Introduction to Lithium Ion Solutions for Data Center 3 Phase UPS

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For Reference: Front View – LIB & VRLA

Li-Ion

VRLA

Li-Ion Batteries Ubiquitous in the 21st Century

Portable Devices Animation Source - http://justsharingwithu.blogspot.com/2013/06/right-tools-to-recover-files-for-right.html?_sm_au_=i5Vp7sPPJFs1LfFn

Cordless Power Tools Picture Source - http://justcordlessdrillreviews.com/

Electric Vehicles Picture Source - http://www.edmunds.com/fuel-economy/electric-car-comparison-test.html

Medical Device Picture Source - http://www.metlabs.com/blog/emc/fda-issues-guidance-on-emc-of-electrically-powered-medical-devices

Brief Comparison of LIB vs VRLA

"Li-ion technology offers a smaller footprint and a dramatic reduction in weight, especially for short run times, plus longer operating lives and the ability to cope easily with large numbers of small 'hits' that can be damaging to lead-acid batteries."

Source: "One Size Doesn't Fit All: Lithium-Ion Technology Choices for Standby Applications" by Jim McDowall, François Danet & Stuart Lansburg; http://www.battcon.com/PapersFinal2016/McDowall%20Paper%202016.pdf

1. Quicker installation
2. Smaller footprint
   1. Area
   2. Weight
3. Less maintenance
4. Greater power & energy densities
5. Faster recharge
6. Wider temperature operating window
7. No Coup de Fouet
8. Lower TCO
9. Longer life

Li-ion batteries do offer legitimate benefits over VRLA (valve-regulated lead-acid) including*:

* **Source:** SE WP 229, Rev 0, “Battery Technology for Data Centers: VRLA vs. Li-ion”

- **Fewer battery replacements** (perhaps none) required over the life of the UPS eliminates the risk of downtime posed by battery replacement
- About **three times less weight** for the same amount of energy
- Up to **ten times more discharge cycles** depending on chemistry, technology, temperature, and depth of discharge
- About **four times less self-discharge** (i.e. slow discharge of a battery while not in use)
- Four or more times **faster charging**, key in multiple outage scenarios

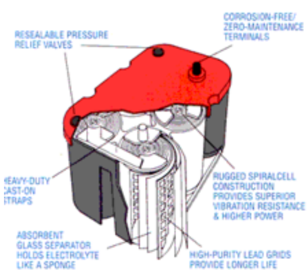
Scale Animation Source:
http://www.clipartbest.com/clipart-dc7oBk9Ki

Batteries A Myriad of Form Factors

VRLA

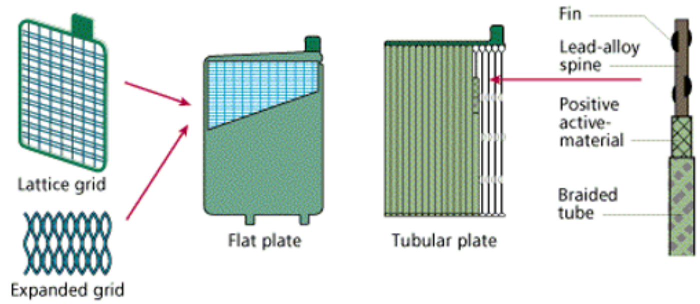
Absorbed Gas Mat (AGM)

Spiral Wound



Source: http://jgdarden.com/batteryfaq/carfaq7.htm#spiral (last accessed 20-July-2016)

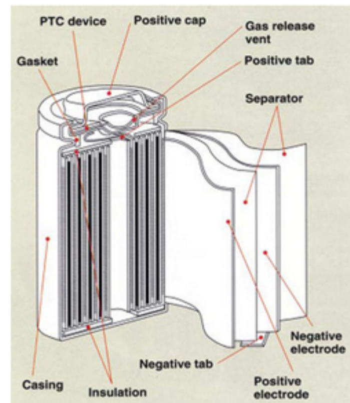
Flat and Tubular Plate



Source: http://jgdarden.com/batteryfaq/carfaq2.htm (last accessed 20-July-2016)

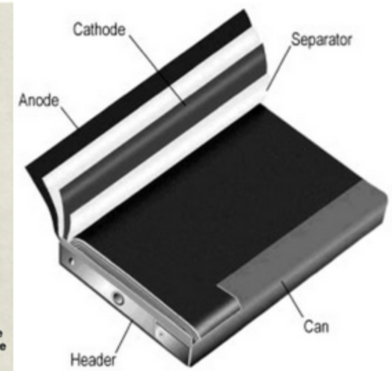
Lithium Ion

Cylindrical Cell



Source: http://batteryuniversity.com/learn/article/types_of_battery_cells (last accessed 20-July-2016)

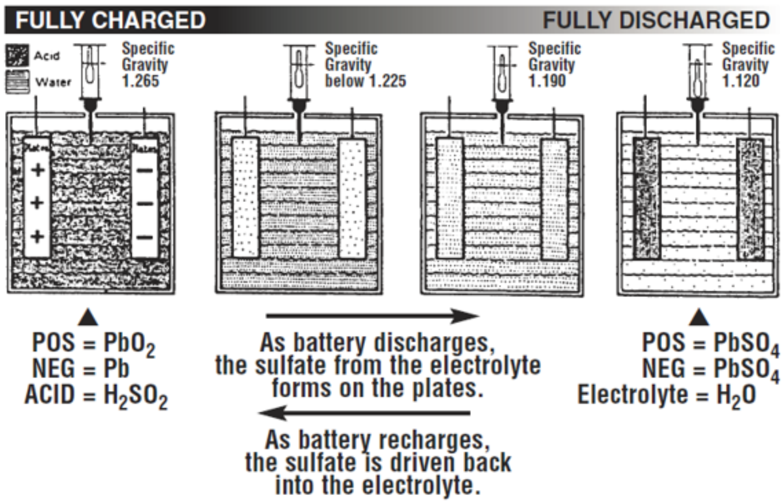
Prismatic Cell



Source: http://batteryuniversity.com/learn/article/types_of_battery_cells (last accessed 20-July-2016)

Battery Material – General (VRLA & Li-Ion)

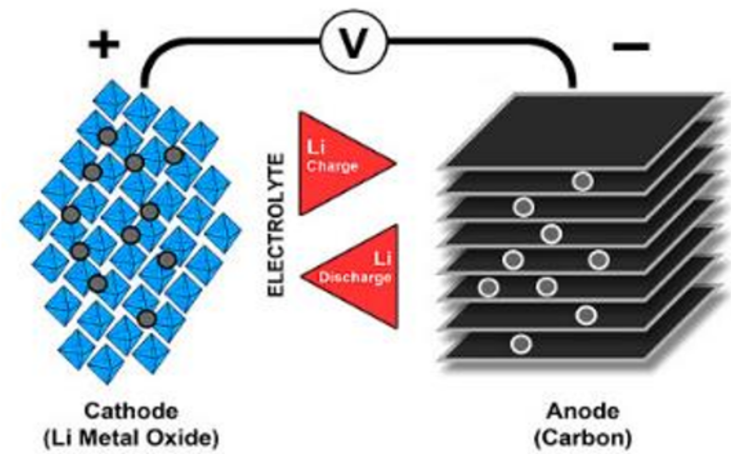
Chemical Reaction



Source: "Valve-Regulated Lead-Acid (VRLA): Gelled Electrolyte (gel) and Absorbed Glass Mat (AGM) Batteries", East Penn Technical Manual 0139.

Intercalation

"reversible insertion of a molecule or ion into a compound w layered structures"



Picture Source:
http://batteryuniversity.com/learn/archive/understanding_lithium_ion
(last accessed 19-July-2016)

Lithium-ion batteries: How do they work?
https://www.youtube.com/watch?v=2PjyJhe7Q1g

Li-Ion Battery (LIB) Chemistries for Data Center Applications

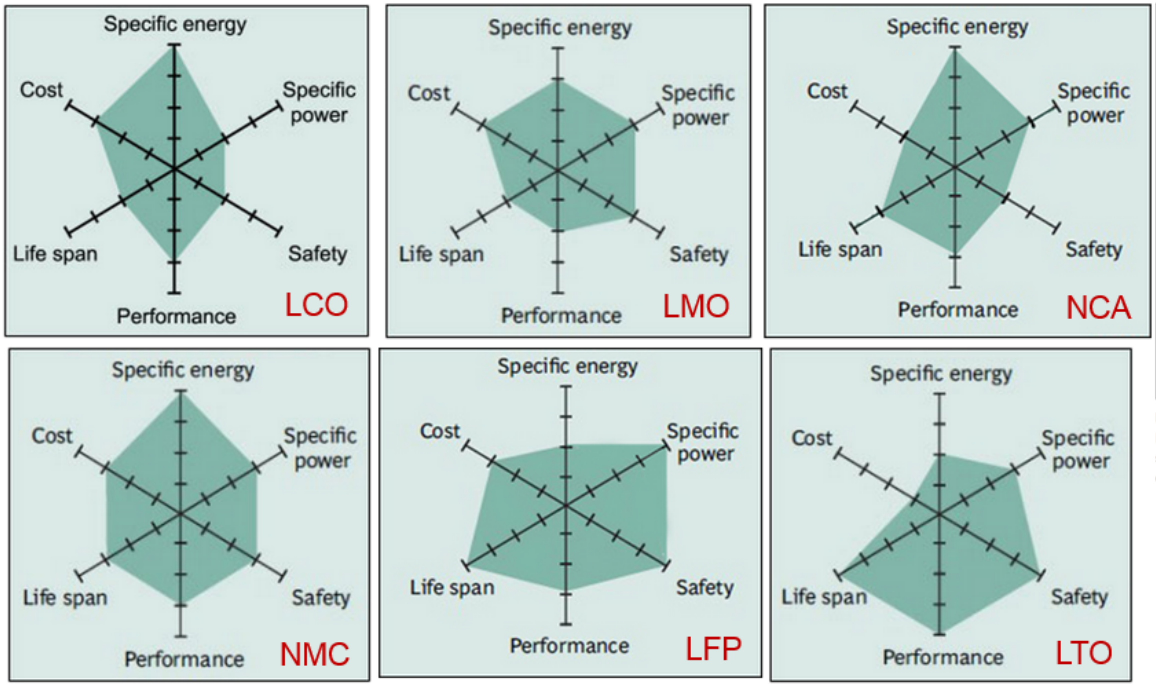
Chemistry Type	Specific Energy	Specific Power	Safety*	Performance	Lifespan	Cost	Chemistry
$LiCoO_2$ (LCO)	Highest	Moderate	Moderate	High	Moderate	Moderate	Lithium Cobalt Oxide
$LiMnCoO_2$ (LMO)	High	High	High	Moderate	Moderate	Moderate	Lithium Manganese Oxide
$LiNiMnCoO_2$ (NMC)	Highest	High	High	High	High	Moderate	Lithium Nickel Manganese Cobalt Oxide
$LiFePO_4$ (LFP)	Moderate	Highest	Highest	High	Highest	Moderate	Lithium Iron Phosphate
$LiNiCoAlO_2$ (NCA)	Highest	High	Moderate	High	High	High	Lithium Nickel Cobalt Aluminum Oxide
$Li_4Ti_5O_{12}$ (LTO)	Moderate	High	HIghest	Highest	Highest	Highest	Lithium Titanate

* Safety refers to how reistant the chemistry is naturally to entering an uncontrolled state of "thermal runaway" situation. Note that the choice of materials, cell packaging, manufacturing quality, and battery management system can be designed to ensure such a condition does not occur despite a given chemistry's propensity to go into a thermal runaway condition or not.

Source: Schneider Electric WP 231. Rev 0, “FAQs for Using Lithium-ion Batteries with a UPS”

Lithium Ion Battery Chemistry Spider Graphs

Spider Graph & Typical specific energy bar graph source: **BU-205: Types of Lithium-ion**, http://batteryuniversity.com/learn/article/types_of_lithium_ion



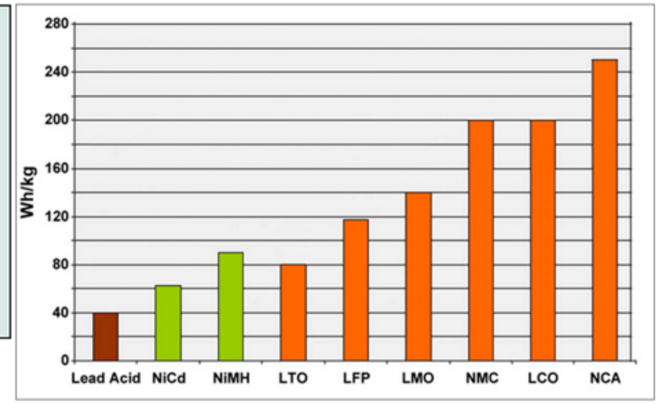


Figure 15: Typical specific energy of lead-, nickel- and lithium-based batteries.
NCA enjoys the highest specific energy; however, manganese and phosphate are superior in terms of specific power and thermal stability. Li-titanate has the best life span.
Courtesy of Cadex

- **Lithium Cobalt Oxide (LiCoO2)**
- **Lithium Manganese Oxide (LiMn2O4 or "LMO")**
- **Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2 or "NMC")**
- **Lithium Iron Phosphate (LiFePO4)**
- **Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO2)**
- **Lithium Titanate (Li4Ti5O12)**

Source: SE WP 229, "Battery Technology for Data Centers: VRLA vs. Li-ion"

Li-Ion Batteries Are Available In:

Several form factors

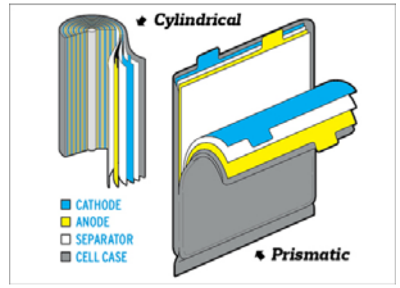
Many chemistries

Varying power and energy densities

Varying levels of intrinsic safety and costs

There is a lot to choose from!

Considerations include but are not limited to:
- Application
- Safety
- Costs



Picture Source: http://auvac.org/newsitems/view/1082

Chemistry Type
$LiCoO_2$ (LCO)
$LiMnCoO_2$ (LMO)
$LiNiMnCoO_2$ (NMC)
$LiFePO_4$ (LFP)
$LiNiCoAlO_2$ (NCA)
$Li_4Ti_5O_{12}$ (LTO)

LIB Already in the Data Center - Decentralized Applications

Open Compute Project Cabinet Power

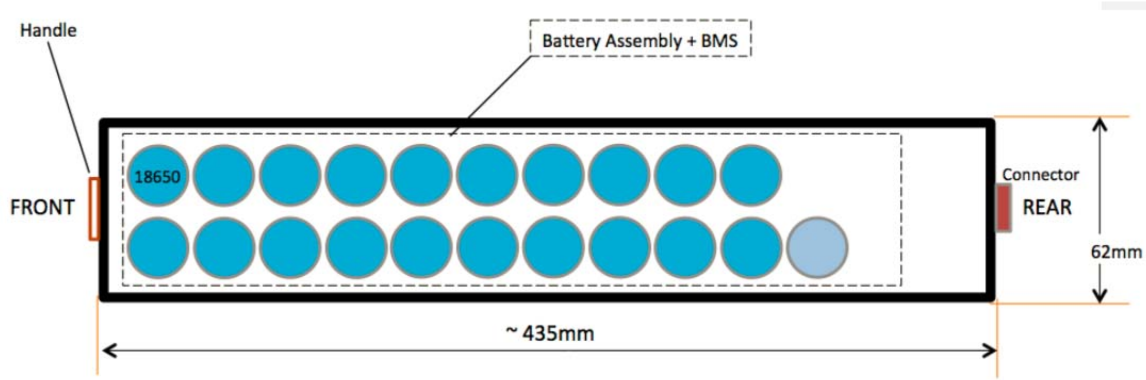
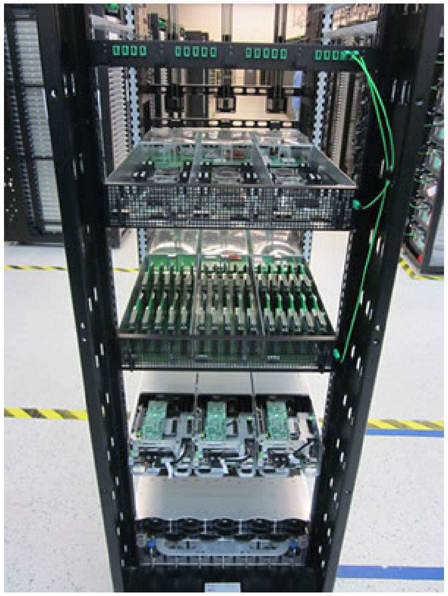


Figure 3: **BBU cell and module arrangement**

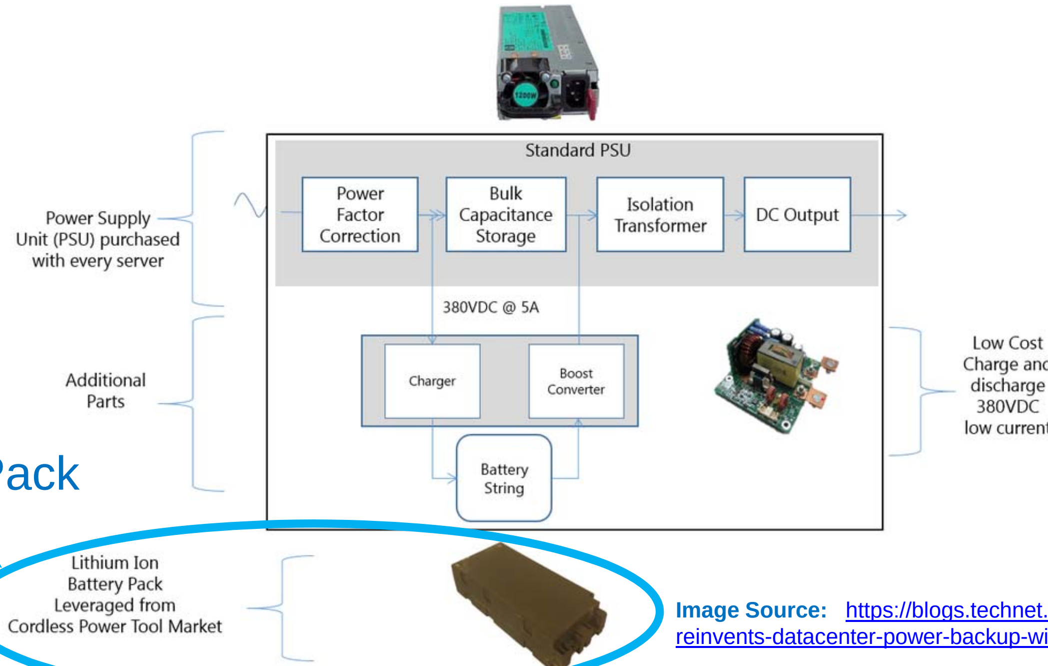
Source: Pierluigi Sarti and Zoh Ebrahimzadeh, Open Compute Project, “BBU Battery Backup Module 3600W for V2 Power Shelf”, 01/05/2015



Picture Source: http://www.opencompute.org/blog/author

“Microsoft Reinvents Datacenter Power Backup with New Open Compute Project Specification”

https://blogs.technet.microsoft.com/hybridcloud/2015/03/10/microsoft-reinvents-datacenter-power-backup-with-new-open-compute-project-specification/



Lithium Ion Battery Pack

Image Source: https://blogs.technet.microsoft.com/hybridcloud/2015/03/10/microsoft-reinvents-datacenter-power-backup-with-new-open-compute-project-specification/

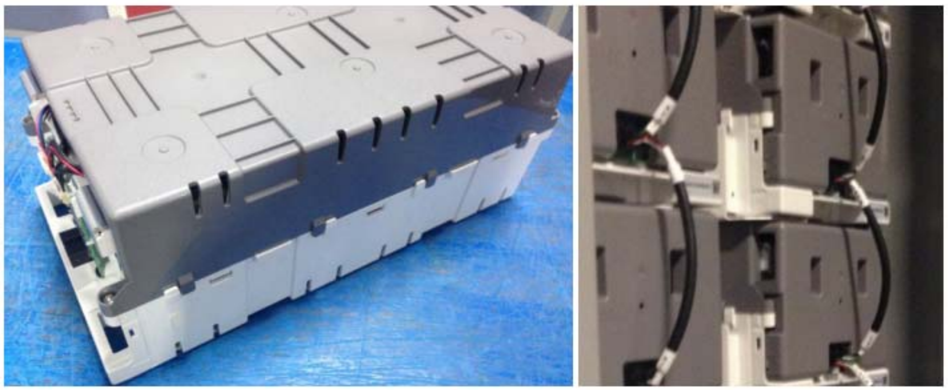
Li-Ion Batteries in Centralized UPS

Includes

- LIB Cabinets
- Battery Modules
- Battery Management System
- Passive Protection Devices

The battery for a UPS is optimized for power density, high current short duration discharges and longevity

LIB Battery Module



Source: SE WP 229, “Battery Technology for Data Centers: VRLA vs. Li-ion”, Figure 1 Li-ion battery module for 3-phase UPS applications (left) and multiple modules connected in a cabinet

LIB Cabinet

Safe Operations a Combination of Active & Passive Controls

<u>The LIB Battery Management System (BMS) is required for safe operation performing the following functions:</u>

1. Monitors LIB (Voltage, Current & Temp.
2. Communicates LIB
   1. State of Health
   2. State of Charge
3. Continuous management of each cell, battery module and cabinet/string
   1. Cell equalization

Brain Animation Source: http://www.the-scientist.com/?articles.view/articleNo/42522/title/Opinion--Can-the-Brain-Be-Trained-/

4. Safety
   1. Detects unacceptable parameters
   2. Communicates Warnings & Alarms
   3. Performs controlling action – **"Management"**
      1. Protecting each cell and battery module

Passive Protection Devices

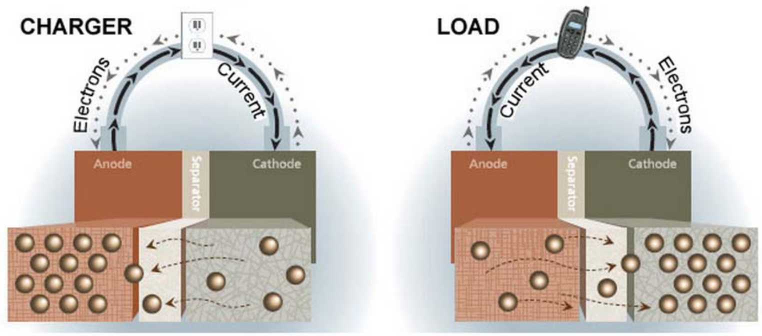
1. Circuit Breakers
   1. Cabinet/Rack/String Level
2. Electrical Fuses
   1. Cabinet/Rack/String Level
   2. Each individual cell (typical)
3. Thermal Fuses
   1. Function of the cell shutdown separator
4. Over Pressure Mitigation

Li-Ion Separators

Should be thin, strong and ability to shutdown battery in high thermal conditions

Source: "A Review of State-of-the-Art Separator Materials for Advanced Lithium-Based Batteries for Future Aerospace Missions" http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090017842.pdf

Passive Over Temperature Protection



Lithium-ion Rechargeable Battery **Charge Mechanism**

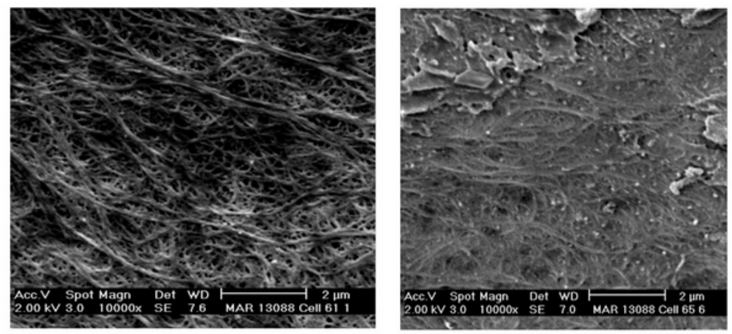
Lithium-ion Rechargeable Battery **Discharge Mechanism**

Figure 1. 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

Source: http://batteryuniversity.com/learn/article/bu_306_battery_separators

Current Separators in Commercial-off-the-Shelf Li-ion Cells



Unactivated Separator **Activated Separator**

Shut-down temperature is very close to temperature at which initiation of thermal runaway occurs.

J. Jeevarajan, Ph.D.29
NASA-JSC

Source: "Power Goals for Human Space Exploration" by J. Jeevarajan, Ph.D. April 2014
http://www.slideshare.net/AndrewGelston/power-goals-for-human-space-exploration

Battery Strings for 2 Symmetra MW UPSs (800 kW each)

Side View

Li-Ion – 3 Strings

VRLA – 6 Strings

Front View – VRLA & Li-Ion

Li-Ion

VRLA

LIB
6 Cabinets =
3 Full Strings

VRLA
3 of 6 Battery Cabinets
(ea. Cab = ½ String)

Li-ion side by side w/ VRLA

Sym MW Battery Modules/Jars in One Cabinet (384Vdc)

Smaller Footprint: Area & Weight

Li-Ion

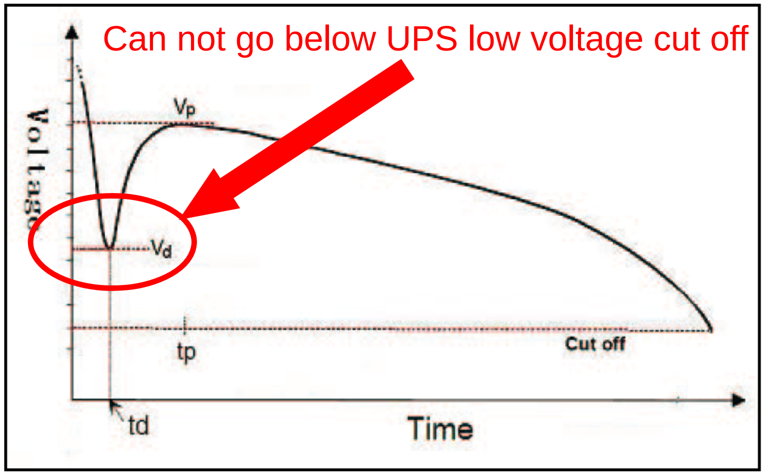
13 LIB Modules (~ 38 lbs. each)

32 VRLA Battery Jars (Typ 100 lbs./jar)

VRLA

Battery Voltage Discharge Curves (VRLA & LIB)

VRLA Battery
Coup de Fouet



Source: Coup de Fouet curve, "IMPORTANT CONSIDERATIONS WHEN REDUCING THE RUN-TIMES OF VRLA UPS BATTERIES" by Mike Nispel, Figure 3

LIB Discharge Curve

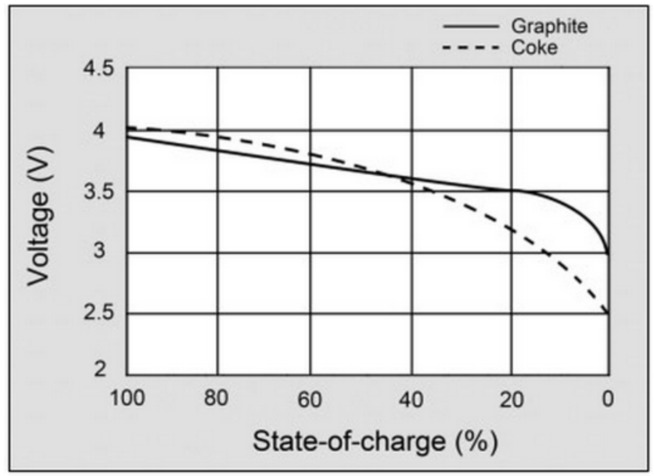


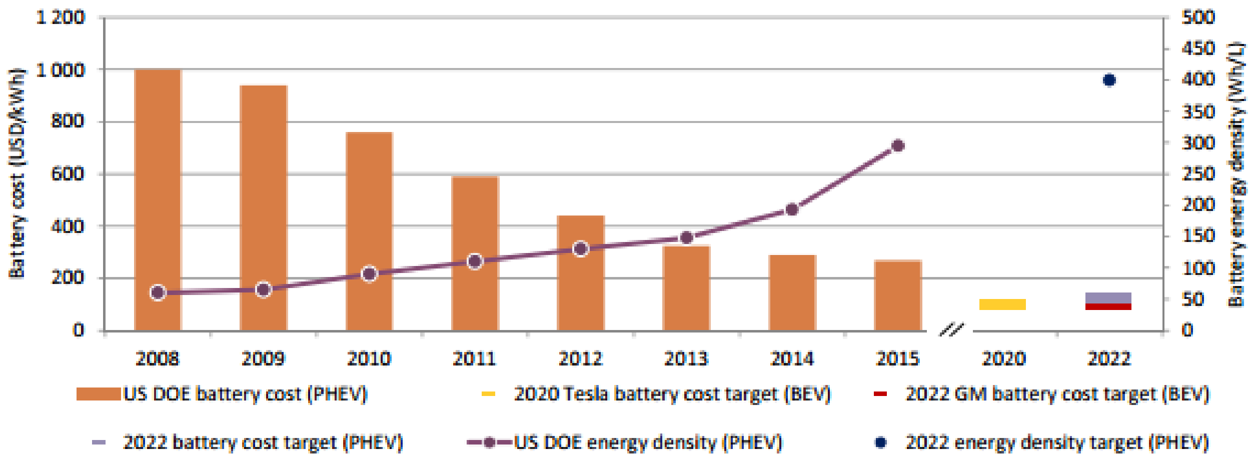
Figure 2: Voltage discharge curve of lithium-ion.
A battery should have a flat voltage curve in the usable discharge range. The modern graphite anode does this better than the early coke version.
Courtesy of Cadex

Source: BU-204: How do Lithium Batteries Work?, Figure 2
http://batteryuniversity.com/learn/article/lithium_based_batteries

Coup de Fouet: "Although the occurrence of the CDF has been recognized for many years, it has been the subject of many studies and it appears there is no simple cause. Crystallization kinetics, oxygen desorption, and electrolyte mass-transport are a few of the proposed explanations for this observation.(Hua, Zhou, Song, & Kong, 2009)(Bode, 1977)"

Battery Energy Density and Cost

Rapid cost declines coupled with performance improvements over the last decade point to a promising continuation of reduced costs with enhanced performance.*



Notes: USD/kWh ▪ United States dollars per kilowatt-hour; Wh/L ▪ watt-hours per litre. PHEV battery cost and energy density data shown here are based on an observed industry-wide trend, include useful energy only, refer to battery packs and suppose an annual battery production of 100 000 units for each manufacturer.

Sources: US DOE (2015 and 2016) for PHEV battery cost and energy density estimates; EV Obsession (2015); and HybridCARS (2015).

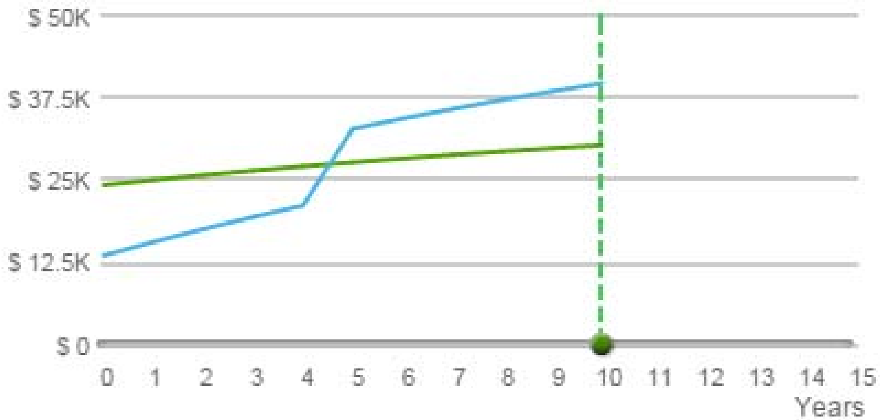
"Evolution of battery energy density and cost"*

"Electric cars include battery electric, plug-in hybrid electric, and fuel-cell electric vehicles (BEVs, PHEVs, and FCEVs)."*

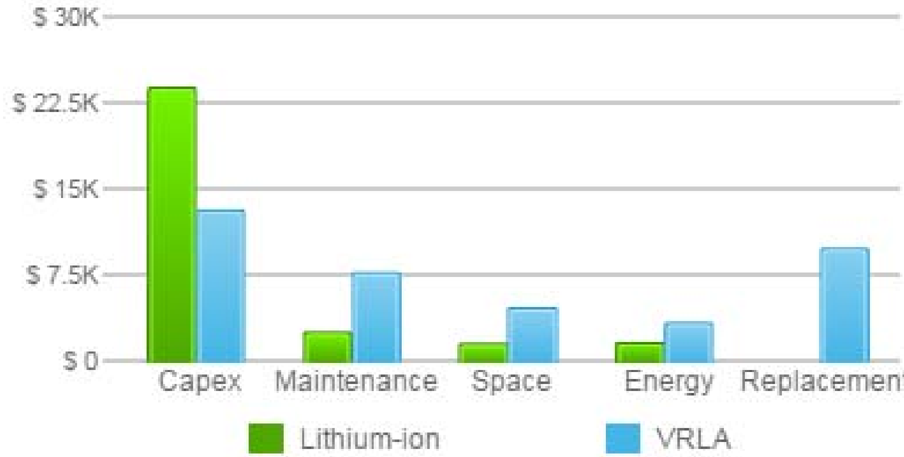
***Source: Global EV outlook 2016 - Beyond one million electric cars**
https://www.iea.org/publications/freepublications/publication/Global_EV_Outlook_2016.pdf

TCO LIB vs VRLA

200 kW UPS, 9 min Back-up time, $0.10/kWh Cost of Capital 6%, Lease Cost $4/ft^2



After 10 years, Lithium-ion batteries cost $30K, 24% less than VRLA batteries which cost $39.4K.



Battery Replacement Period

LIB = 10 years

VRLA = 5 years

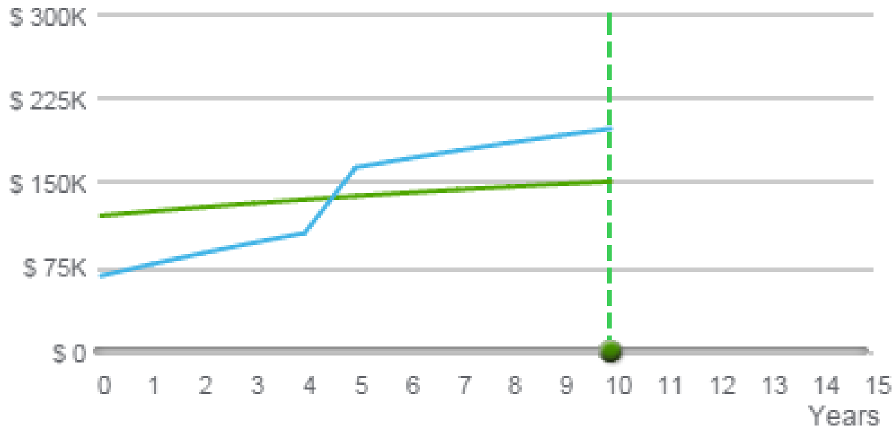
SE LIB Trade Off Tool

http://www.schneider-electric.com/b2b/en/solutions/system/s1/data-center-and-network-systems/trade-off-tools/lithium-ion-vs-vrla-battery-calculator/tool.html

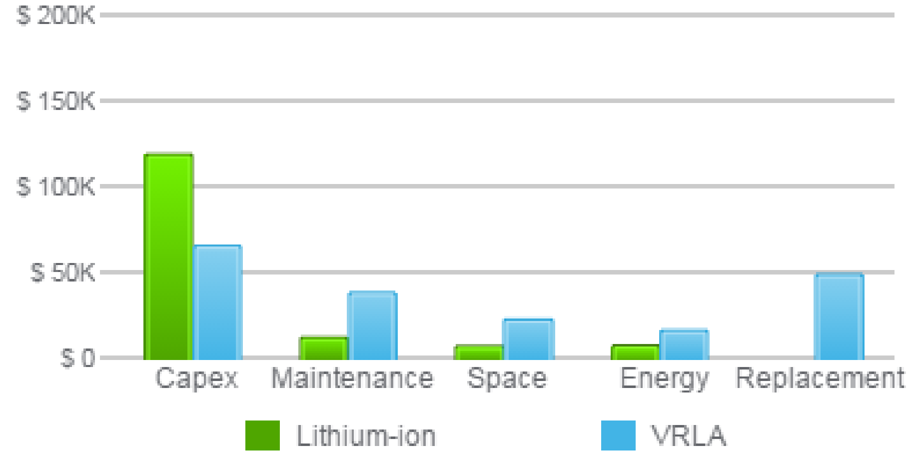
BMS is included on VRLA system

TCO LIB vs VRLA

1000 kW UPS, 9 min Back-up time, \$0.10/kWh Cost of Capital 6%, Lease Cost \$4/ft^2



After 10 years, Lithium-ion batteries cost \$150K, 24% less than VRLA batteries which cost \$197K.



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BMS is included on VRLA system

TCO Trade Off Tool Assumptions

Assumptions

- Ambient operating temperature fixed at 25°C (77°F)
- 3-phase UPS system is assumed to be the same in both battery types
- UPS system losses are excluded
- UPS loaded to 100%
- Lithium-ion cell chemistry is LMO/NMC
- Battery fixed losses from trickle charging (as % of rated UPS capacity) is 0.1% for lithium-ion and 0.2% for VRLA
- Battery transient losses not included (These are losses incurred during a power outage that require battery discharging and subsequent charging)
- Battery space lease cost does not include cost of service clearances
- Battery installation labor is not included
- Battery transportation cost is not included
- Battery maintenance cost as percent of battery capex is 1.5% for lithium-ion and 8% for VRLA
- Battery management system (BMS) cost is included in the lithium-ion battery cost
- Battery management system (BMS) in the VRLA battery is 20% of the VRLA battery cost
- Cooling system removes heat generated by the battery system
- Cooling system use 0.33 watts of energy for every 1 kW of heat rejected by the battery system

BATTERY MAINTENANCE COMPARISON

	VRLA					LIB		
Task (IEEE 1188 Section 5)*	Monthly	Quarterly	Annual	Initial	Task (OEM Recommended Maintenance)**	Daily	Monthly	Annual
Overall float voltage @ battery terminal	X				Rack/Cabinet voltage (float charge voltage)	X		
Charger output current and voltage	X				Cell voltage range (w/in recommended range)	X		
Ambient temperature	X				Rack/Cabinet electrically connected to DC bus	X		
Condition of ventilation equipment	X				Check if alarms have been triggered	X		
Condition of monitoring equipment	X				Check if faults have been triggered	X		
Visual condition check for corrosion	X				Ambient temperature and humidity	X		
Visual condition check for general appearance & cleanliness	X				Visual inspection - general condition		X	
Visual condition of jar for cracks and leakage	X				Check recorded data (voltage and current)		X	
Excessive jar/cover distortion	X				Check date & time of charge and discharge cycles		X	
DC float current/string	X				Trend analysis of recorded data			X
Cell internal ohmic values		X			**Tasks may vary depending upon LIB system OEM criteria			
Temperature of Negative terminal of each cell		X						
Voltage of each cell		X						
Cell to Cell & terminal connection resistance			X	X				
AC ripple current &/or voltage imposed on the battery			X	X				

* IEEE 1188-2005 IEEE Recommended Practice for Maintenance, Testing, and Replacement of Valve-Regulated Lead-Acid Batteries for Stationary Applications

Maintenance Man Animation Source:
http://www.clipartpanda.com/clipart_images/download-maintenance-clipart-69972749

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							S			

Maintenance & Testing Codes and Standards

Applicable codes and standards must be complied with and vary by state, province and region

VLA / VRLA

- ANSI/IEEE 450, *Recommended Practice for Maintenance, Testing and Replacement of Vented Lead-Acid Batteries for Stationary Applications*
- IEEE 1188, *Recommended Practice for Maintenance, Testing and Replacement of Valve-Regulated Lead Acid (VRLA) Batteries for Stationary Applications*
- NFPA 70B (2016) Chapter 11, section 11.14 Battery Testing

Lithium Ion

- Per OEM requirements and recommendations

Inspector Animation Source:
http://www.clipartpanda.com/clipart_images/inspector-8301057

NFPA 70 – (2017) NEC®

Article 480 Storage Batteries

480.10 Battery Locations.

- Informational Note No. 1: See NFPA 1-2015, Fire Code, Chapter 52, for ventilation considerations for specific battery chemistries.
- Informational Note No. 2: Some battery technologies do not require ventilation.

Inspector Animation Source:
http://www.clipartpanda.com/clipart_images/clip-art-classroom-inspector-62326132

NFPA-1 Fire Code 2015 ed.

“Chapter 52 Stationary Storage Battery Systems

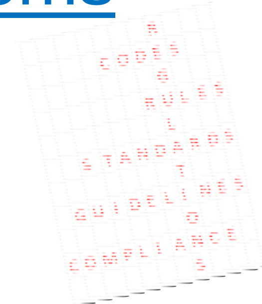
52.1* General. Stationary storage battery systems having an electrolyte capacity of more than 100 gal (378.5 L) in sprinklered buildings or 50 gal (189.3 L) in unsprinklered buildings for flooded lead-acid, nickel-cadmium, and valve-regulated lead–acid (VRLA) batteries or 1000 lb. (454 kg) for lithium-ion and lithium metal polymer batteries used for facility standby power, emergency power, or uninterrupted power supplies shall be in accordance with Chapter 52 and Table 52.1.”

Table 52.1 Battery Requirements

	Nonrecombinant Batteries		Recombinant Batteries		Other
Requirement	Flooded Lead-Acid	Flooded Nickel-Cadmium (Ni-Cd)	Valve-Regulated Lead–Acid (VRLA)	Lithium-Ion	Lithium Metal Polymer
Safety caps	Venting caps	Venting caps	Self-resealing flame-arresting caps	No caps	No caps
Thermal runaway management	Not required	Not required	Required	Not required	Required
Spill control	Required	Required	Not required	Not required	Not required
Neutralization	Required	Required	Required	Not required	Not required
Ventilation	Required	Required	Required	Not required	Not required
Signage	Required	Required	Required	Required	Required
Seismic control	Required	Required	Required	Required	Required
Fire detection	Required	Required	Required	Required	Required

Source: NFPA-1 2015 , Chapter 52 Stationary Storage Battery Systems, article 52.1 General & Table 52.1

NFPA 70 (2017) Article 706 Energy Storage Systems



706.2 Definitions

- Energy Storage System, Pre-Engineered of Matched Components.

- Energy storage systems that are not self-contained systems but instead are pre-engineered and field-assembled using separate components supplied as a system by a singular entity that are matched and intended to be assembled as an energy storage system at the system installation site.

Informational Note: Pre-engineered systems of matched components for field assembly as a system will generally be designed by a single entity and ***comprised of components that are tested and listed separately or as an assembly.*** (emphasis added)

Root Cause of LIB Cell Failure

"Generally, the root causes of energetic cell and battery failures can be classified into:

- Thermal abuse
- Mechanical abuse
- Electrical abuse
- Poor cell electrochemical design
- Internal cell faults associated with cell manufacturing defects."

Source: "Lithium-Ion Batteries Hazard and Use Assessment Final Report", Fire Protection Research Foundation, http://www.prba.org/wp-content/uploads/Exponent_Report_for_NFPA_-_20111.pdf (last accessed 22-July-2016)

Causes of Failures

"Both energetic and non-energetic failures of lithium-ion cells and batteries can occur for a number of reasons including:

1. poor cell design (electrochemical or mechanical),
2. cell manufacturing flaws,
3. external abuse of cells (thermal, mechanical, or electrical),
4. poor battery pack design or manufacture,
5. poor protection electronics design or manufacture, and
6. poor charger or system design or manufacture.

Thus, **lithium-ion battery reliability and safety is generally considered a function of the entirety of the cell, pack, system design, and manufacture**." (emphasis added)

Source: "Lithium-Ion Batteries Hazard and Use Assessment Final Report", Fire Protection Research Foundation, http://www.prba.org/wp-content/uploads/Exponent_Report_for_NFPA_-_20111.pdf (last accessed 22-July-2016)

Transportation & Recycling

Transportation of Li-Ion Batteries
Rules and regulations governing the transportation of Li-Ion Batteries are more stringent than for VRLA batteries.

Recycling of Li-Ion Batteries
A LIB recycling program is in its infancy at the time of this presentation unlike the present recycling program in place for lead acid batteries.

3 Phase UPS LIB ESS Recommendations (Safety & Functionality)

1. Deploy systems supported by the UPS OEM
2. LIB and BMS should be a package from the OEM
3. The complete system LIB & BMS must ***meet and or exceed safety testing*** such as UL or regional equivalent.
4. Use only battery manufactures who have in place a stringent and **proven QA/QC program**.
5. The installation must be ***in compliance with all required codes and standards.***
6. Installation, start-up and commissioning should be performed by trained and qualified personnel.

Handshake Animation Source: http://www.imageif.com/image/free-handshake-clipart-pictures-clipartix

Teamwork Animation Source: http://www.clipartpanda.com/clipart_images/working-together-42700637

Source: http://route249.com/2012/03/17/tubes-vs-solid-state/

Source: https://davescomputertips.com/can-you-hear-me-now-landline-vs-cellphone

“The stone age came to an end not for lack of stones And the oil age will come to an end not for lack of oil”

— Sheikh Yamani, former Saudi Oil Minister

Resources for Further Study

A good starting point for additional information on LIB systems includes but is not limited to:

- **Vendor Neutral**
  - Battery University: http://batteryuniversity.com/
  - Battcon Presentations/Whitepapers: http://www.battcon.com/Battcon_Archive_Papers.htm
  - IEEE papers and proceedings
  - Underwriters Laboratory documents
- **LIB System Manufactures**
- **UPS Manufacturers White Papers**

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Questions

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Mud Tracks Animation Source: http://www.cliparthut.com/muddy-tire-clip-art-clipart-9roacM.html