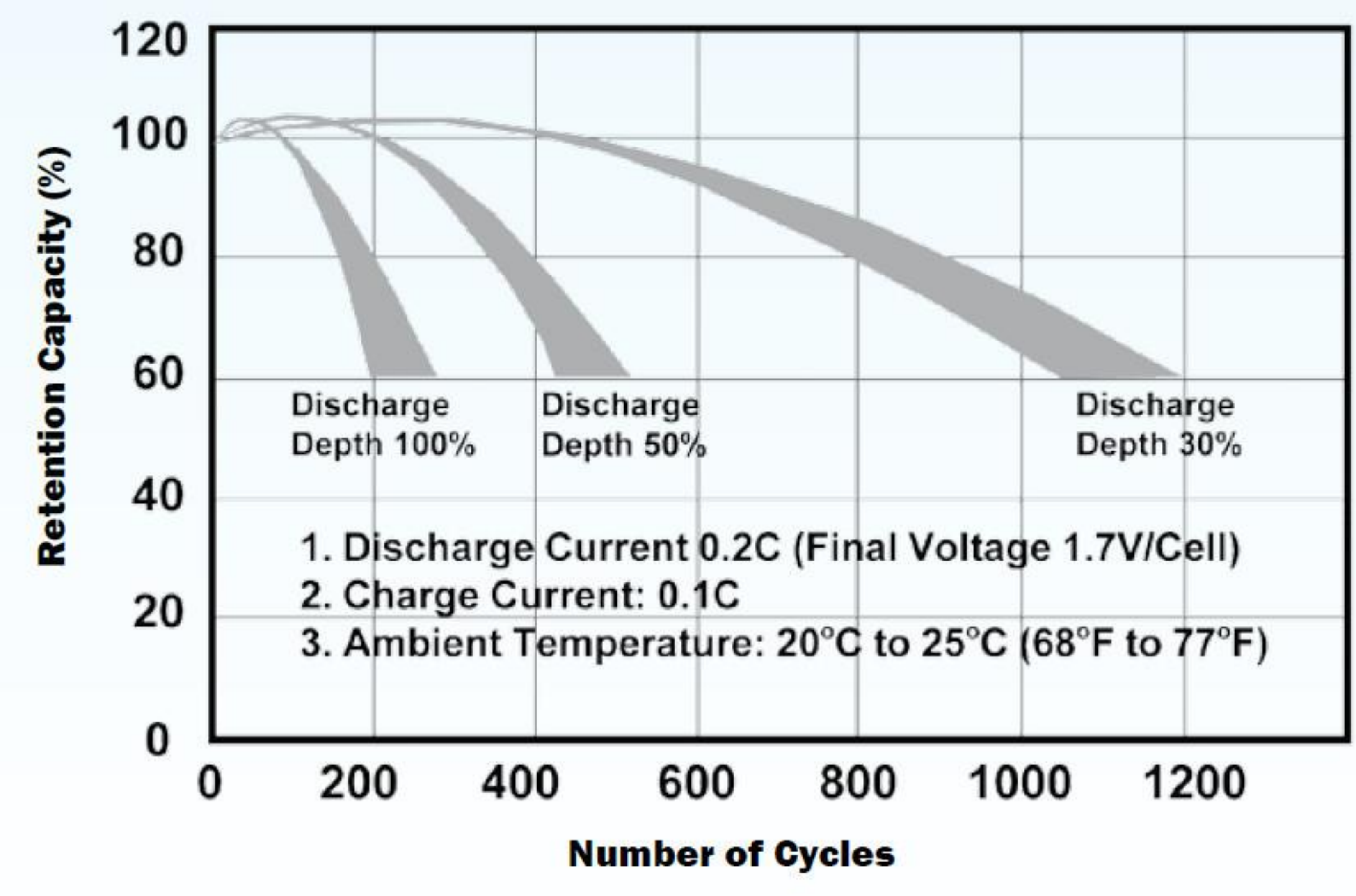
End of Life

- Often defined as 60% or less of capacity when new
- Capacity at which the battery no longer meets an application's needs
- Time to end of life – it depends on a number of factors …

Battery Life & Factors Impacting It

Cycling depth versus battery service life

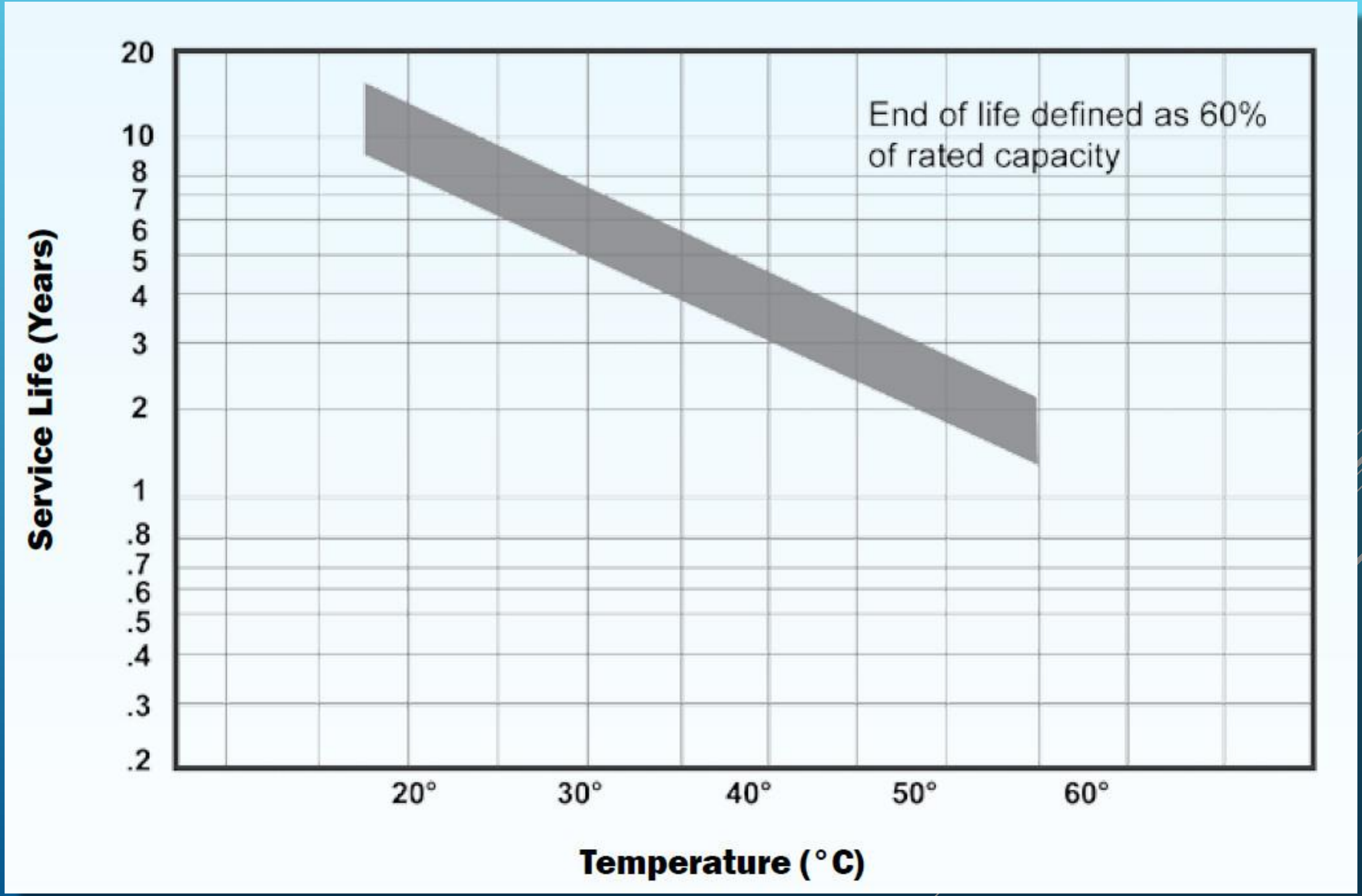
- Repeated deep discharging will damage the battery & result in early failure



Battery Life & Factors Impacting It

Temperature & Service Life

- More about this in the Temperature & Batteries section



Temperature & Batteries

Battery terminal voltage temperature coefficient

- Terminal voltage does not change with temperature when the battery is fully charged.
- The table below shows the temperature coefficient for a 12 V battery versus SoC and electrolyte specific gravity

SoC	SG	% w/w	tempco
100%	1.30	39	0 mV/° C
100%	1.25	33	0 mV/° C
0 %	1.07	10	- 1 mV/° C

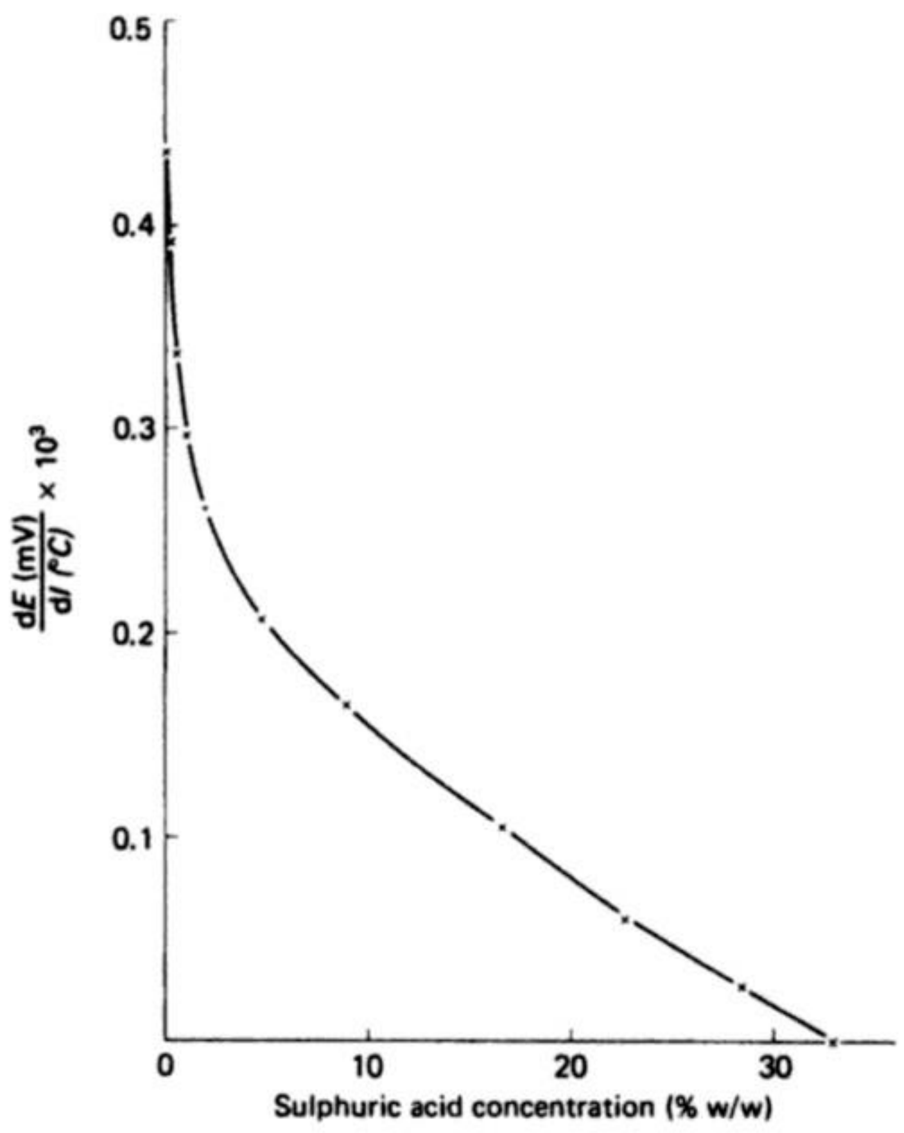


Figure 1.10 Relationship of temperature coefficient of e.m.f. with sulphuric acid concentration in lead–acid battery

Temperature & Batteries

Battery terminal voltage temperature coefficient

Table 1.6 Electromotive force and temperature coefficient of voltage for various concentrations of sulphuric acid electrolyte in the lead–acid battery

Sulphuric acid concentration (% by weight)	*E*			*Temperature coefficient, dE/dT*			*Decrease in e.m.f. (V) with 25°C temperature rise*
	15°C	25°C	40°C	15–25°C	25–40°C	15–40°C	
0.097	1.9043	1.8999	1.8934	0.000 44	0.000 43	0.000 44	0.0109
0.196	1.9172	1.9133	1.9074	0.000 39	0.000 39	0.000 39	0.0098
0.487	1.9333	1.9299	1.9249	0.000 34	0.000 33	0.000 34	0.0084
0.970	1.9446	1.9417	1.9372	0.000 29	0.000 30	0.000 30	0.0074
1.920	1.9556	1.9530	1.9491	0.000 26	0.000 26	0.000 26	0.0065
4.67	1.9706	1.9685	1.9654	0.000 21	0.000 20	0.000 21	0.0052
8.92	1.9835	1.9819	1.9794	0.000 16	0.000 17	0.000 16	0.0041
16.39	2.0002	1.9992	1.9976	0.000 10	0.000 11	0.000 10	0.0026
21	2.0100	2.0092	2.0082	0.000 07	0.000 07	0.000 07	0.0018
22.72	2.0133	2.0127	2.0118	0.000 06	0.000 06	0.000 06	0.0015
28.16	2.0254	2.0253	2.0250	0.000 01	0.000 02	0.000 02	0.0004
29	2.0263	2.0262	2.0260	0.000 01	0.000 01	0.000 01	0.0003
32.88	2.0308	2.0308	2.0308	0.000 00	0.000 00	0.000 00	0.0000

Temperature & Batteries

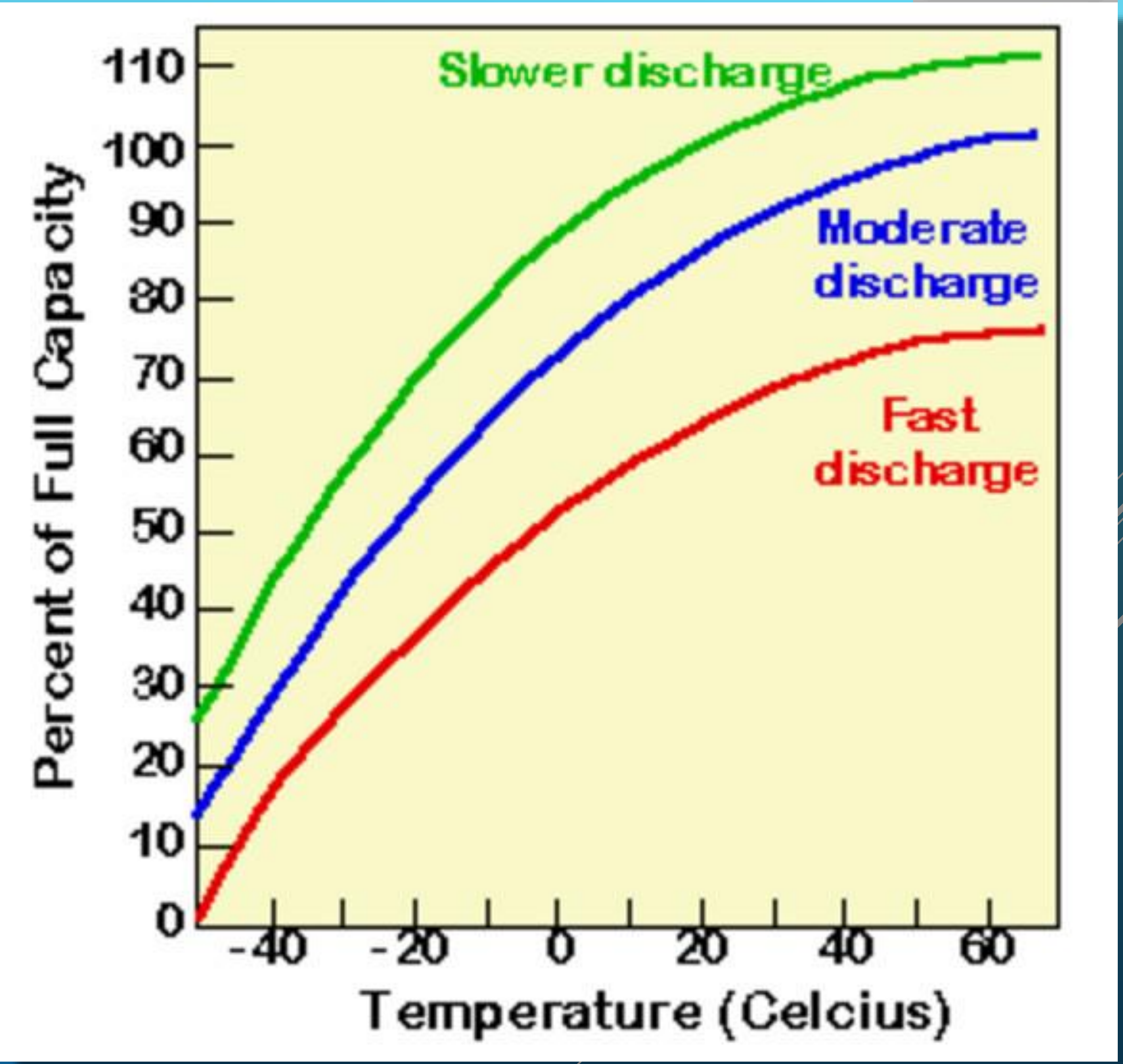
Charge efficiency & temperature compensated charging

- As temperature rises battery electrochemical activity increases (charge efficiency increases)
- As temperature rises charging voltage should be reduced to prevent overcharging. As temperature falls charging voltage should be increased to prevent undercharging
- Temperature coefficient depends on battery manufacturing typically 3-4mV/° C.

Temperature & Batteries

Capacity vs. ambient temperature

- Capacity decreases by about 1% per ° C as the temperature is lowered below 20 ° C



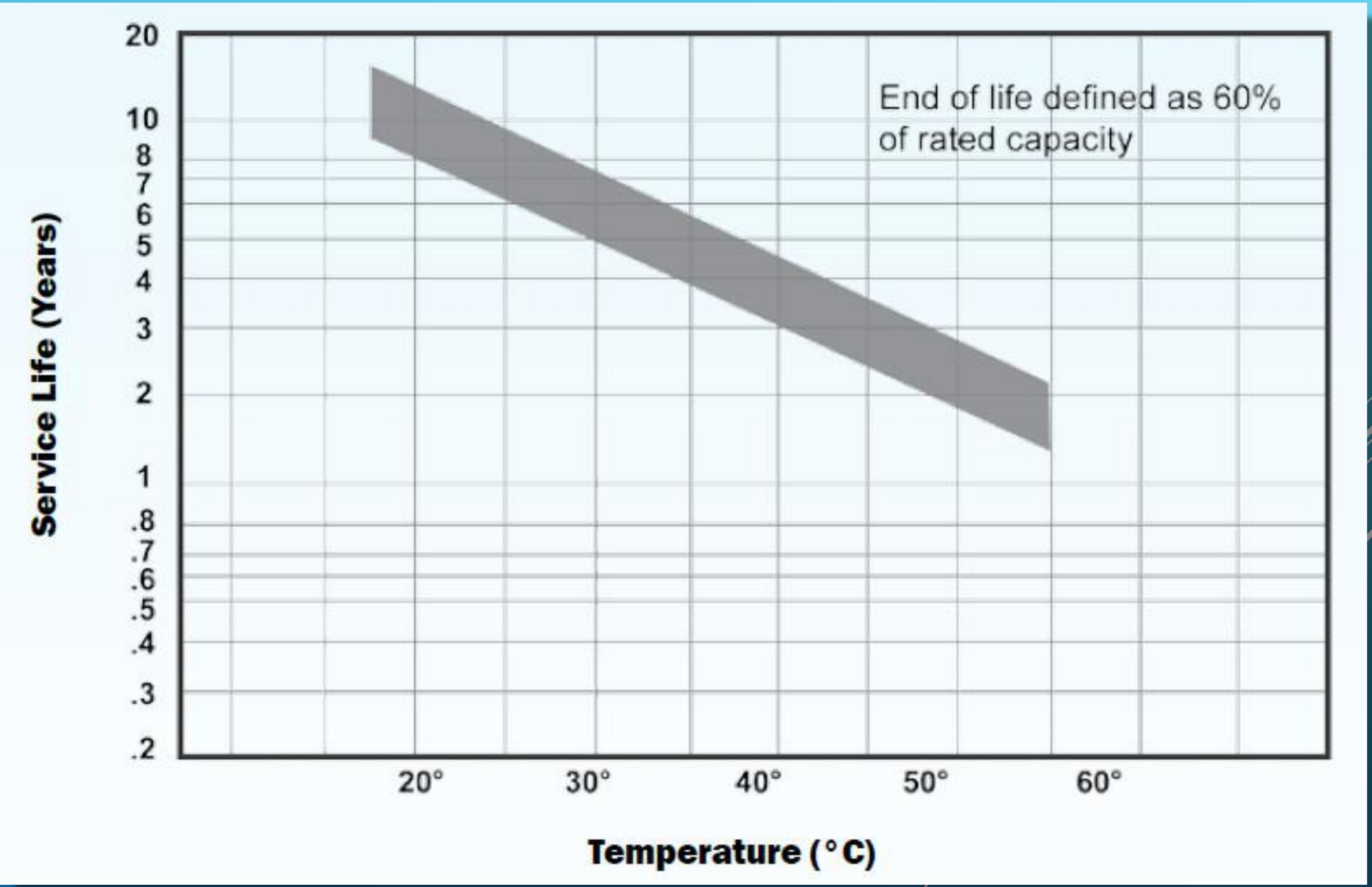
Temperature & Batteries

Service life & temperature's impact

- Battery service life is approximately halved for every 10 ° C increase above 20 ° C.

Self-discharge change with temperature

- Significant impact detailed in the Shelf Life & Storage section next…



Shelf Life & Storage

Shelf Life

- The duration a battery can be kept in storage and still retain it's ability to provide a specified performance

Storage time determined primarily by…

- Self-discharge rate
- Temperature

Shelf Life & Storage

Storage guidelines to prevent permanent damage from sulfation

- Disconnect the battery from all loads
- Store batteries in a cool location 10 - 25 ° C away from any heat sources. Storage at higher temperatures accelerates self-discharge. Doubles every 10 ° C above 25 ° C
- Recharge batteries as soon as possible after each use before storing
- Store batteries fully charged
- Recharge every 6 months or when battery is at 60-70% of capacity

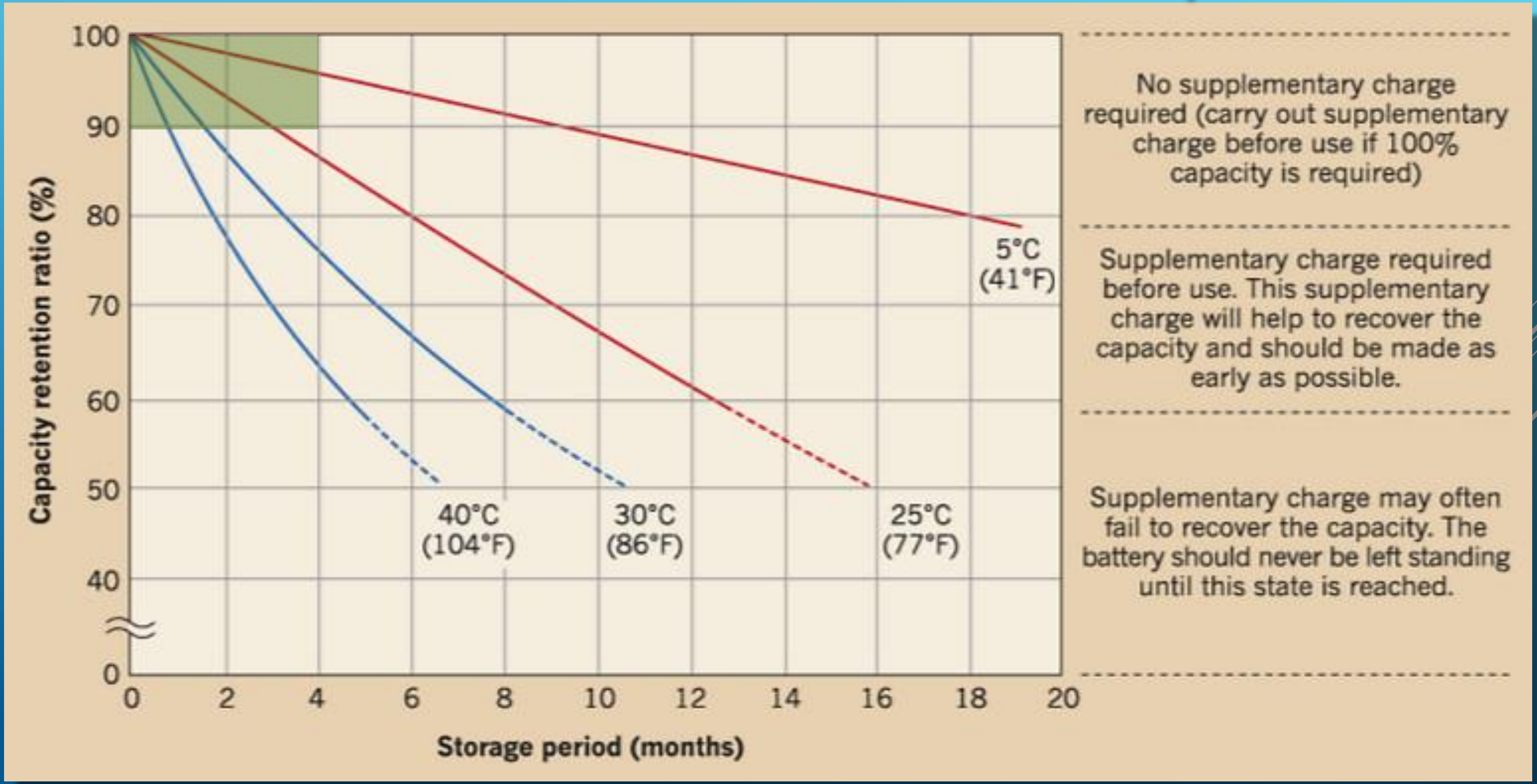
Storage temperature significantly changes storage time

- Time halves for every 10 ° C. above 20 - 25 ° C.
- Time increases at lower temperatures … see graph following slide

Shelf Life & Storage

Green shaded area shows BK II objectives

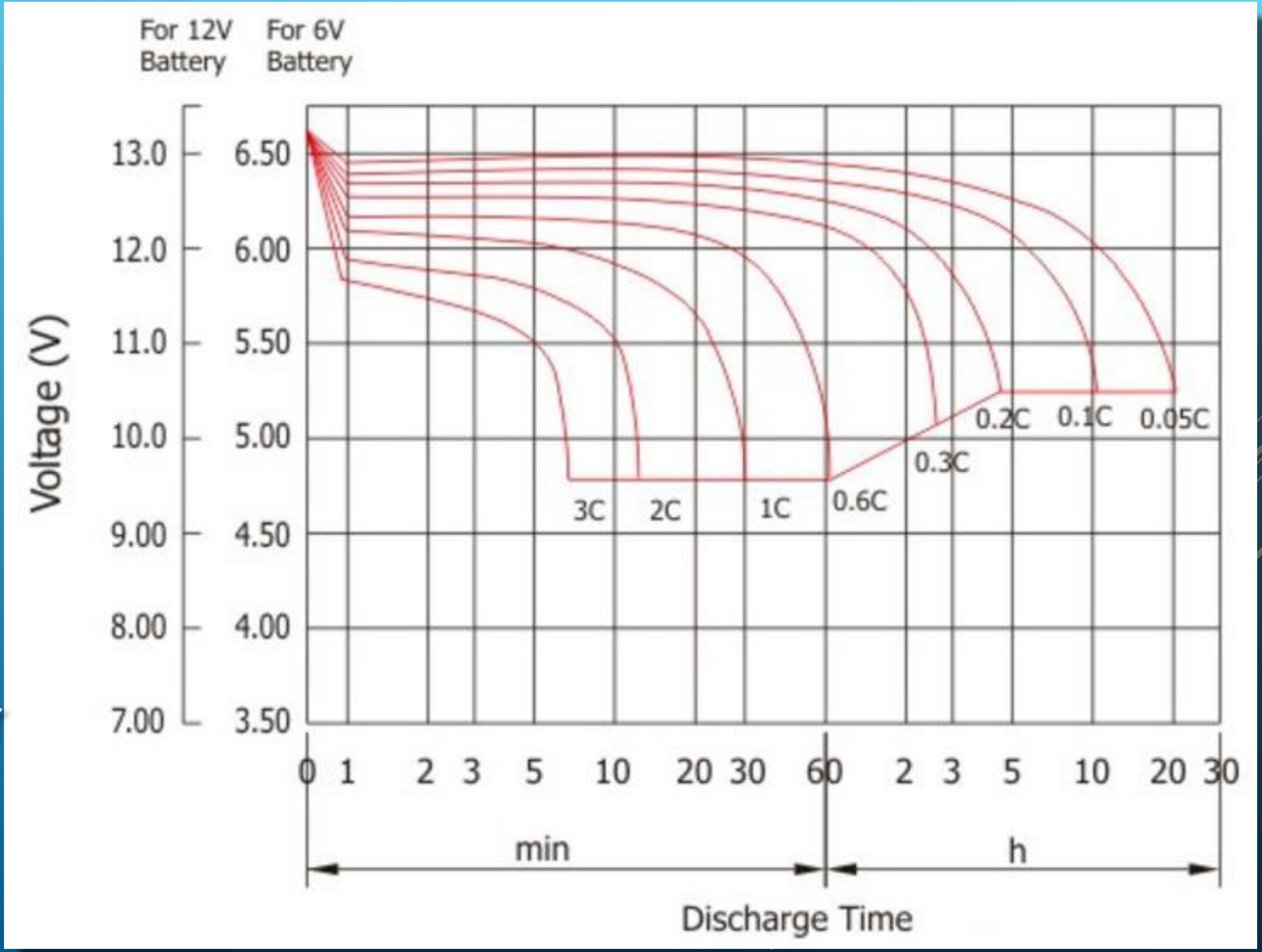
Storage



Battery Capacity & Discharge Rate

The manufacturer's spec says xx Ah but…

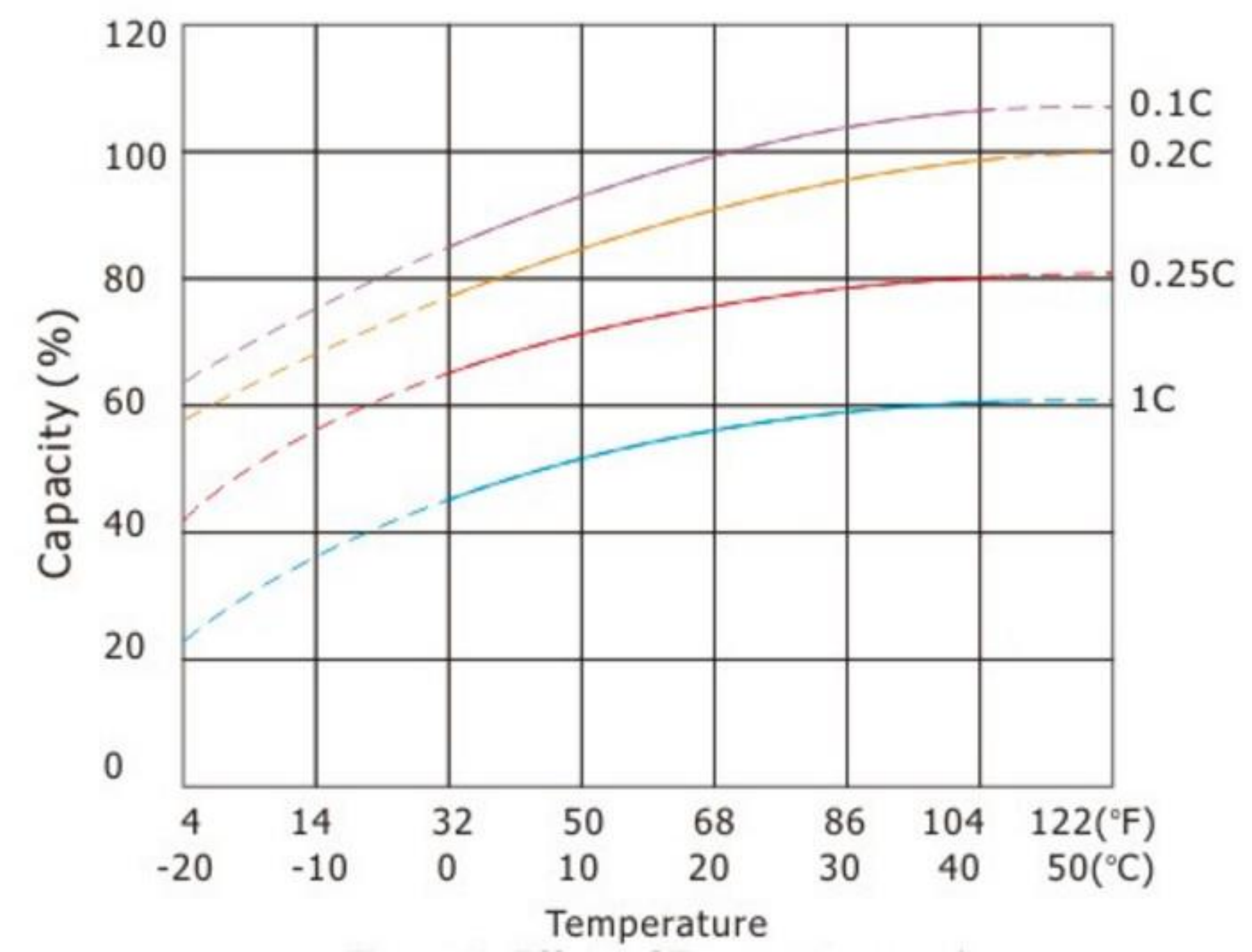
- Most manufacturers rate battery capacity at C/20
- Rate of discharge significantly changes a battery's capacity.
- The relationship between battery capacity and discharge current isn't linear less energy is recovered at faster discharge rates (read about Peukert's Law)



Battery Capacity & Discharge Rate

And Temperature…

- Capacity decreases with decreasing temperature



Battery Charging Methods

Battery performance & service life depend on controlled charging

Standard Multi-stage Charging

Bulk Charge

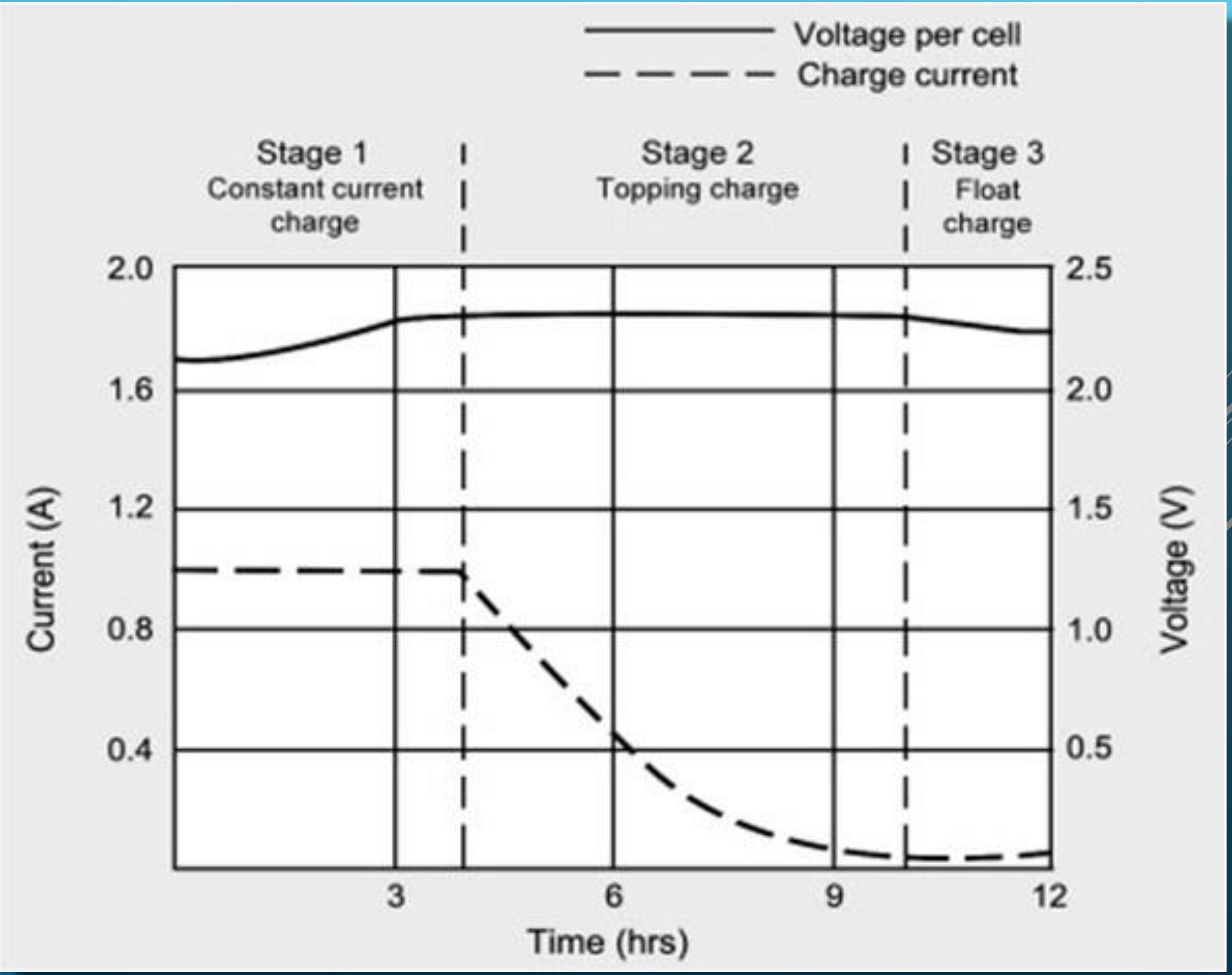
- Constant current is applied, battery voltage rises

Taper Charge

- Constant voltage applied, battery current tapers off

Float Charge

- Voltage is lowered – compensates for self-discharge



Battery Charging Methods

Bulk Charge

- Constant current should be limited to about 0.3C and NEVER used as a single method
- Battery charges to around 70% to 80% of its capacity in this mode
- Switches to taper charge as the target cell voltage is achieved

Constant Voltage (Taper Charge)

- Good for finishing a charge. Current will taper off to C/100 to C/200 and remain steady when the battery is fully charged
- Not suitable for initial charging unless current is limited – can result in very high currents
  - Can increase battery temp - cause outgassing & permanently damage the battery
- Target voltage is manufacturer specific but will be between 2.3 and 2.45 V per cell 13.8 and 14.7 volts for a 12 volt battery

Float Charge

- Constant lower voltage 2.25 – 2.28 V/cell 13.5 to 13.7 for a 12 volt battery

Battery Charging Methods

Charging Efficiency

- If discharged by over about 15% of capacity on recharging most batteries will need about 105% to 115% of the amp hours removed to fully recharged
- Shallow discharges 10 % or so recharge less efficiently

Overcharging

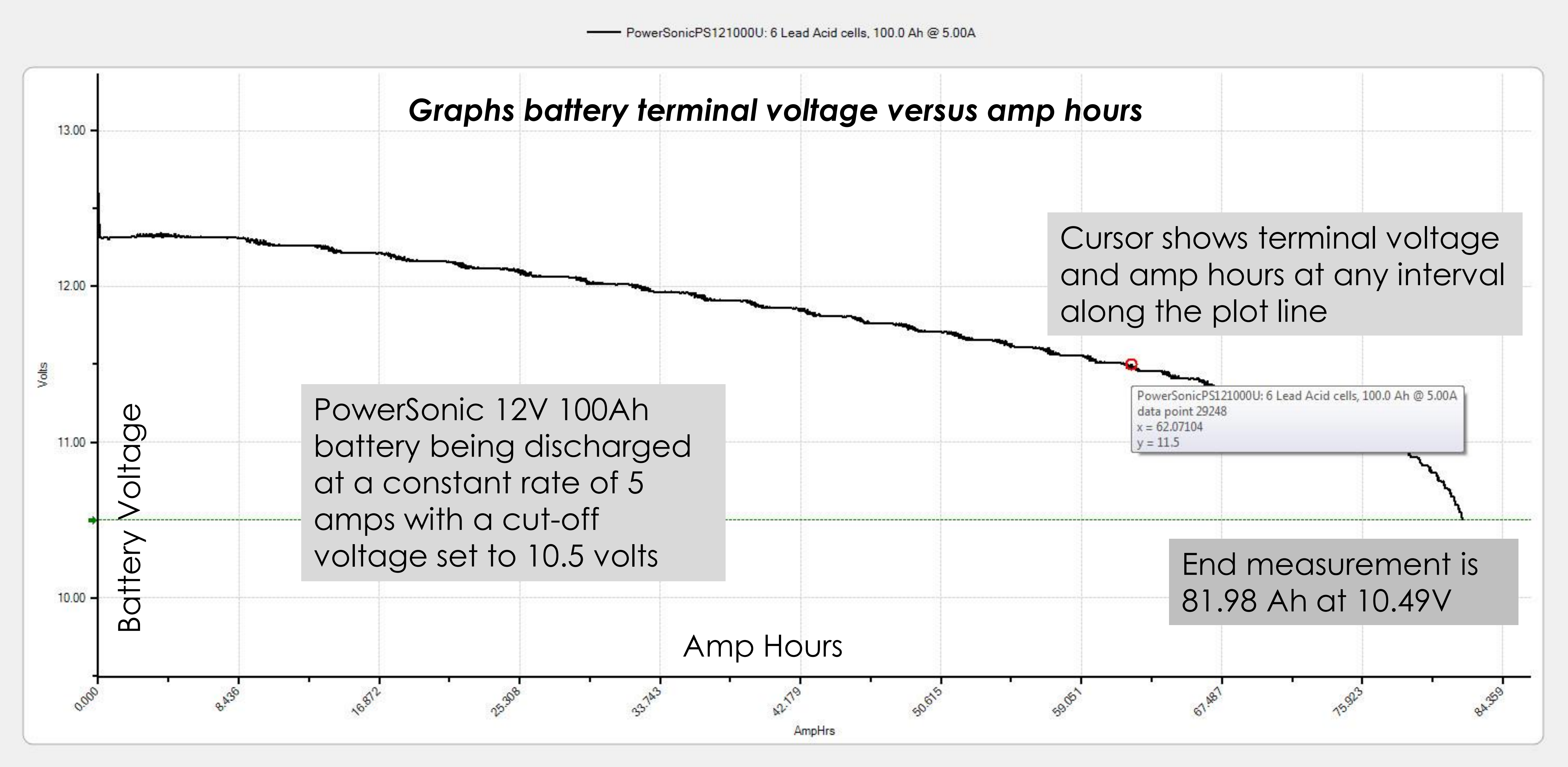
- Charging at too high a rate or forcing more energy into the battery that was required to replace a charge constitutes overcharging.
- Causes grid corrosion & outgassing, both permanently reduce battery service life

Measuring Battery Capacity

One Methodology

- Computerized Battery Analyzer (CBA) from West Mountain Radio
  - Constant discharge current 10mA – 40A
  - Automatic shut off with user selectable low voltage cut-out threshold
- Used sparingly as each run removes one deep discharge cycle from the battery's service life
- Provides a graph of battery voltage vs. Ah capacity like this…

Measuring Battery Capacity



Battery Myths & Useful Tips

Batteries should not be stored on a concrete floor

- Modern batteries are not harmed or discharged in any way but historically…
  - Very first batteries consisted of glass cells enclosed in a tar-lined wooden box. A damp floor swelled the wood breaking the glass cells
  - Nickel-iron battery (Edison cell) was encased in steel & those not isolated in crates would discharge into concrete
  - Early batteries were encased in a somewhat porous rubber that often contained carbon. Moisture it the concrete floor in combination with the carbon in the case could create electrical current between the cells

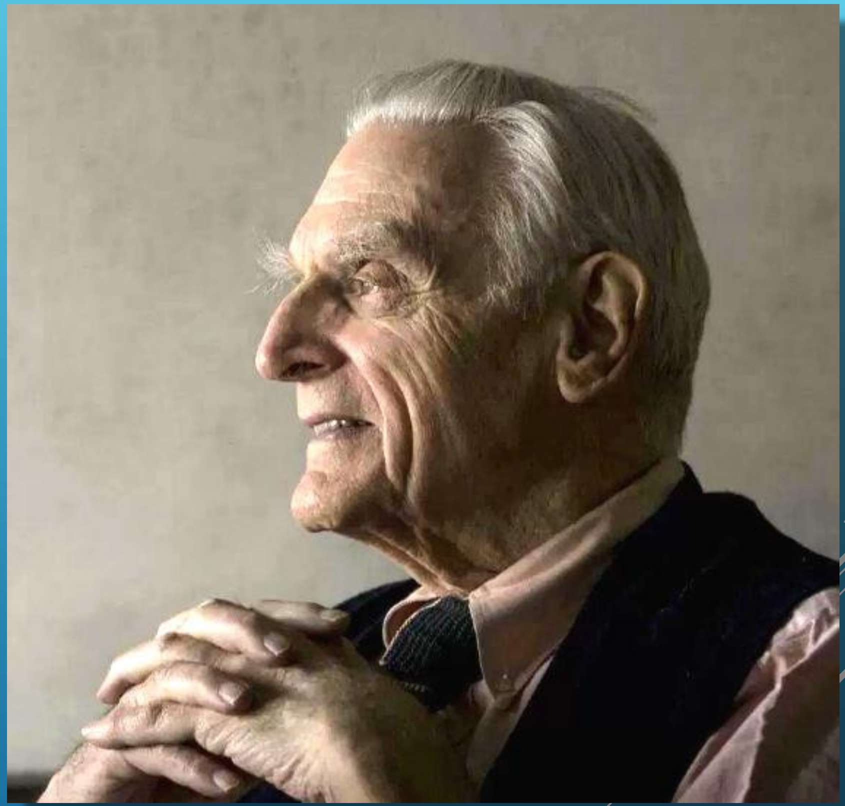
When buying a lead acid battery

- Check the terminal voltage. If under 12V leave it on the shelf.

Lithium Ion Batteries

History

- In 1980 at Stanford University Ned A. Godshall et al and at Oxford John Bannister Goodenough & Koichi Mizushima invented lithium ion's cobalt – oxide cathode & lithium metal as the anode. $LiCo_2$ was the first stable material that made lithium cells viable
- First commercially introduced by Sony Energy in 1991

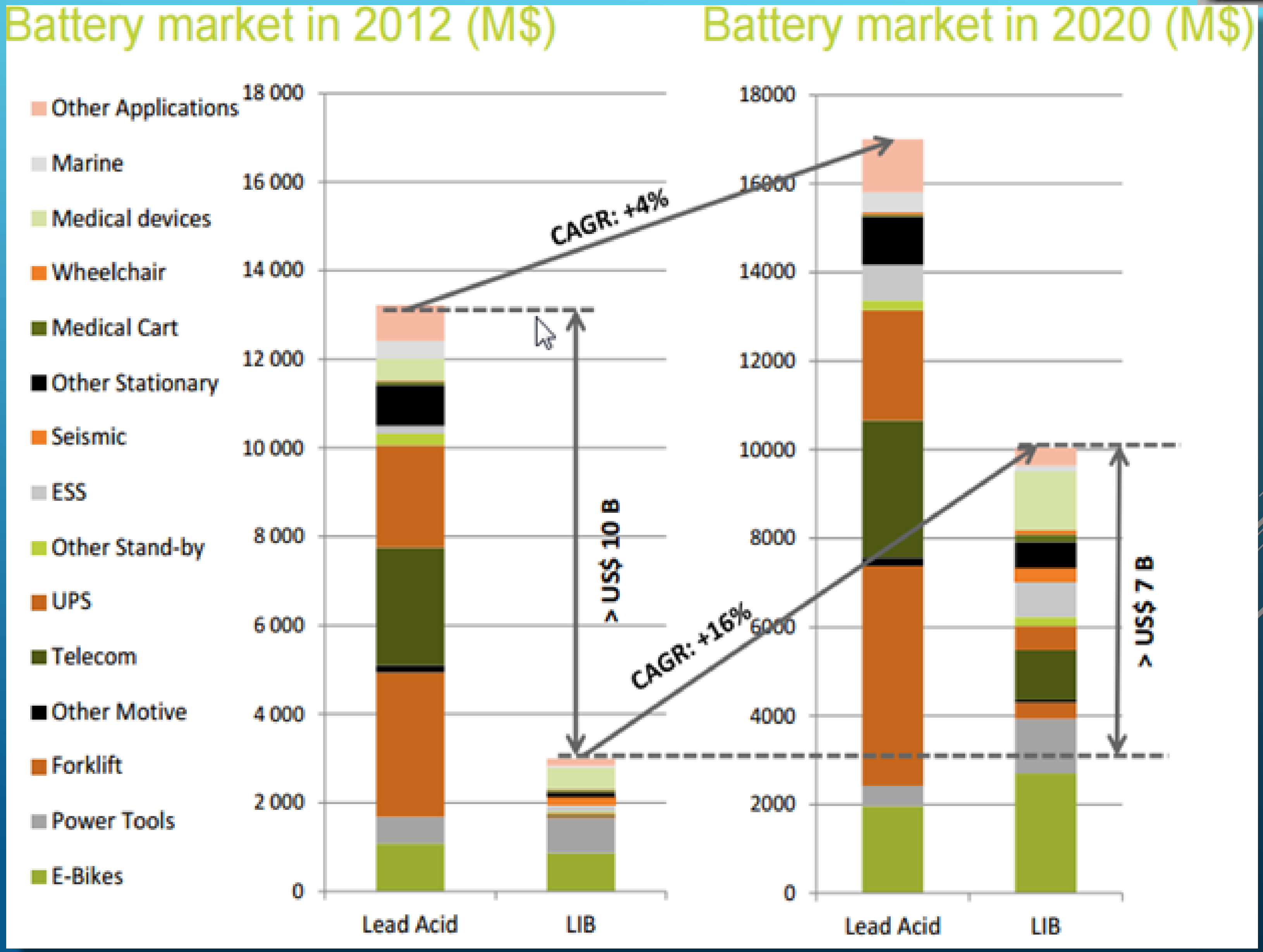


John Bannister Goodenough

Lithium Ion Batteries

Market share

- Gradually replacing lead acid as R&D investment continues to drive cost down and increase capacities



Source: B3, a consulting company in Japan

Lithium Ion Cells

Key Attributes

- Lighter than other rechargeable batteries for a given capacity
- Low self discharge about 1.5% per month or less
- High discharge currents while maintaining terminal voltage
- Partial charge does not impact capacity
- No memory effect
- Flexible packaging
- Longer life cycle than lead acid
- High charge efficiency close to 99%

Issues

- Poor cycle life especially in high current applications
- Internal resistance increases with cycling and age
- Safety concerns if overheated or overcharged
- Poor charging efficiency at low temperatures

Lithium Ion Cell Form Factors

Cylindrical

- 18650 cells (18mm diameter by 65 mm length)
- Capacity increasing with R&D effort
- Variants for high & mid rate
- Offers good cycling ability & long life
- Drawbacks heavy & low packing density

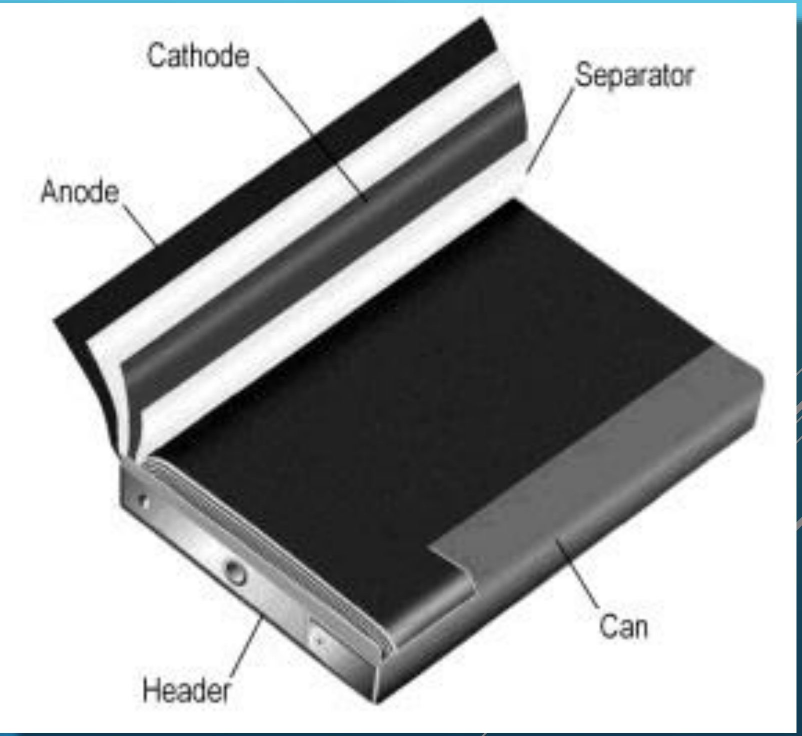
Button Cells (Coin Cells)

- Introduced in 1980's
- Most not rechargeable
- But some rechargeable but not vented so can swell if charged too rapidly

Lithium Ion Battery Form Factors

Prismatic Cells

- Introduced in early 1990's
- Rectangular layered cells in metal enclosure
- Principal applications cell phones, tablets, low profile computers
- Typically 800 – 4000 mAh & formed to fit an application
- Better packing density than cylindrical but more expensive to manufacture, less efficient thermal management and may have shorter cycle life



Lithium Ion Battery Form Factors

Pouch Cells (Polymer Cells)

- Introduced in early 1995
- Extremely space efficient 90-95%
- Flexible foil type case
- Eliminates metal enclosure reducing weight
- Light weight 20% lighter than prismatic
- Lower manufacturing cost
- Mostly Li-polymer (LiPo)
- Unlimited user designed form factors
- Bag or sandwich of polypropylene and aluminum heat sealed around outer edge
- Can swell (gas generation not vented) typically 8-10% over 500 cycles but can be significant if overcharged

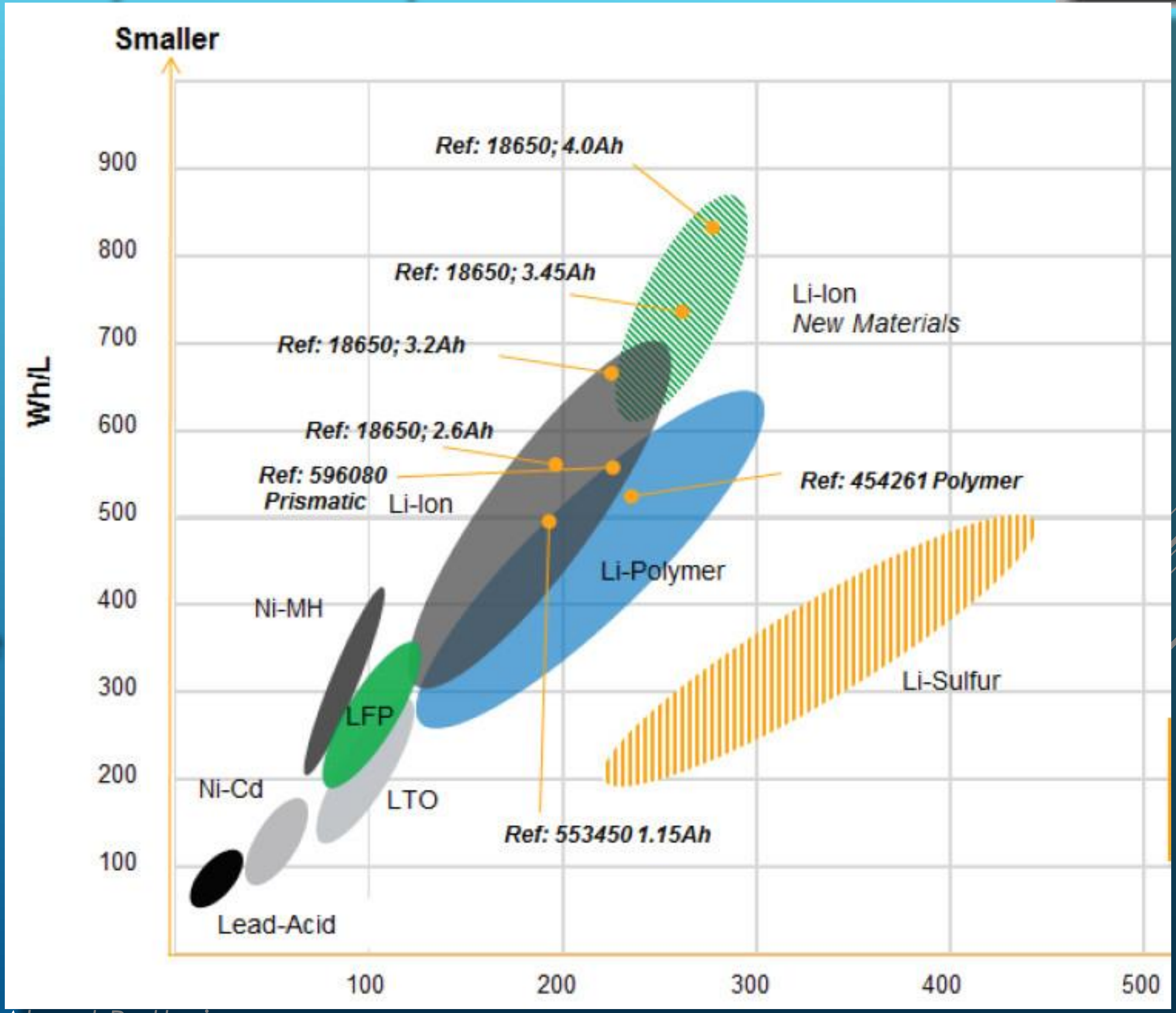
Lithium Ion Battery Chemistries

Name	LCO	LNO	NCA	NMC	LMO	LFP	LTO
Items	Lithium Cobalt Oxide	Lithium Nickel Oxide	Lithium Nickel Cobalt Aluminium Oxide	Lihium Nickel, Manganese Cobalt Oxide	Lithium Manganese Spinel	Lithium Iron Phosphate	Lithium Titanate
Cathode	LiCoO2	LiNiO2	Li(Ni0,85Co0,1 Al0,05)O2	Li(Ni0,33Mn0,3 3Co0,33)O2	LiMn2O4	LiFePO4	e.g.: LMO, NCA, …
Anode	Graphite	Graphite	Graphite	Graphite	Graphite	Graphite	Li4Ti5O12
Cell voltage	3,7 - 3,9V	3,6V	3,65V	3,8 - 4,0V	4,0V	3,3V	2,3 – 2,5V
Energy density	150mAh /g	150Wh/kg	130Wh/kg	170Wh/kg	120Wh/kg	130Wh/kg	85Wh/kg
Power	+	o	+	o	+	+	++
Safety	-	o	o	o	+	++	++
Lifetime	-	o	+	o	o	+	+++
Cost	--	+	o	o	+	+	o

Battery Energy Density Comparison

Key

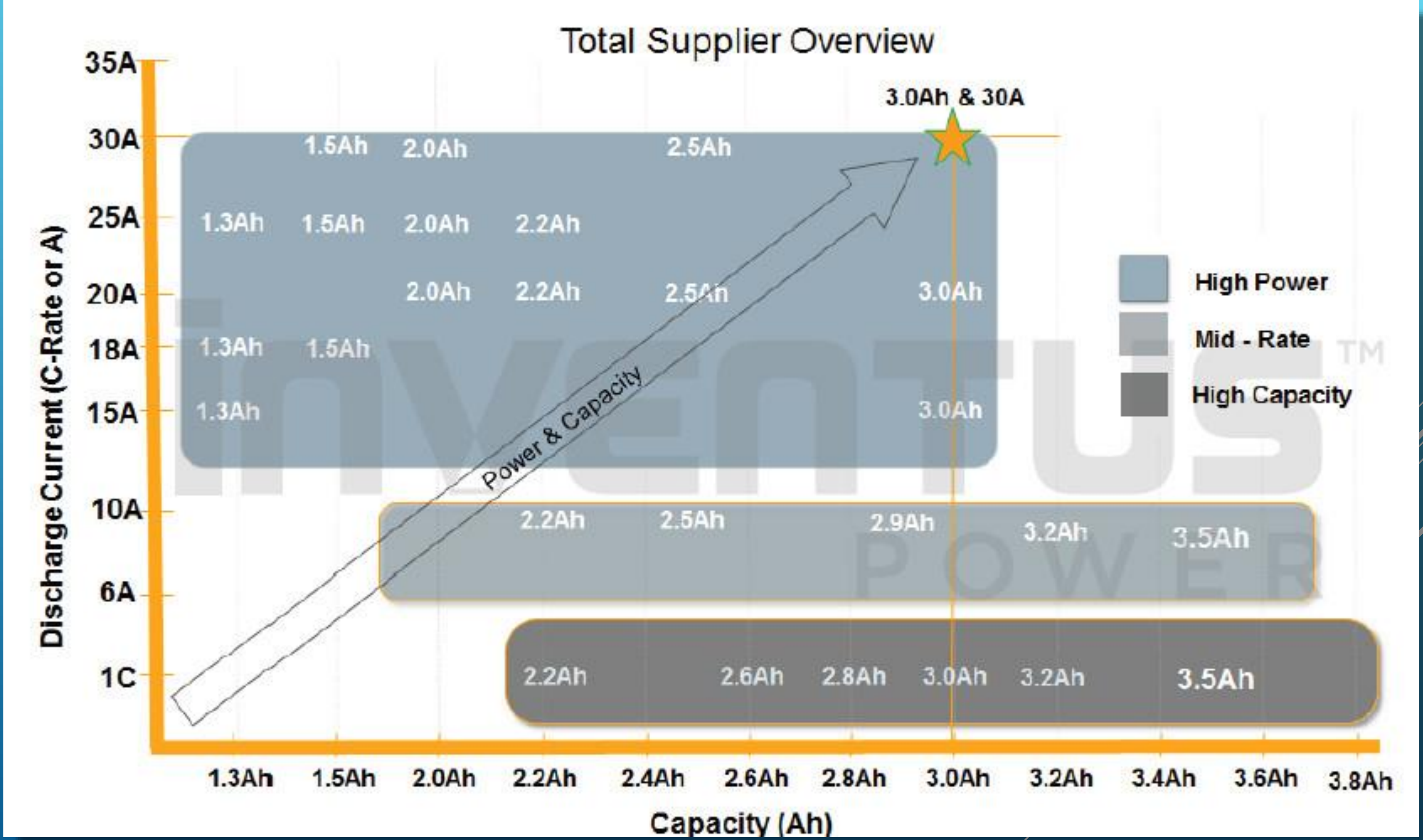
- Graph shows watt hours per liter versus watt hours per kilogram
- Crosshatched regions are emerging technologies
- LTO Lithium Titanate
- LFP = Lithium Iron Phosphate



Evolution of Li Ion Cells

Cylindrical 18650

- Remain a significant portion of the overall market
- Capacity increasing over time started at 1.3 Ah now > 3.5 Ah
- Variants 20650 high-rate power tools 21700 mid-rate auto apps



Evolution of Li Ion Cells

Physical and chemical advances fill special market needs

- High Rate cylindrical cells have somewhat lower Ah capacity but low series resistances mean they can deliver 15 - 30 A or more.
- High Rate polymer & prismatic cells now coming on line
- Mid Rate for E-Bikes compromise rate & capacity use 21700 formant delivering 3.2 Ah at an 8A discharge rate
- Large format cells 10- 50 Ah for grid applications & electric vehicles

Charging Lithium Ion Batteries

Some key considerations

- Unlike lead acid batteries lithium ion cells can be left partially charged without impacting capacity or cycle life
- Cycle life can be extended by not fully charging a cell
- Cells should not be allowed to fully discharge
- Lithium ion cells can't be left on a trickle charge

Battery life

- Lithium ion batteries do not die completely they just gradually lose capacity
- End of life considered to be 70 - 80 % of original capacity.

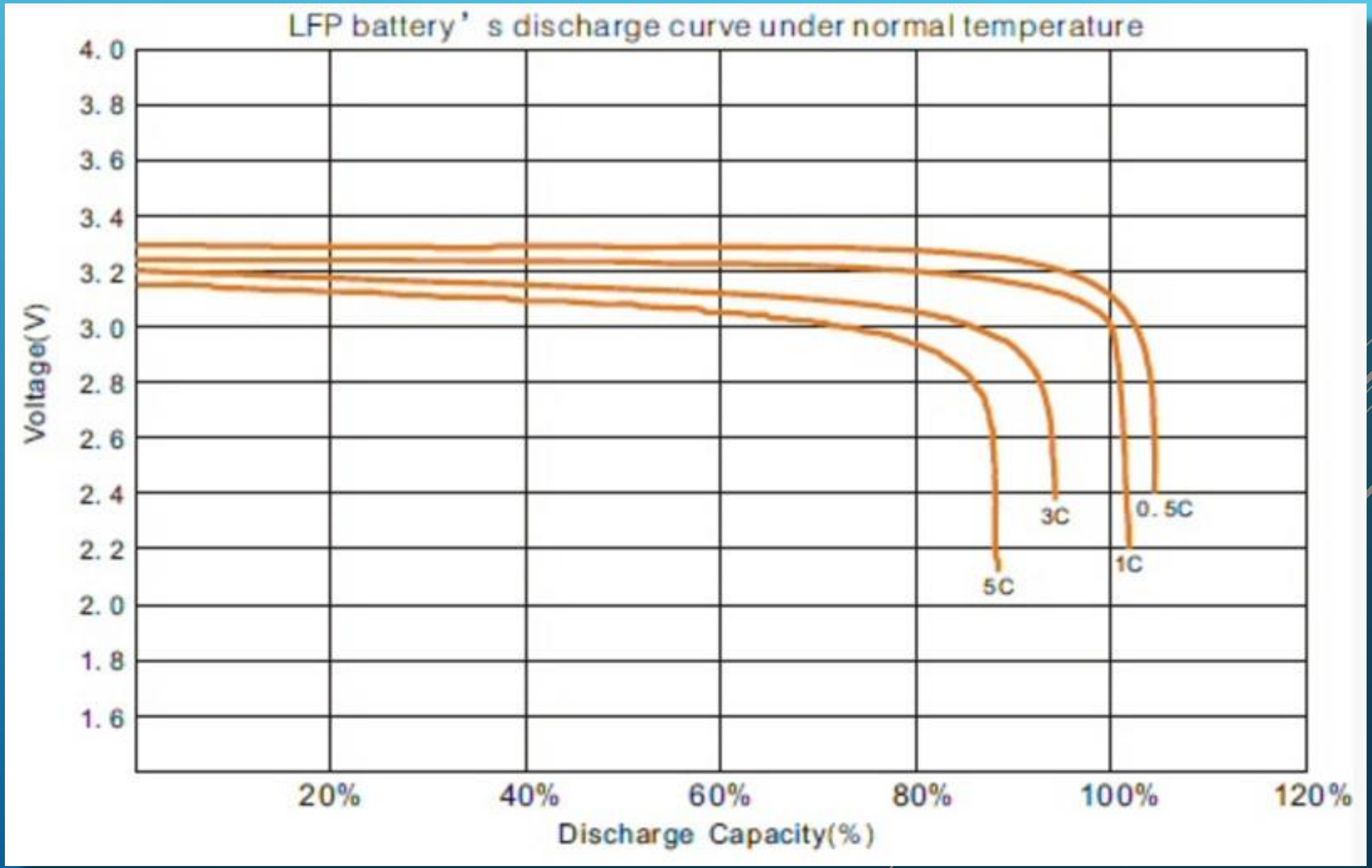
Estimating State of Charge (SoC)

- Problems created because of the very flat discharge curve so small changes in terminal voltage can mean large changes in SoC

Charging Lithium Ion Batteries

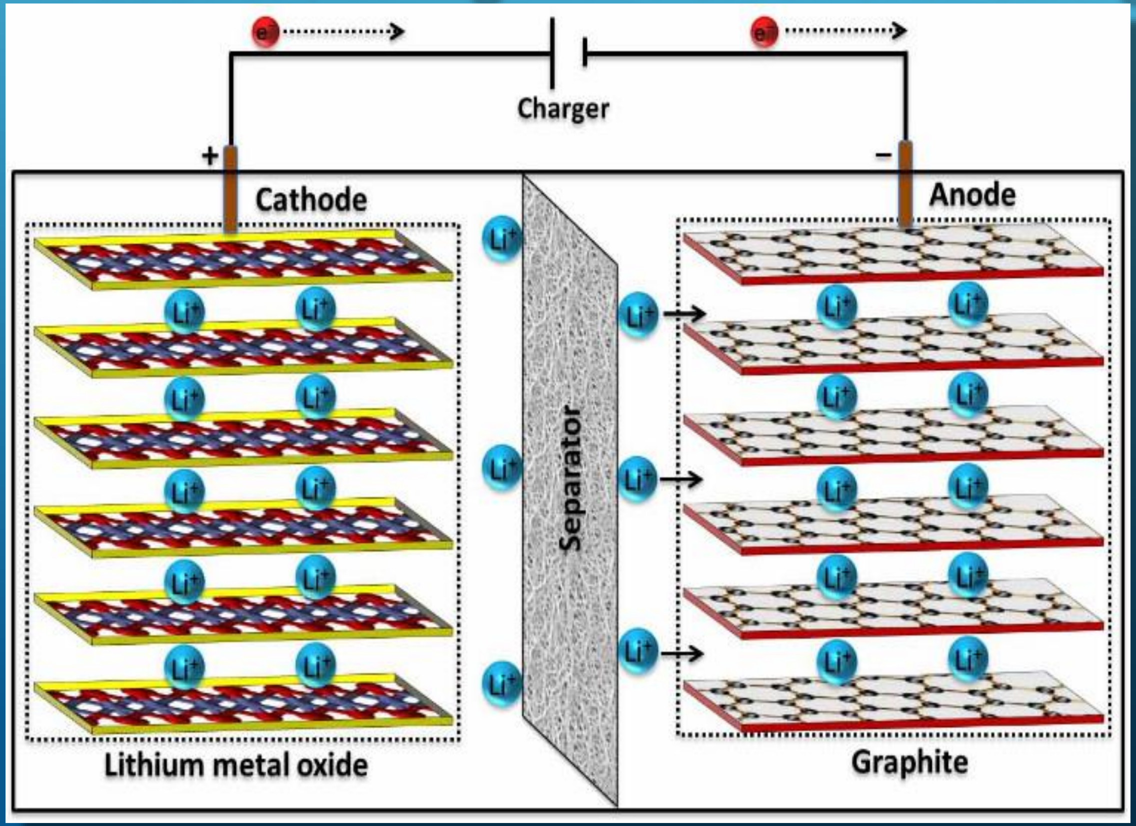
Cells can accept large charge and discharge currents

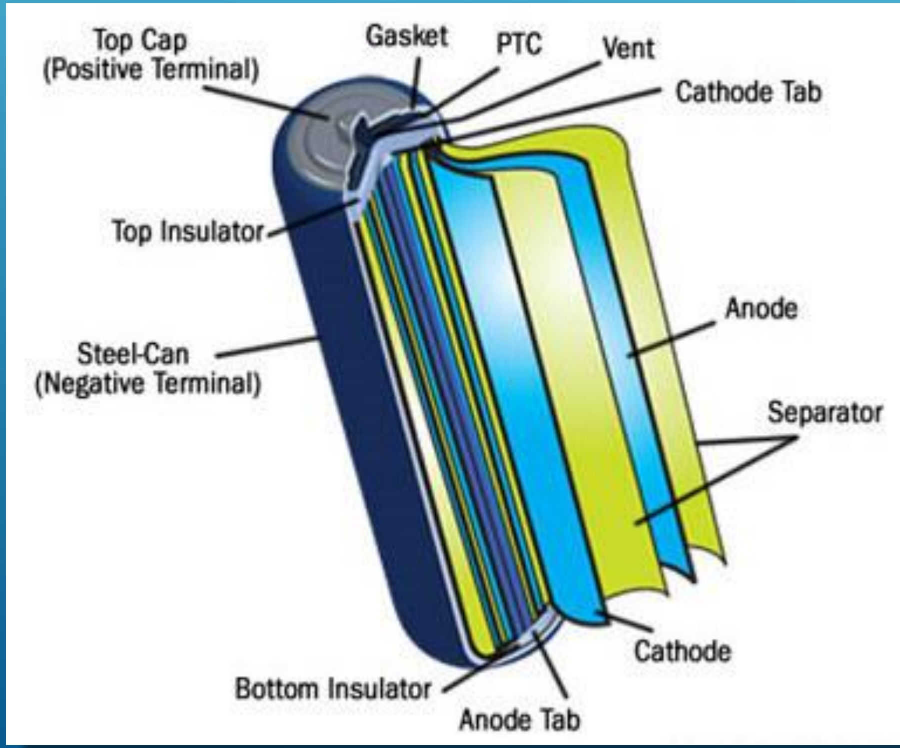
- Smaller capacity loss with increasing load current than lead acid battery's Peukert effect
- Small change in terminal voltage with capacity during charge or discharge leading to difficulty determining SoC



Li-Ion Charge & Discharge Chemistry

- When the cell charges and discharges, ions shuttle between 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.

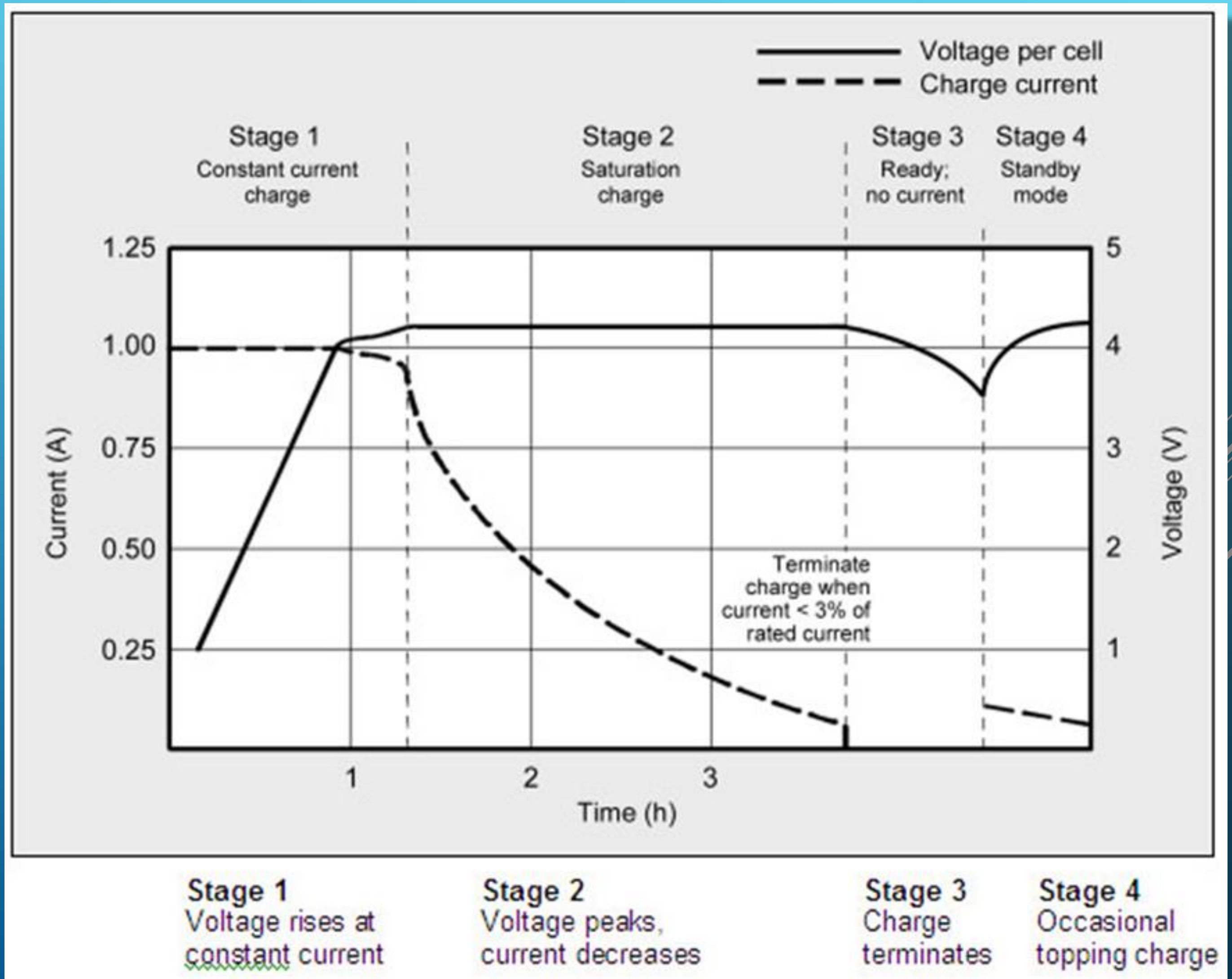




Charging Lithium Ion Batteries

How to safely charge Li-Ion Batteries

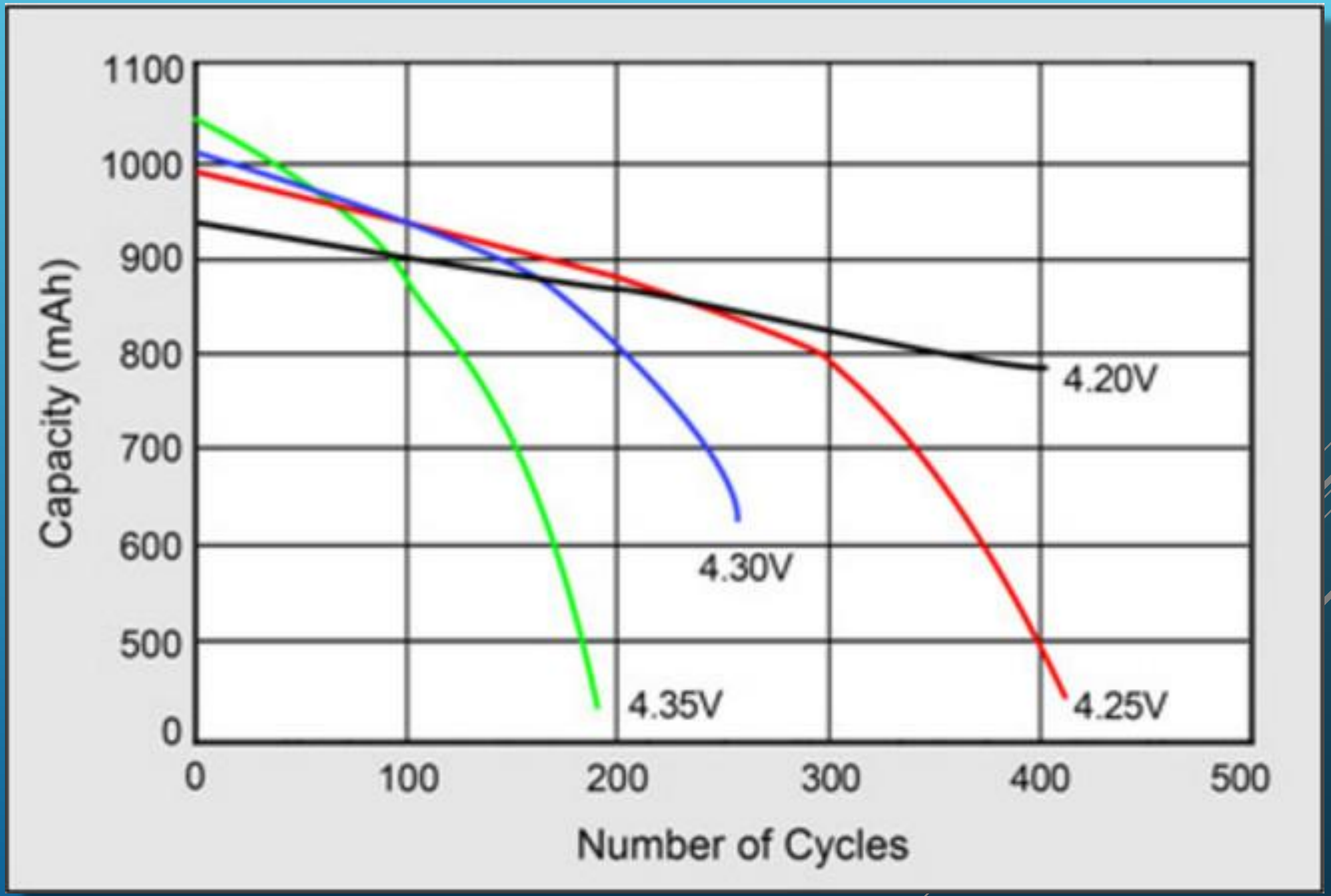
- Bulk charge battery voltage rises with applied charge
  - Apply constant voltage based on battery chemistry, current limited to between .5 to .8 C
- Saturation charge – current decreases when the battery reaches the voltage threshold
  - Terminate charge at 3-5 %
- Do NOT trickle charge
  - Causes plating of metallic lithium at anode which compromise safety



Charging Lithium Ion Batteries

Effects on cycle life with elevated charge voltages

- Higher charge voltages boost capacity but impair service life and safety



Charging Lithium Ion Batteries

Overcharging

- Prolonged overcharging above 4.3V for Li-Ion designed for 4.2V will plate metallic lithium onto the anode. The cathode material them becomes an oxidizing agent, loses stability and produces carbon dioxide gas increasing the cell pressure
- Electrolyte vaporizes causing swelling resulting in delamination and bad contact to internal cell layers reducing reliability & cycle life
- Apple iPhone 3GS LiPo battery

  expands due to short circuit

Charging Lithium Ion Batteries

Charging & Temperature

- Lithium batteries do not readily accept charge at temperatures below freezing
  - Charge only at temperatures above 5 deg. C
  - 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 have reduced capacity and reliability
  - If it is necessary to charge a cell below 5 deg. C present best practice is to limit charge current as temperature decreases below zero to around .02 C at -30 deg. C. (over 50 hour charge time)
- Fast charging is acceptable in the 5 to 45 deg. C temperature range

Extending Lithium Battery life

Cycle and life time

- Li-Ion charged @ 4.2V double cycle life for every .1V reduction in chg. Volt
- Every 50mV reduction in charge voltage lowers overall capacity by 10%
- Charging at 3.92 V per cell eliminates virtually all stress so lower V not necessary

Charge level (V/cell)	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	~80%
3.92	2,400 – 4,000	~75%

Charge V/cell	Capacity at cut-off voltage	Capacity with full saturation
3.80	60%	~65%
3.90	70%	~75%
4.00	75%	~80%
4.10	80%	~90%
4.20	85%	100%

Extending Lithium Ion Battery Life

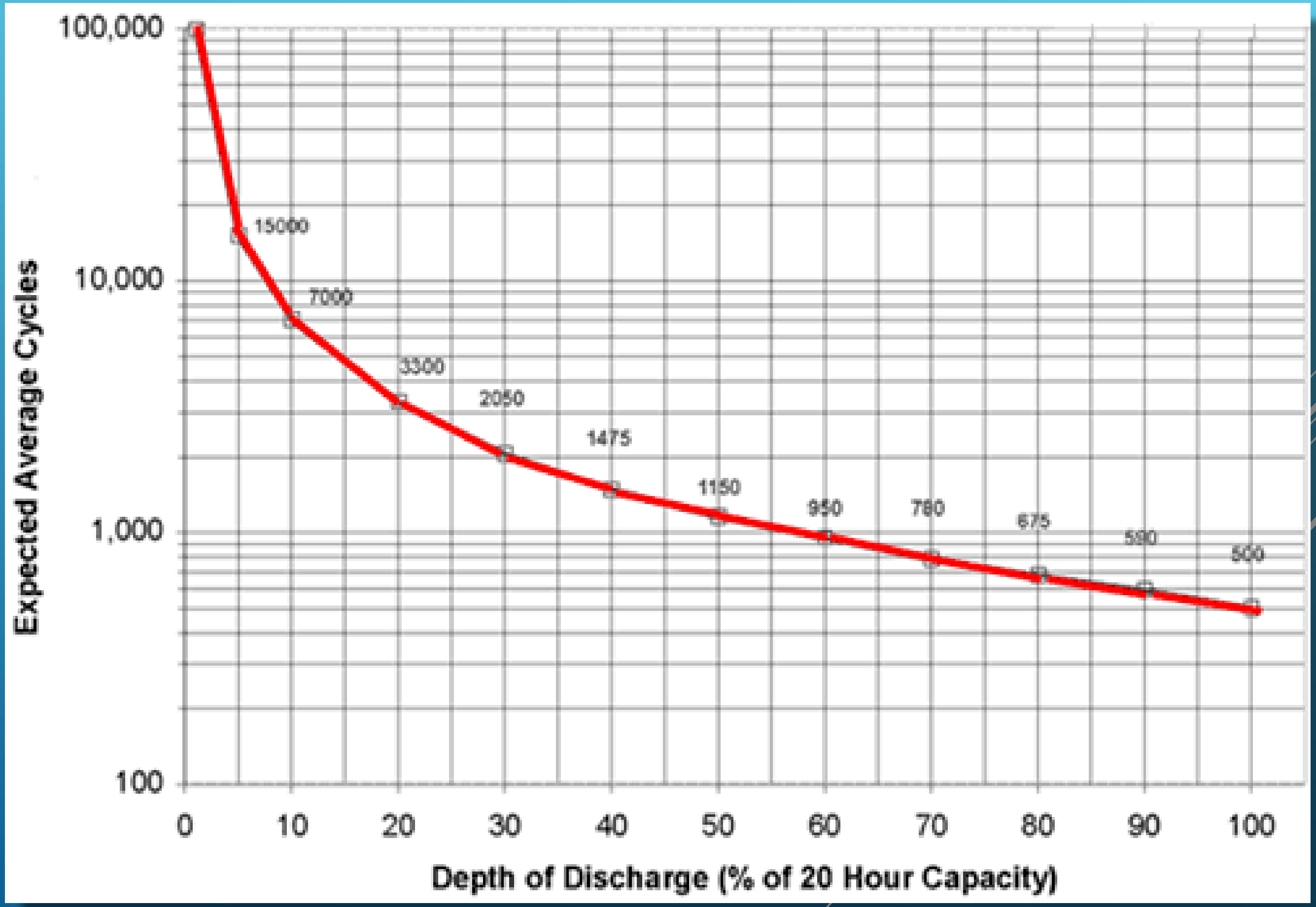
Summary

- Lithium Ion cells does do not suffer capacity loss from partial charging like lead acid.
- Charging cells to 100% capacity stresses the battery reducing cycle life
- Reducing the charge to terminate at 75 to 80% capacity can increase battery cycle life by about a factor of 6 to 8 times.
- Technique requires charging system cut off at specific voltage avoiding most of the saturation portion of the charge

Depth of Discharge impact on Cycle life

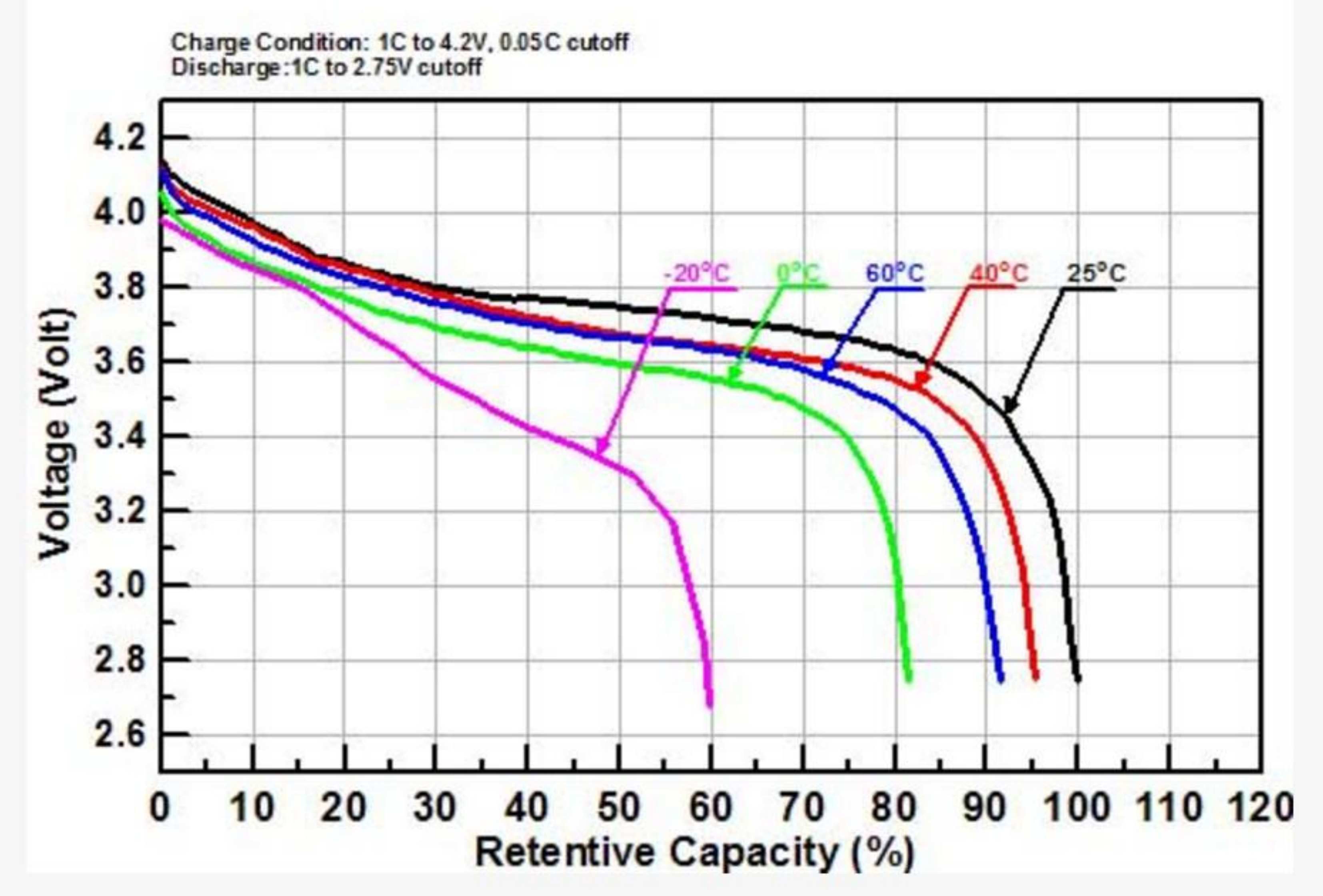
DoD impact on Cycle life

- Impacts virtually all battery chemistries although the y axis scale may vary for different battery chemistries
- Battery life depends on total energy throughput
- One cycle at 100% DoD is roughly equivalent to 2 cycles at 50% or 10 cycles at 10% or 100 cycles at 1%



Lithium Battery Temperature Effects

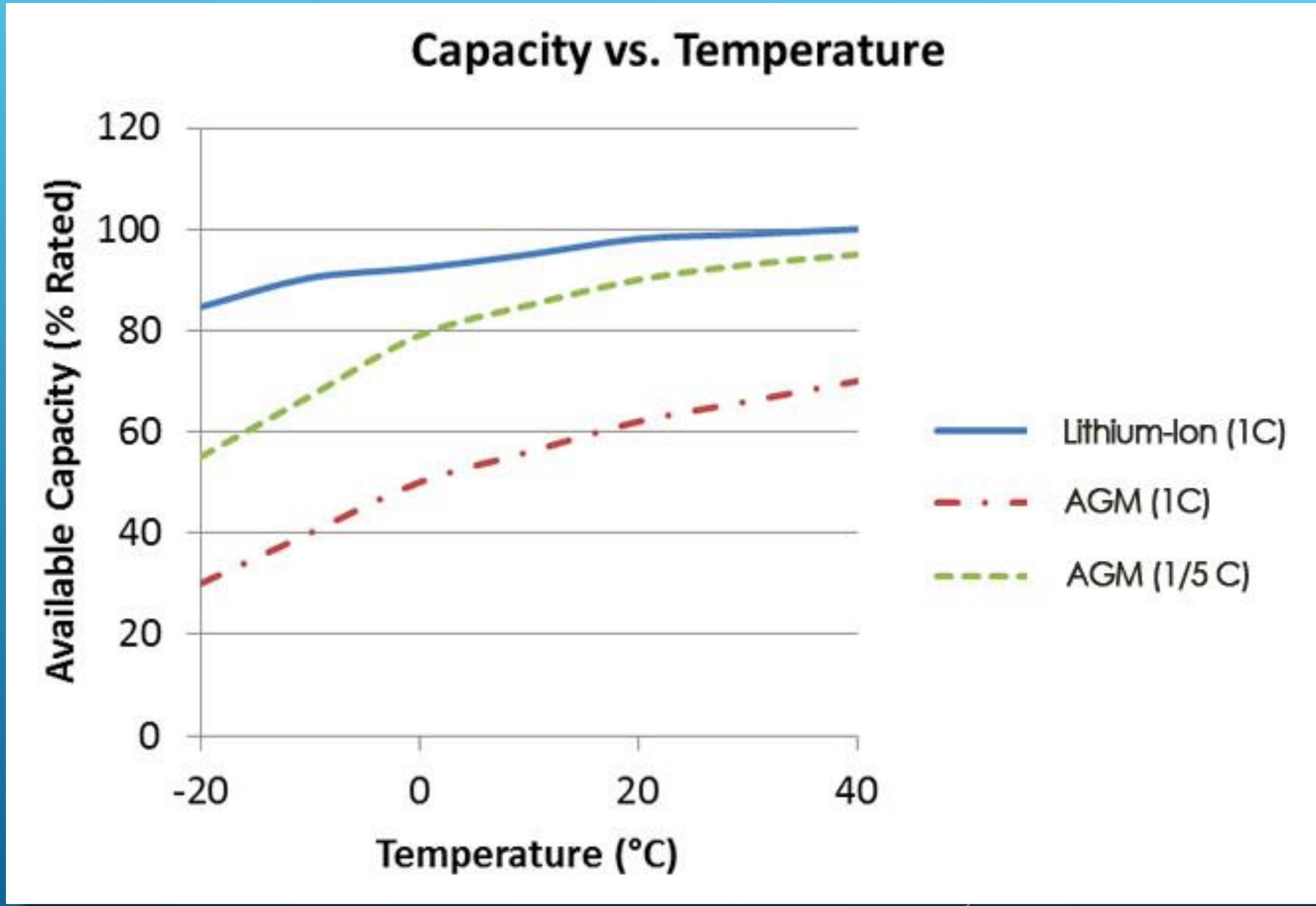
Temperature impact on capacity



Lithium Battery Temperature Effects

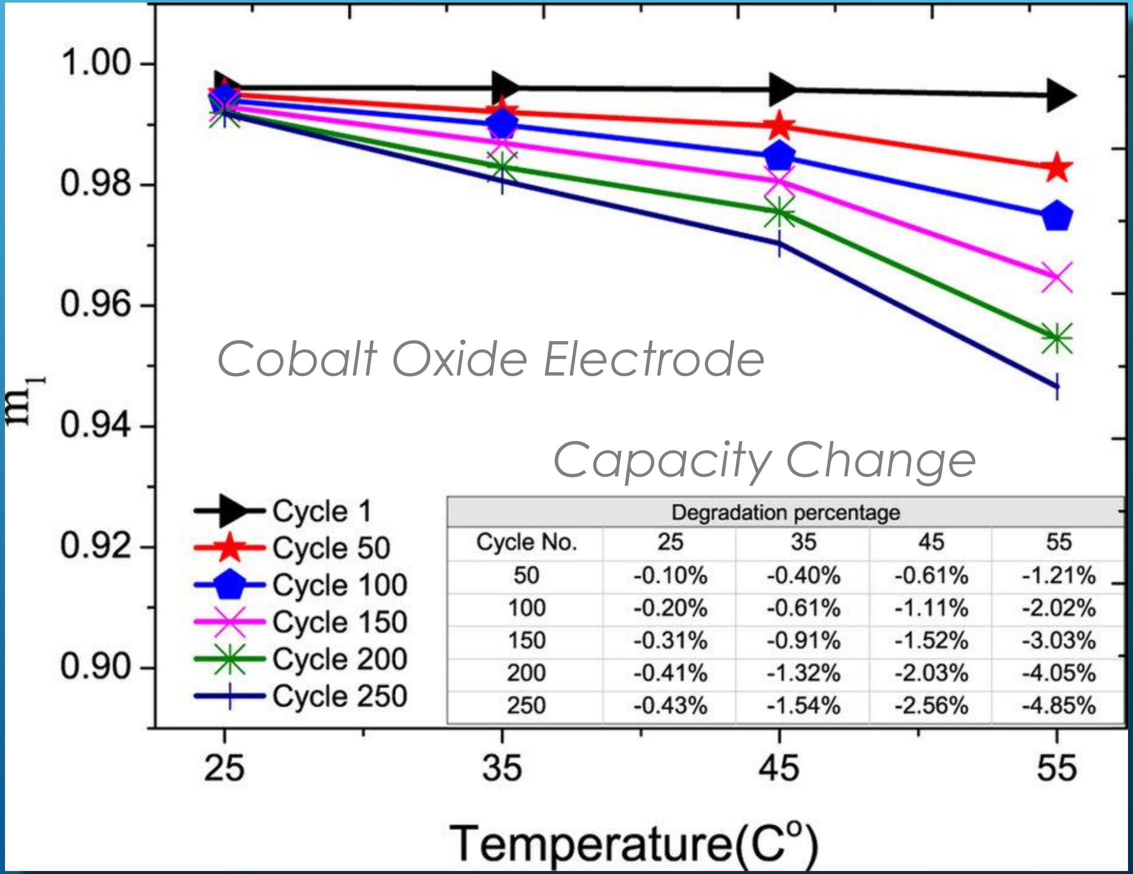
Temperature impact on capacity

- Compared to lead acid

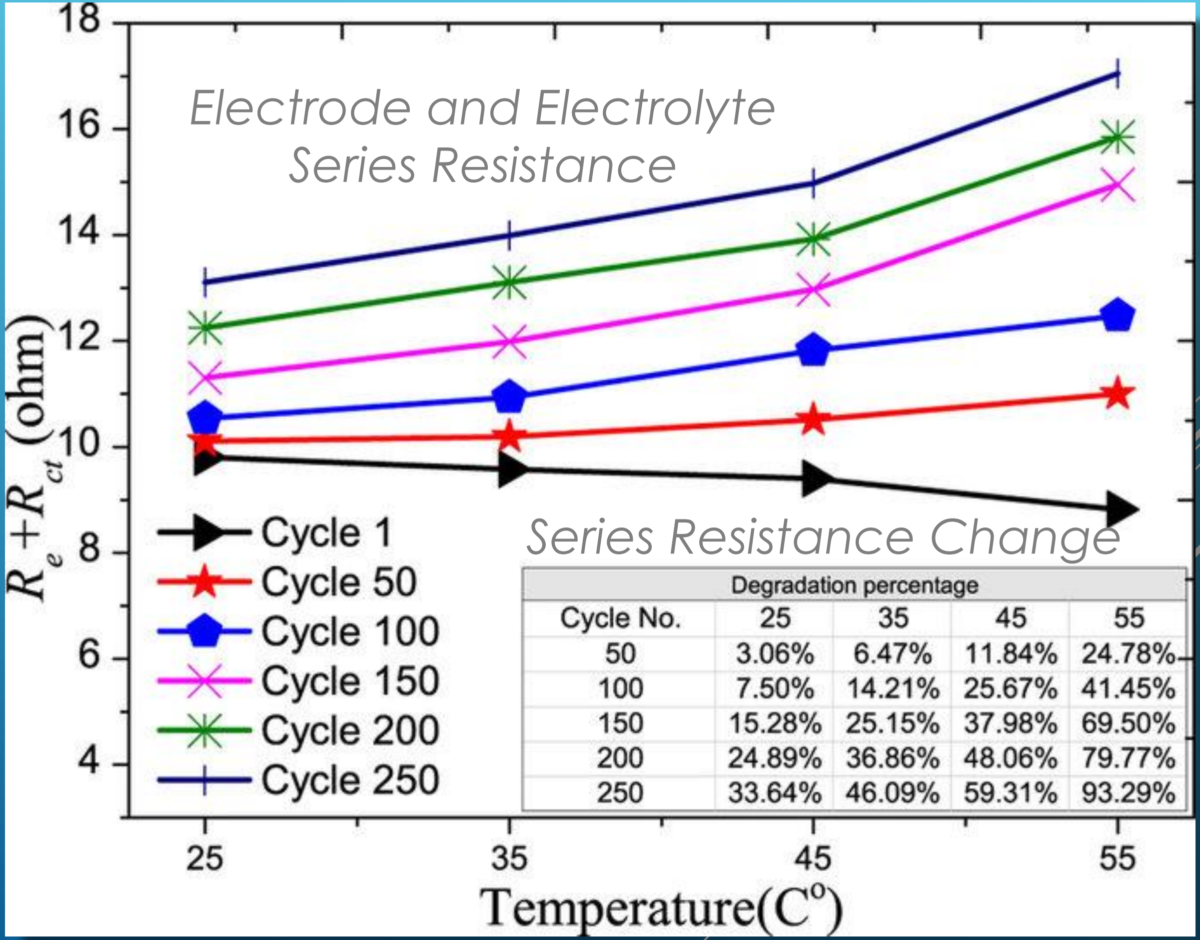


Lithium Battery Temperature Effects

Charts show temperature & aging (cycling) impact on capacity % & electrode resistance



Degradation percentage				
Cycle No.	25	35	45	55
50	-0.10%	-0.40%	-0.61%	-1.21%
100	-0.20%	-0.61%	-1.11%	-2.02%
150	-0.31%	-0.91%	-1.52%	-3.03%
200	-0.41%	-1.32%	-2.03%	-4.05%
250	-0.43%	-1.54%	-2.56%	-4.85%

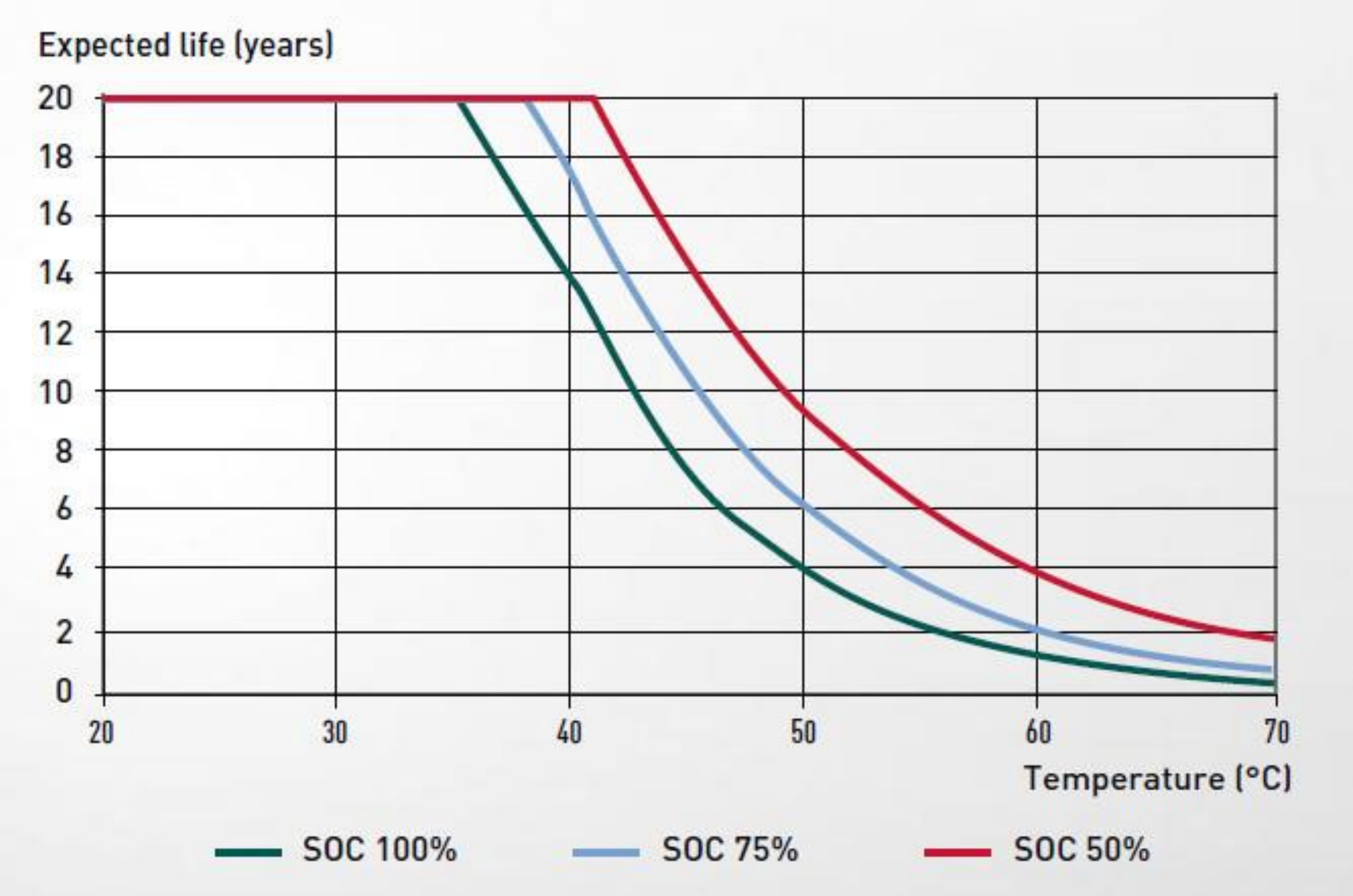


Degradation percentage				
Cycle No.	25	35	45	55
50	3.06%	6.47%	11.84%	24.78%
100	7.50%	14.21%	25.67%	41.45%
150	15.28%	25.15%	37.98%	69.50%
200	24.89%	36.86%	48.06%	79.77%
250	33.64%	46.09%	59.31%	93.29%

Lithium Battery Temperature Effects

Expected life vs Temp

- Calendar life versus SoC & Temperature
- End of life = 20 – 30 % loss of capacity



Storing Lithium Ion Batteries

Storage

- Can be stored for up to 10 years with only moderate capacity loss
- 40 to 50 % SoC at 15 deg. C is optimum
- Partial charge minimizes age related capacity loss while still allowing some room for self discharge
- Don't allow cell voltage to dip below 2 volts per cell
  - Copper shunts form inside the cell that cause elevated self discharge or lead to shorts and make the battery unstable on recharge

Storing Lithium Ion Batteries

Temperature impact on storage

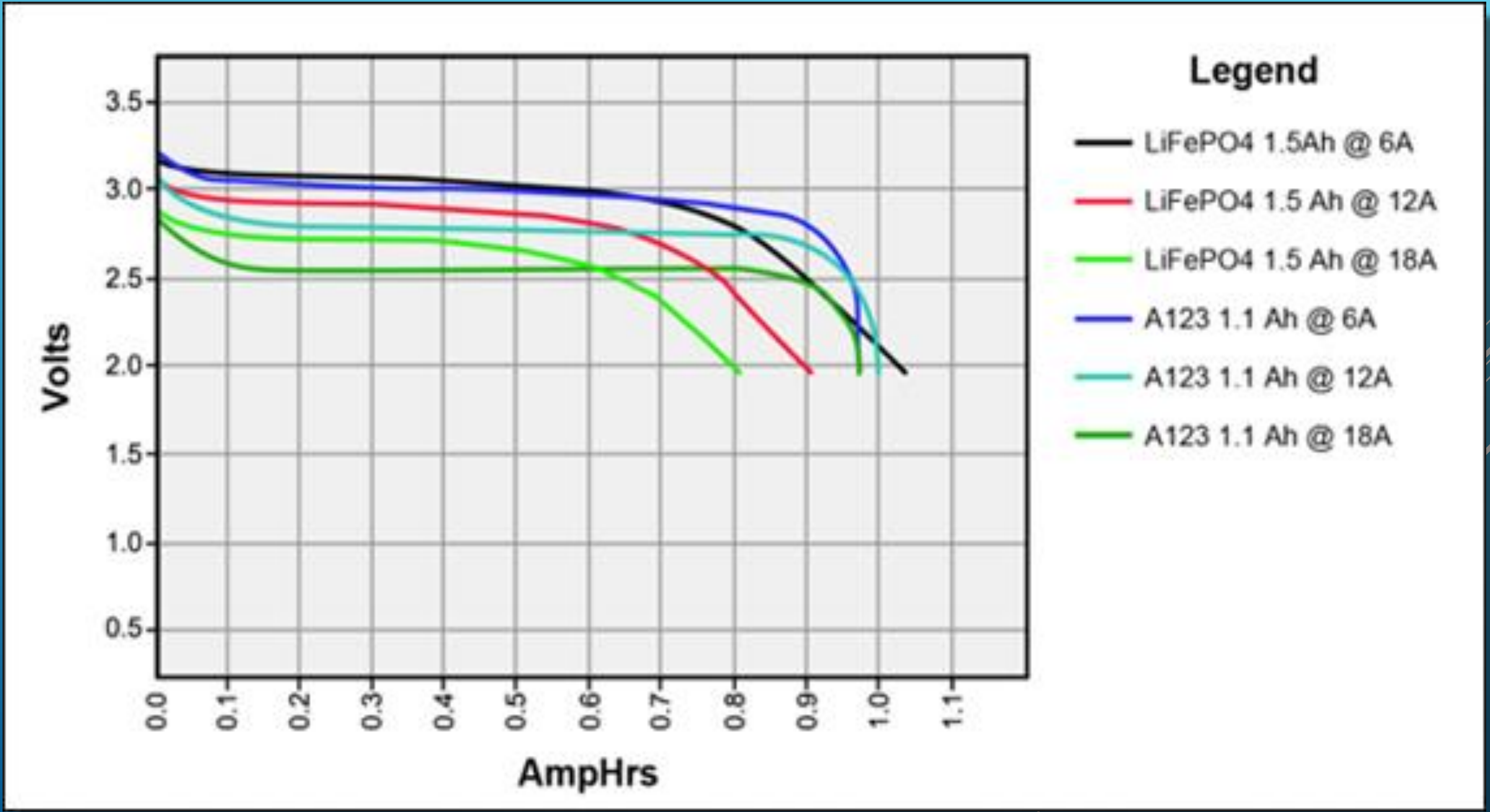
- Temperatures above 30 deg. C will shorten battery life
- Chart shows capacity remaining after one year

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

Estimating Lithium Battery SoC

State of Charge (SoC)

- Impractical to estimate during charge
- Let battery rest for several hours then measure terminal voltage
- Flat discharge curve means using terminal voltage provides only rough estimate of SoC.



Estimating Lithium Battery SoC

Coulomb Counting…more accurate but still not perfect

- Measures the charge and discharge current flow over time
  - One coulomb per second is one amp
- Needs to account for temperature aging self discharge etc.
- ‘Smart battery’ calibration needed
  - periodic full charge & discharge points
- Accuracy 15 – 25 % error typical

Lithium Ion Battery Packs

Built up by placing multiple cells in series

- End terminal voltage depends on chemistry

Cell Balancing

- Capacity of each cell in a battery must be made equal to the others (balanced) to prevent over charging or over discharging
- Battery chargers feature capability to manage charge on individual cells in a pack
- Battery packs provide separate connection to each cell to enable balancing

Lithium Ion Battery Packs

Battery Management System(s) BMS

- Manages cells or packs protecting the battery from operating outside its save operating area. For battery packs monitors each cell reports to controller
  - Limits charge & discharge current
  - Over voltage during charging - Minimum voltage during discharge
  - Over pressure - Over or Under temperature

Lithium Ion Batteries Avoid the Hazards

State of Charge needs to be controlled

- Over charging or over discharging
  - Creates unwanted exothermic reactions
  - Chemical instability Li is plated to the anode / Cu dendrites

Short Circuits & high electrical currents

- Increase battery temperature

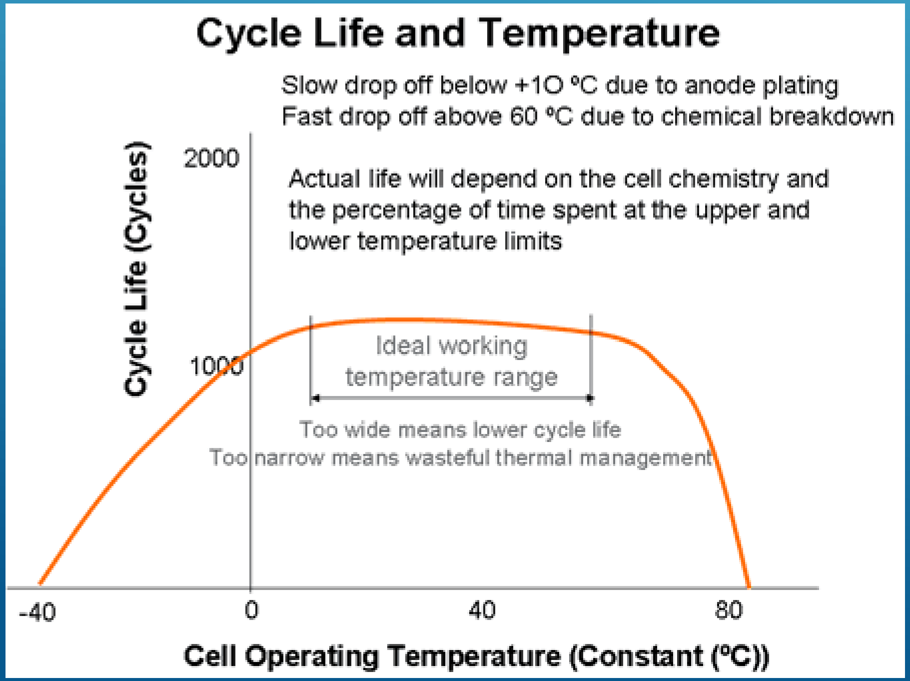
Thermal run-away

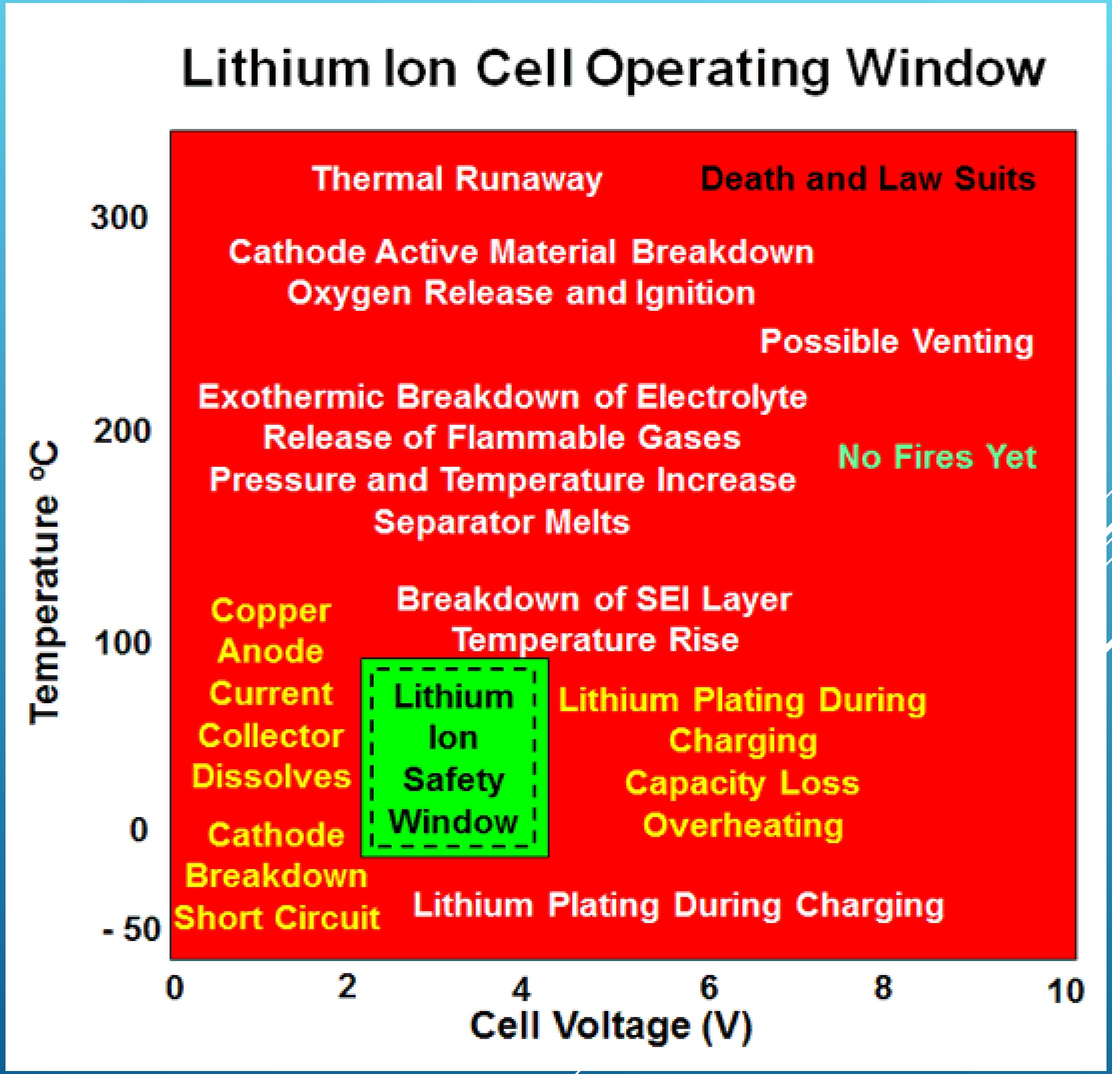
- Cells stable up to 80 deg. C
- Exothermic reactions cause by damage at elevated temperatures
  - 120-130C passivation layer Solid Electrolyte Interface on neg electrode graphite breaks down
  - At 130-170 separator melts

Lithium Cell safe operating area

Some closing advice

- Don't overcharge
- Don't allow cell voltages below 2V in discharge or storage
- Don't place a battery in a potential short circuit environment, protect contacts when transporting & not in use





Nickel Iron Batteries

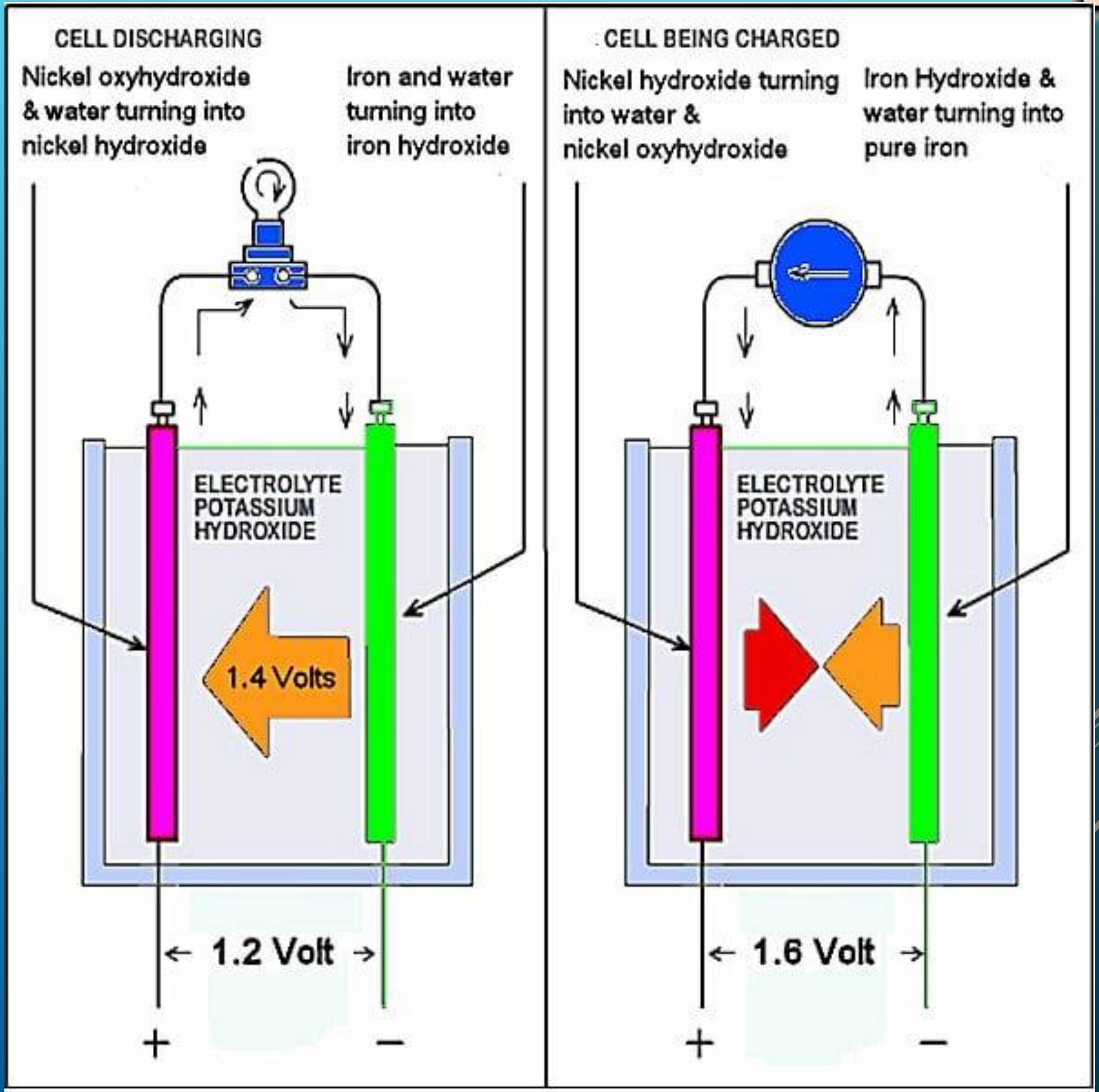
History

- Edison first developed this battery in 1901
- Finding renewed interest in renewable energy applications because of its robustness and longevity

Nickel Iron Batteries

Construction

- Nickel hydroxide cathode
- Iron anode
- Potassium hydroxide electrolyte (20% diluted potash
- Charge using CV at 1.65V / cell. Keep charge current under C/2



Nickel Iron Batteries

Key Positive Attributes

- Robust - very high tolerance to overcharging & discharging
- Durability & life span much longer than most other chemistries
- Longevity with electrolyte changes will last 30 to 100 years
- Cycling – low solubility of reactants in the electrolyte
  - Battery life typically greater than11000 cycles at 80% DoD
- Unaffected by overcharging
- Discharge characteristics
  - Battery life not affected by deep discharge
  - High discharge capacity batteries typically specified at C/5 not C/20C
- Low maintenance – periodic electrolyte topping up & replace every 7-10 yrs.

Nickel Iron Batteries

And on the down side

- Heavy weight
- Low energy density
  - Specific energy 10-25 Wh/kg Energy density 30 Wh/l is under half lead acid
- Charge efficiency is around 65%
- Discharge efficiency is around 85%
- High self discharge rate 15-30 % per month
- Initial cost 2x plus lead acid

Resource List

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