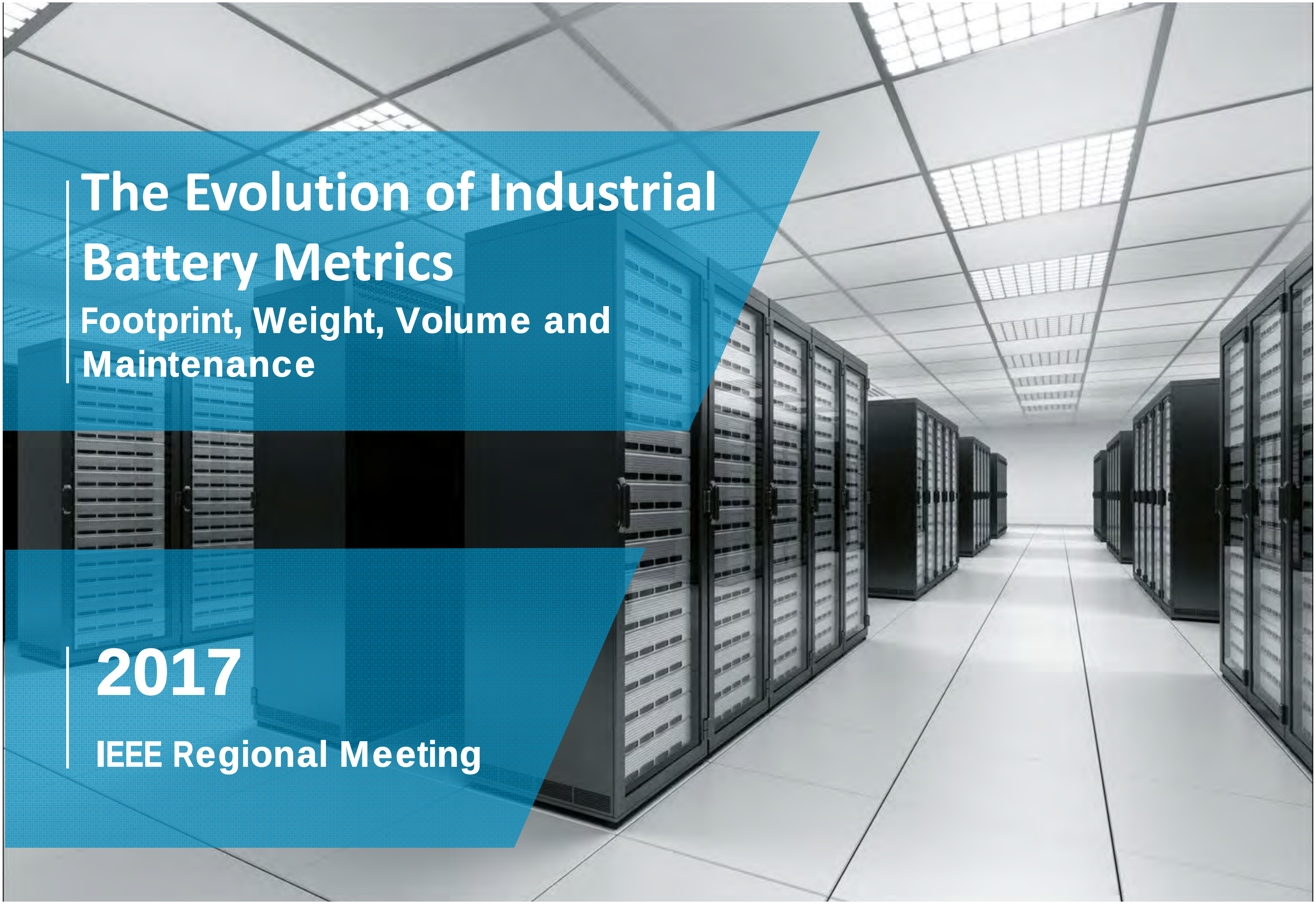


The Evolution of Industrial Battery Metrics

Footprint, Weight, Volume and Maintenance

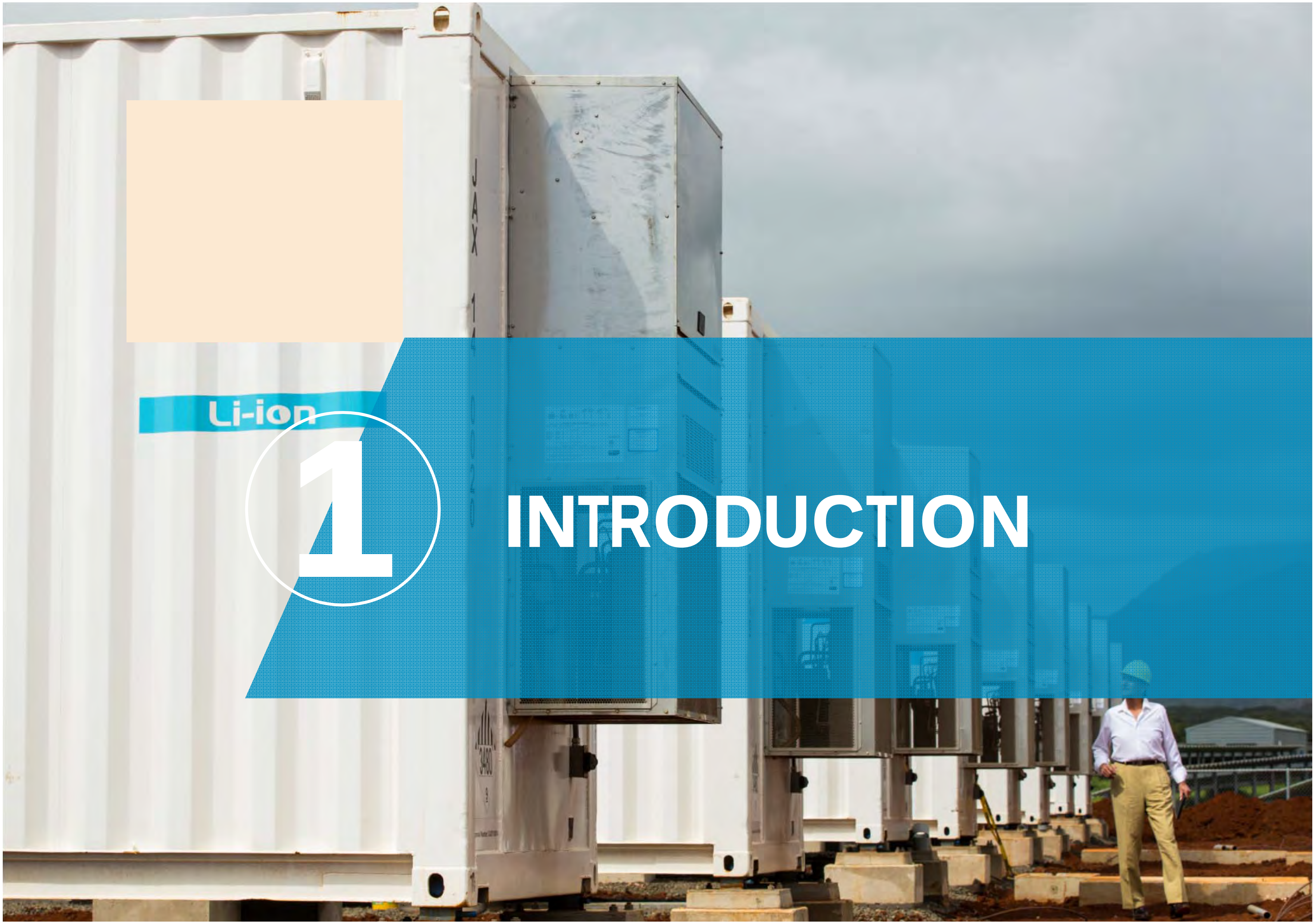
2017

IEEE Regional Meeting

Agenda

1. Introduction
2. Traditional Technologies
3. New Industrialized Lithium-ion Technologies
4. Application Case Study
5. Maintenance Comparisons

1 INTRODUCTION



Definitions – Battery terms

Ah – Ampere-hours

- Battery's rating of capacity
- 1 amp for 1 hour = 1Ah

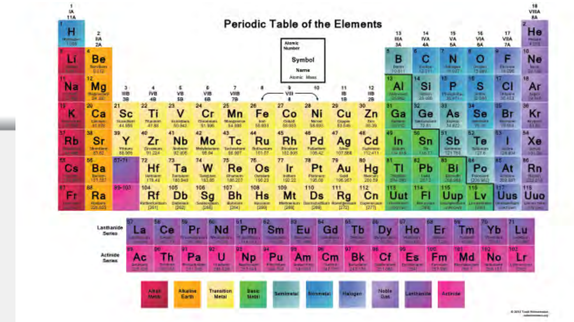
Rated capacity of a battery

- Amps available at a fixed time, to a fixed end of discharge voltage, at a standard temperature
- Ni-Cd batteries rated capacity is measured at: (per IEC60623)
  - 5 hours, to 1.00Volts per cell (Volts/Cell) at 77°F, at fully charged state; Example: 235Ah = 47A for 5 Hours
- Lead-Acid Batteries rated at the 8hr rate to 1.75VPC @ 77F.

Power = Instantaneous (V x I)

Energy = Power x Time

Battery Basics



Traditional Products

– Electrolyte and Active Materials:

- Lead & Acid
  - o Sulfuric Acid (H_2SO_4)
    - – pH = ~2
    - – Nominal Cell Voltage = 2.0VDC

Equation 1 Electrolyte	H_2SO_4	$\rightleftharpoons$	$H^+ + HSO_4^-$
Equation 2 Negative Electrode	$Pb_{(metal)} + HSO_4^-$	Discharge $\rightleftharpoons$ Charge	$PbSO_4 + H^+ + 2e^-$
Equation 3 Positive Electrode	$PbO_2 + 3H^+ + HSO_4^- + 2e^-$	Discharge $\rightleftharpoons$ Charge	$PbSO_4 + 2H_2O$
Equation 4 Total Reaction	$Pb_{(metal)} + PbO_2 + 2H_2SO_4$	Discharge $\rightleftharpoons$ Charge	$2PbSO_4 + 2H_2O$

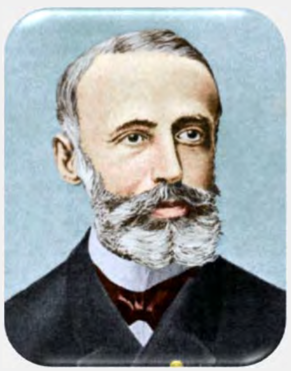
- Nickel-Cadmium
  - o Electrolyte: Potassium Hydroxide (no part of the chemical equation)
    - – pH = ~11
    - – Nominal Cell Voltage = 1.2VDC
    - – Electrolyte acts as preservative and means to transfer energy

$$2\ NiOOH + 2H_2O + Cd \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} 2\ Ni(OH)_2 + Cd(OH)_2$$

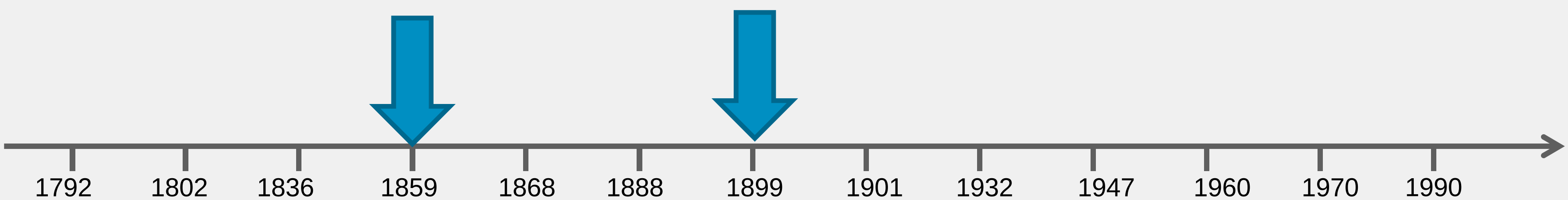
Battery Basics
History

The Early Day of Batteries

– Gaston Plante
  - French Physician
  - Invented the first rechargeable (secondary lead-acid battery in **1859**



– Waldemar Jungner
  - Swedish Chemist
  - Invented the first rechargeable nickel-cadmium battery in **1899**



Battery Basics
History

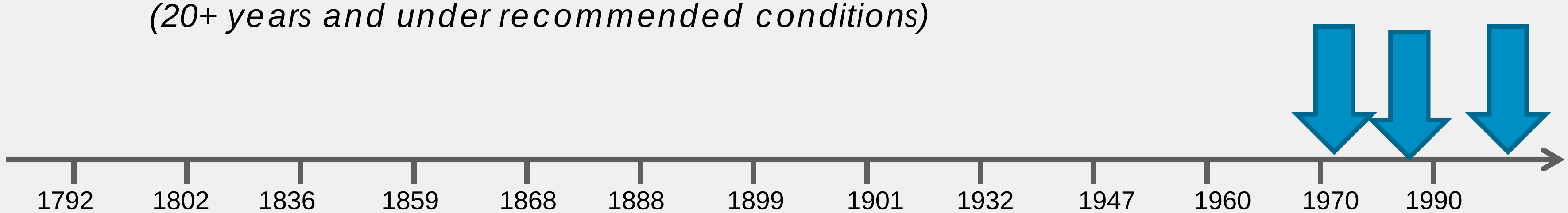
Traditional Battery Improvements…

– 1970’s: the development of valve regulated lead-acid batteries

– 1980’s: Market introduces “ultra low” maintenance nickel-cadmium batteries

– 2010: Saft introduces maintenance-free* nickel-cadmium batteries

- *The term maintenance-free means the battery does not require water during it’s entire service life (20+ years and under recommended conditions)*

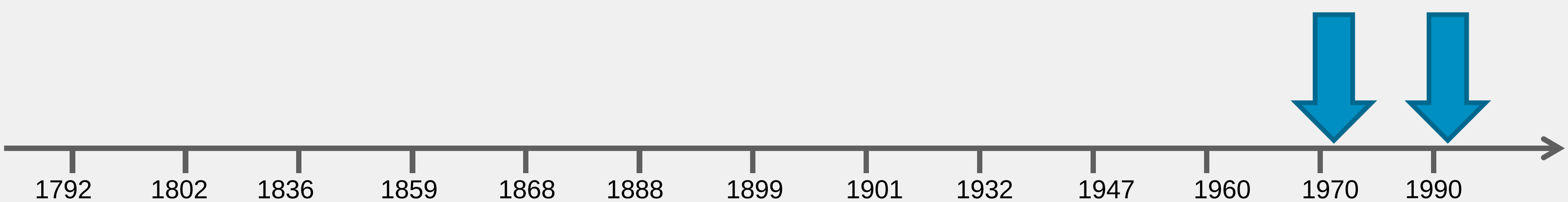


The future of batteries – Lithium-ion

- 1991: Sony introduced the first Li-ion cell (18650 format)

- 1992: Saft introduced its commercially available Li-ion cell

- 1976: Exxon researcher – Whittingham described lithium-ion concept in Science publication entitled "Electrical Energy Storage and Intercalation Chemistry"



Overview of Battery Types

Global Market of Batteries

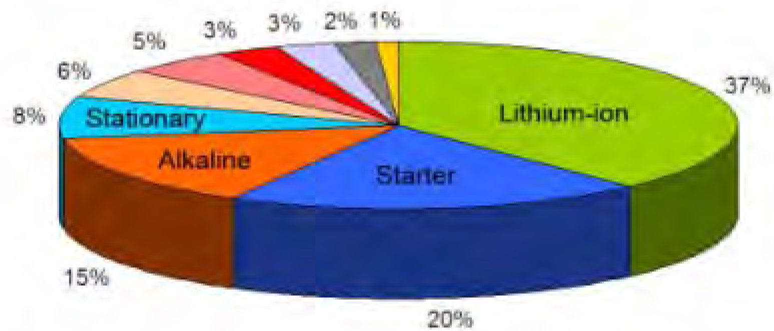


Figure 1: Revenue contributions by different battery chemistries

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)

2 TRADITIONAL TECHNOLOGIES

Lead Acid Batteries

- Lead Acid Batteries - VLA – vented / flooded cells
  - Calcium, Selenium, Antimony and Planté – plate designs
  - Nominal 2.00 volts per cell
  - Designs established 1880s and 1890s
  - 20th-century work limited mainly to alloy research
  - Electrolyte - Sulfuric acid (H2So4) 1.205 - 1.275 Sp. Gr.
  - Typical Service life 12 – 15 years {Planté – 25 years}
- Lead Acid Batteries - VRLA – Valve Regulated Lead Acid
  - Introduced in 1973 - current VRLA designs established in 1980s
  - Suitable for controlled non-critical environments
  - Low cost ? Low maintenance ? With monitoring equipment ?
  - Typical Service life 3 – 7 years

Lead Acid Batteries

Nickel Cadmium Batteries

- Nickel Cadmium – vented / flooded – IEC 60623
  - Pocket Plate – plate designs
  - Nominal 1.20 volts per cell
  - Design established 1900 – 1901
  - L, M and H rate plate types established 1960s
  - New plate types (plastic bonded, fiber) established 1950s
  - Electrolyte - Potassium hydroxide / lithium (KoH) - 1.190 - 1.250 Sp. Gr.
  - Design life 20 – 25 years

- Nickel Cadmium – vented / flooded – Gas recombinant – IEC 62259
  - L & M rate low maintenance types established towards the end 1980s
  - L & M rate maintenance-free types established 2012
    - The term maintenance-free means that no addition of water is necessary during the life time of the product when operating under recommended conditions.

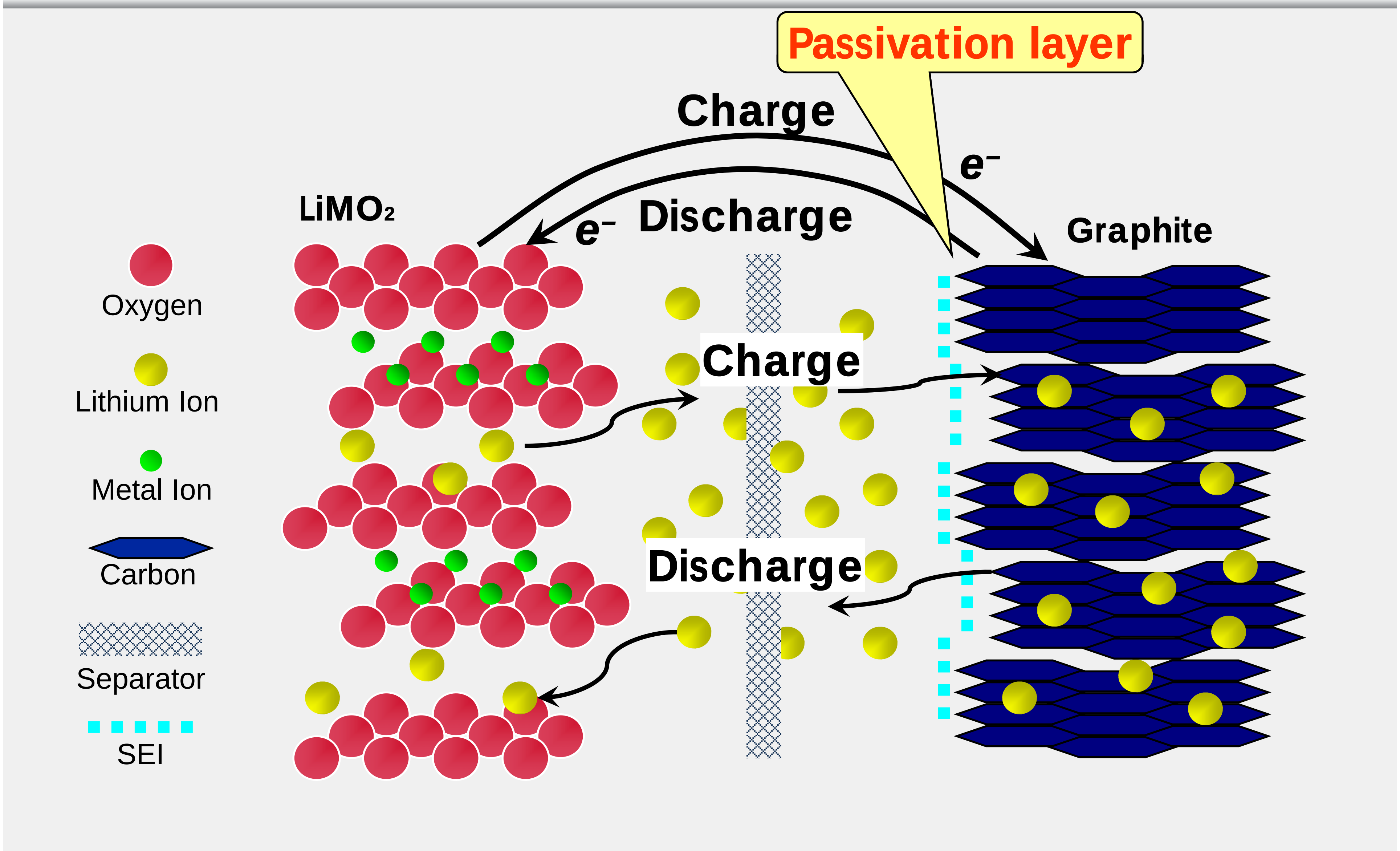
Nickel Cadmium Batteries

3 LI-ION BATTERIES

Li-ion: What's Different?

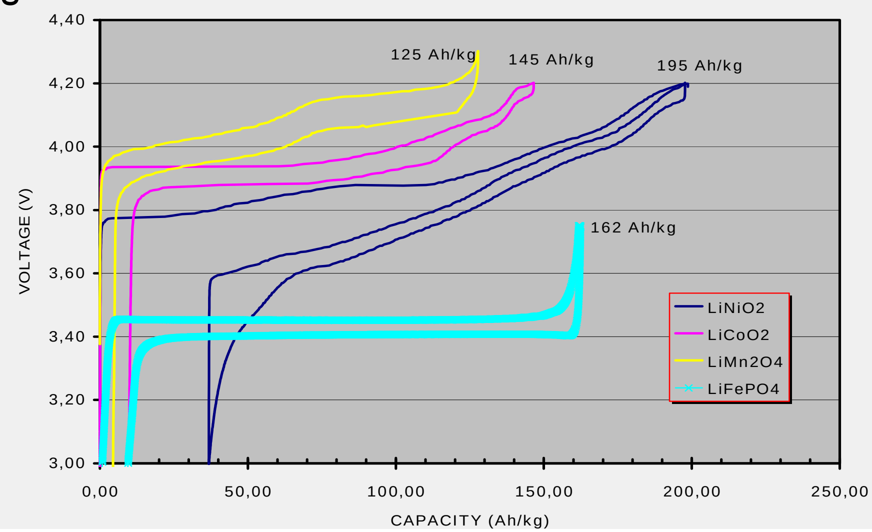
- Aqueous cells – use water based electrolyte, water electrolyzes at 1.3 V (Ni-Cd) and 2.15 (Pb-acid) thermodynamically
  - Acidic electrolyte
    - E.g. Pb-acid using H2SO4 solution as electrolyte; cell voltage is 2.2V
  - Alkaline electrolyte
    - Ni-Cd (1.2V), Ni-MH (1.25V) using KOH solution
- Li cells – use organic electrolyte in order to be stable at cell voltage exceeding 3V.
  - Li primary cells – use Li metal as the negative electrode
  - Li-ion – no metallic Li, uses graphite to host Li-ions in a mix of carbonate solvents with Li-salt as electrolyte
  - Li polymer- like Li ion but with a gel electrolyte

Li-ion reaction mechanism

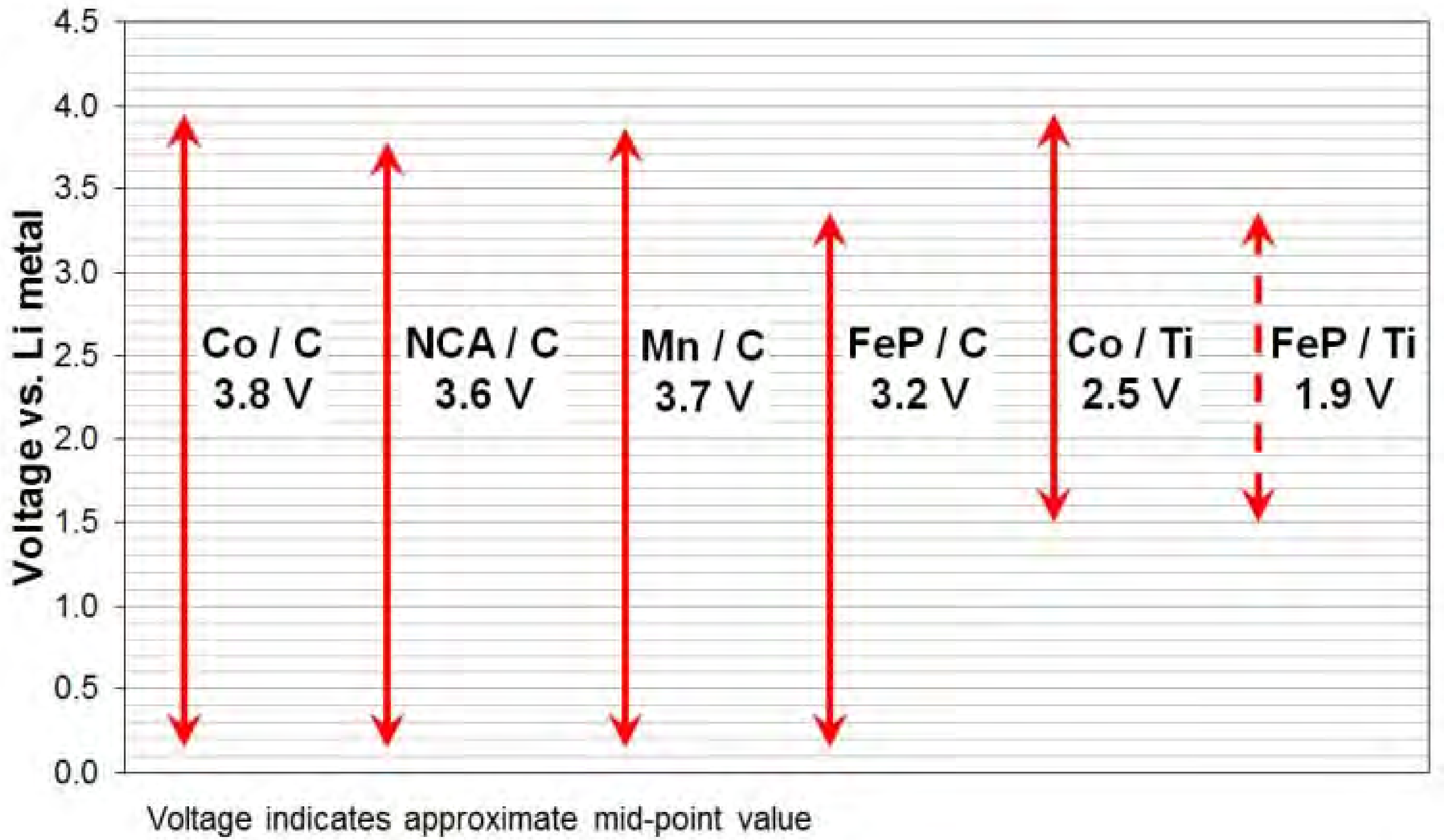


Li-ion: Many Flavors

- Currently Used Cathodes
  - $LiCoO_2$ = LCO – Cell Phones, Tablets, Cameras
  - $LiNiCoAlO_2$ = NCA – Industrial, EV's
  - $LiNiMnCoO_2$ = NMC – E-bikes, Medical Devices, EV's
  - $LiMn_2O_4$ = LMO – Power Tools, Medical Devices
  - $LiFePO_4$ = LFP – Portable and Stationary, high load applications
- Currently Used Anodes
  - Graphite = Carbon (C)
- Emerging anodes
  - $Li_4Ti_5O_{12}$ = Lithium Titanate Oxide (LTO)
  - Alloy anodes = Si and Sn based (Silicon and Tin)

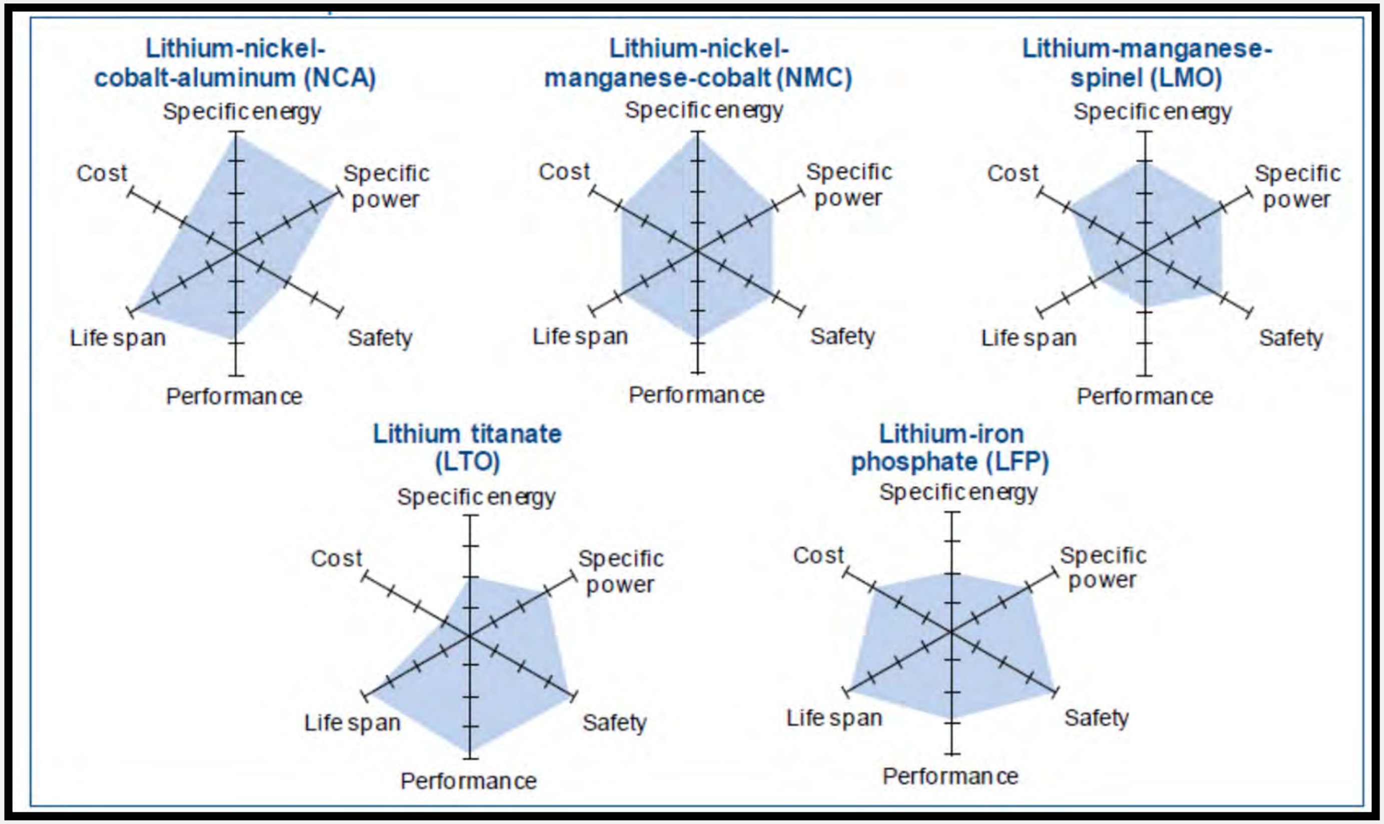


Li-ion Chemistries: Nominal Cell Voltages



Major Lithium Ion Chemistries

Tradeoffs among the five principal lithium ion battery technologies



Source: BCG Research

The furthered colored shape extends along a given axis, the better the performance along that dimensi

Cell Formats

- Cylindrical
  - Provides best support for expansion and contraction of electrodes during cycling
  - Suitable for higher capacity levels per cell
  - Required for some chemistries that produce low levels of gas over life (easier containment)
  - Less factory handling required
- Prismatic
  - Better energy density with thermal barriers
- Pouch
  - Difficult to seal for long life
- Capacities determined by geometry (up to 80Ah per cell)

Li-ion Modular Assemblies

- Smart batteries require communications
- BMM Battery management module
- Master - BMM for multiple strings
- SOC – State of charge
- SOH – State of health
- Temperature management
- Safety functions

Cell Pack (cutaway)


✓ Foot print saved

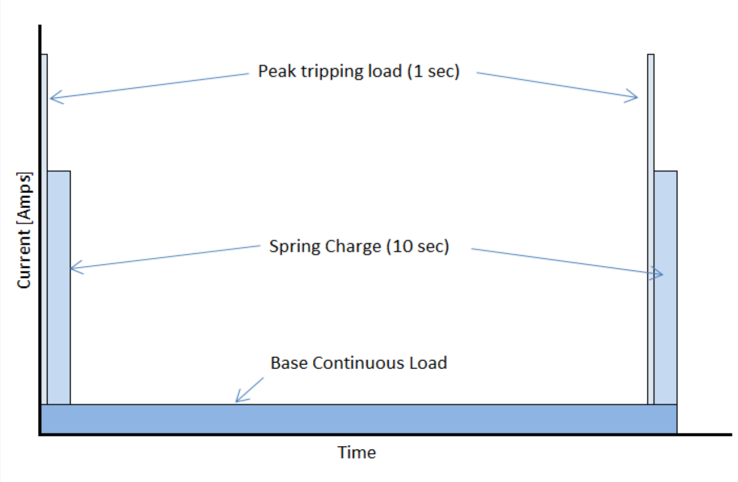
4 SWITCHGEAR CASE STUDY

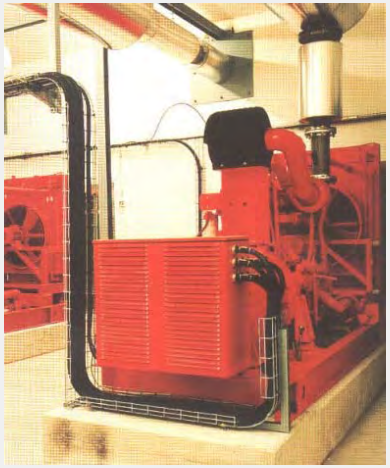
Introduction

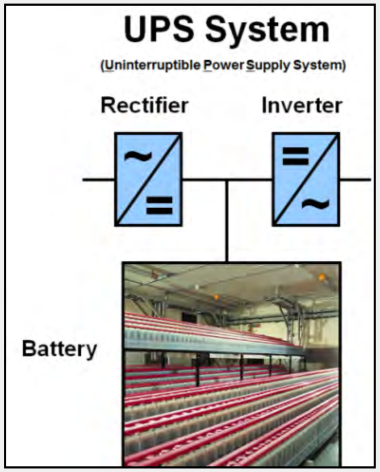
– We are all familiar with battery applications and today we are going to look at other considerations that can influence our industrial battery selections.
  - Battery Technologies
  - The “Load Profile”- you do really need this
  - The Initial Battery Cost
  - Footprint
  - Volume
  - Weight
  - Cycle Life
  - Power Density
  - Preventive Maintenance or Maintenance Free
  - Life Cycle Cost

Main "Standby" Applications

- Switchgear
  - Medium to High Performance Requirements
  - Load Profile!
  - 48V and 120V
  - Industrial and Utility
- UPS
  - Short Duration Commercial = High Performance
  - Long Duration UPS = Long or Medium Performance
  - Industrial, Data Center and OEM
- Engine Starting (the forgotten application)
  - 12V or 24V
  - Diesel Genset
  - Fire Pumps
- DC Controls
  - SCADA
  - Turbine Control
  - Emergency Lighting







Load Profile and Environmental Parameter

- Vmin = 105 Vdc
- Vnom = 125 Vdc
- Vmax = 140 Vdc

- *t* min = 32°F
- *t* nom = 68°F
- *t* max = 104°F

- Design Margin = 1.10
- Aging Factor = 1.25
- Recharge time = 8 – 12 hrs

- L_1 = 146A for 1 min {*0.017 min}
- L_2 = 13A for 1 min {*0.017 min}
- L_3 = 18A for 1 min {*0.58 min}
- L_4 = 6A for 474 mins {*478.77 min}
- L_5 = 146A for 1 min {*0.017 min}
- L_6 = 13A for 1 min {*0.017 min}
- L_7 = 18A for 1 min {*0.58 min}

- Note: Ni-Cd & Li-ion discharge periods are 1 second or greater {*}

Results - Capacity

VRLA

SLA type battery.
60 cells.

160Ah

VLA

Selenium Type
60 cells

300Ah

NiCd

S/PBE battery.
93 cells.

115Ah

Li-ion (LFP)

1 String of 5 x 23Volt Modules, integrated management system 35 cells, 2x internally parallel

76Ah

Results – Footprint / Volume / Weight

VRLA

L-36.7” x W-30” x H-61.5”

FP = 7.6 sq.ft.

V = 39.2 cu.ft.

1704 lbs

VLA

L-94” x W-29” x H-66”

FP = 19.0 sq.ft.

V = 104.6 cu.ft.

3870 lbs

NiCd

L-47.2” x W-23.2” x H-66”

FP = 7.6 sq.ft.

V = 40. cu.ft.

463 lbs

Li-ion (LFP)

L-24” x W-20.5” x H-52”

FP = 3.42 sq.ft.

V = 14.6 cu.ft.

440 lbs

Summary

Application Summary

Battery	Energy	Footprint	Volume	Weight
VLA	100%	100%	100%	100%
VRLA	53%	40%	37%	44%
NiCd	38%	40%	38%	12%
Lithium-ion	25%	18%	14%	11%

Battery Properties

Battery	Energy Density (wh/kg)	Power Density (w/kg)	Cycle Life	Operating Temperature
VLA	25 – 40	20 - 30	400	-10°F to 104°F
VRLA	35 – 45	30 - 70	250 – 800	-10°F to 104°F
NiCd	35 – 50	40 - 160	600 – 2000	-40°F to 122°F
Li-ion*	100 - 250	200 - 680	3500 - 4000	-4°F to 140°F

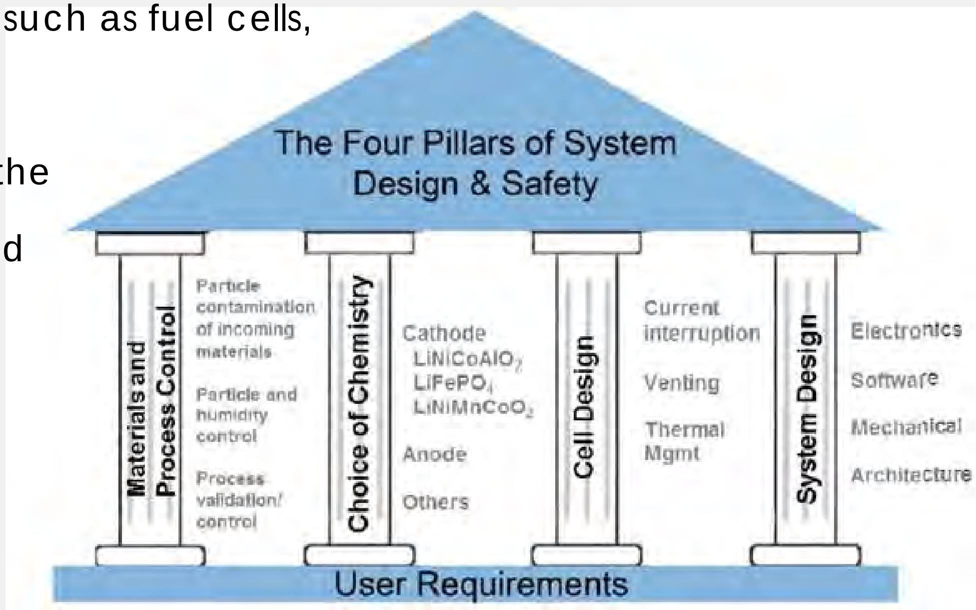
*based on SLFP chemistry

Related Standards for Emerging Technologies

– IEEE Std 1679-2010
  - IEEE Recommended Practice for the Characterization and Evaluation of Emerging Energy Storage Technologies in Stationary Applications
  - Recommended information for an objective evaluation of an emerging energy storage device or system for any stationary application
  - The storage medium may be electrochemical (e.g., batteries), kinetic (e.g., flywheels), electrostatic (e.g., electric double-layer capacitors), thermal, or some other medium
  - Devices recharged by non-electrical means, such as fuel cells,
  - are beyond the scope of this document
  - The document provides a common basis for the
  - expression of performance characteristics and
  - the treatment of life-testing data

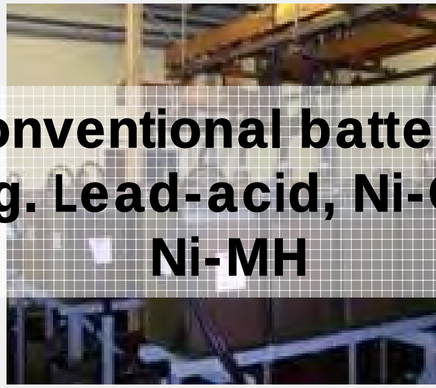
– IEEE Std 1679.1 – draft format

– UL1642, UL1778, UL1973



5 BEYOND LI-ION

Battery technology differentiation



Conventional batteries
e.g. Lead-acid, Ni-Cd, Ni-MH

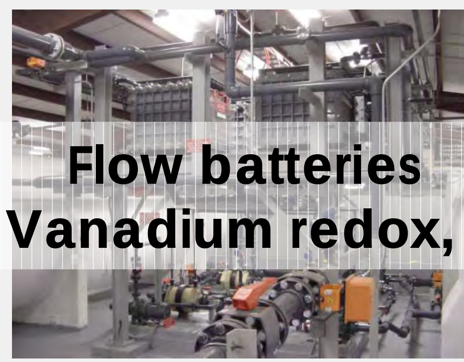
Remove water

Lithium batteries
e.g. Li-ion, Li-polymer, Li-metal polymer, Li-S

Add heat

Separate power from energy

High-temperature batteries
e.g. Na-S, Na-$NiCl_2$



Flow batteries
e.g. Vanadium redox, Zn-Br

Sodium-Ion

What is it?

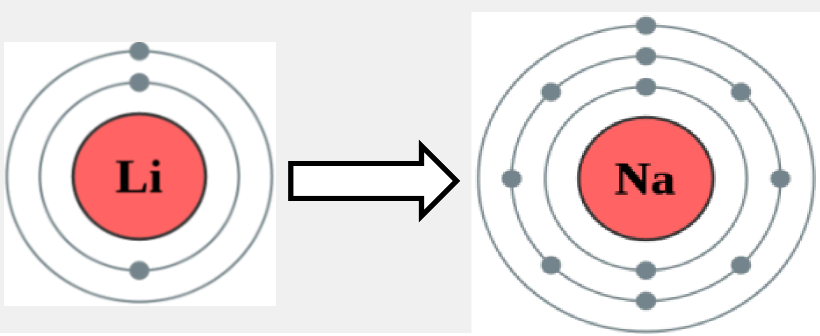
– Similar to Li-ion, but one step down on the periodic table. Replaces Li with Na. Could be multiple families, like Li-ion

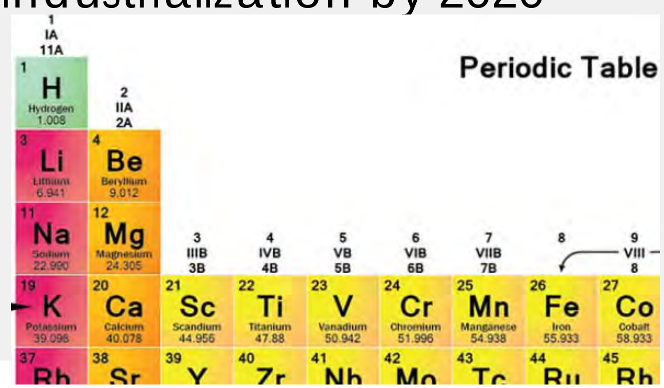
What are the advantages?

– Cost is a driving force. Na is more abundant and cheaper than Li. Could be used for stationary applications, because will not compete against Li in energy density.

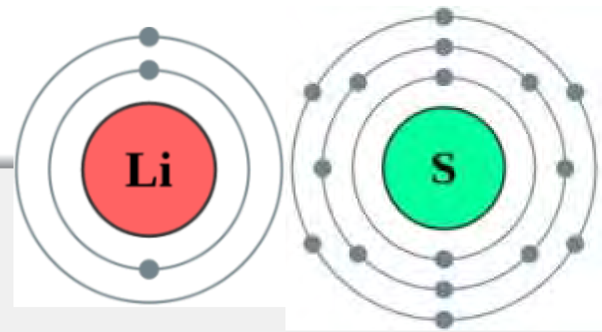
When can we expect it?

– The cell components would be the same as Li-ion. The development is on electrode materials, with hopes for industrialization by 2020





Lithium-Sulfur



What is it?

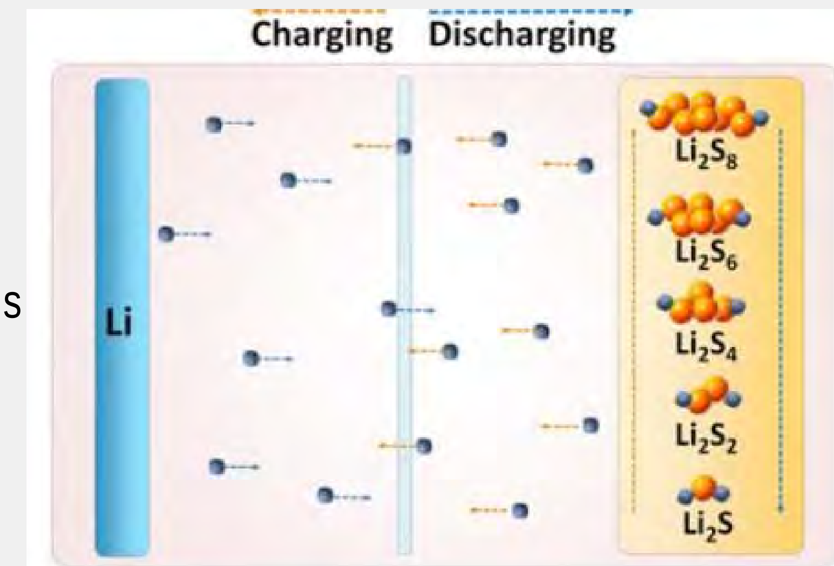
– Making a primary cell, rechargeable. There are no host structures for ions. Lithium anode is consumed and sulfur is transformed during discharge, opposite occurs for charging.

What are the advantages?

– Extremely light weight. 4x to 5x more energy dense than Li-ion. Great fit for aviation, drone and space applications

When can we expect it?

– Li-S technology needs more research and development to improve life. Industrialization for long life applications is not for 5 years.



Solid-State

What is it?

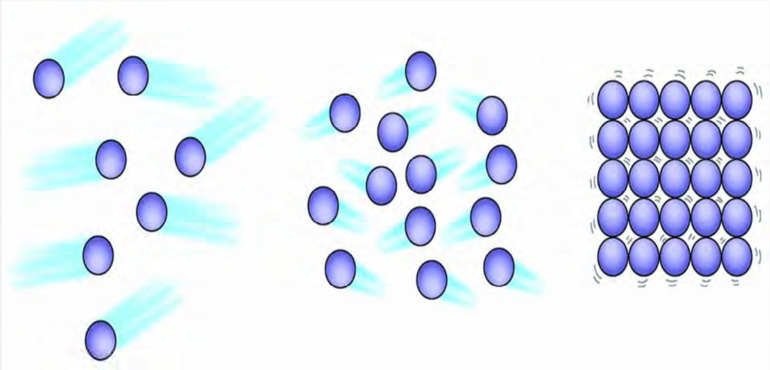
– Replaces liquid electrolyte with solid compound, but allows Lithium-ions to move within it.

What are the advantages?

– Safety is key. Inorganic solid electrolytes are non0flammable when heated. This technology also permits the use of innovative, high-voltage, high-capacity material, enabling denser, lighter batteries.

When can we expect it?

– Several kinds of all-solid-state batteries are likely to come to market as technological progress continues. First will be graphite-based, but with much higher safety and performance.



Thank you for attending