Batteries for Energy Storage

by

Keith Adendorff

FIRST NATIONAL BATTERY
THROUGH CARING WE LEAD
http://www.battery.co.za

Batteries for energy storage

- Battery types
- Battery selection criteria
- Secondary batteries
- Applications
- Conclusions

Battery Types

- Primary
- Secondary (Rechargeable)
- Reserve
- Flow batteries
- Metal air
- Fuel Cells

Secondary batteries

- Lead acid battery
- Nickel – cadmium (NiCad)
- Nickel – metal hydride (NiMH)
- Sodium sulphur
- Sodium nickel chloride (Zebra)
- Lithium batteries

Battery selection criteria

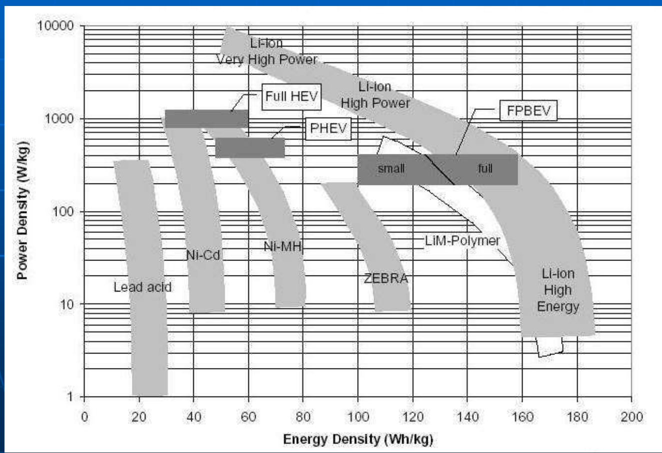
- Energy density (Wh/kg, Wh/l)
- Power density (W/kg)
- Voltage
- Power requirements and duration
- Cycle life
- Temperature (and management)
- Self discharge
- Maintenance
- Safety
- Cost
- Physical dimensions
- Charger characteristics and requirements
- Environmental (& recycling)
- Other (reliability, ease of manufacture, warranty)

Battery selection criteria

Cell reactions & specific energies					
Battery		Cell reaction			Specific energy
+ve	-ve	Charge	Volts	Discharge	(Wh/kg)
PbO_2	Pb	$PbO_2+2H_2SO_4+Pb$	2.0 ⇔	$2PbSO_4+2H_2O$	171 (35)
NiOOH	Cd	$2NiOOH+2H_2O+Cd$	1.2 ⇔	$2Ni(OH)_2+Cd(OH)_2$	217 (50)
NiOOH	MH	2NiOOH+MH	1.2 ⇔	$2Ni(OH)_2$ +M	+280 (70)
S	Na	2Na+3S	2.0 ⇔	Na_2S_3	760 (120)
$NiCl_2$	Na	$2Na+NiCl_2$	2.5 ⇔	2NaCl+Ni	790 (120)
$LiCoO_2$	LiC_6	LiC_6+CoO_2	3.6 ⇔	$C_6+LiCoO_2$	766 (140)
$LiNiO_2$	LiC_6	$LiC_6+Ni_{0.8}Co_{0.2}O2$	3.7 ⇔	$C_6+LiNi_{0.8}Co_{0.2}O2$	766 (180)
Petrol			→	CO_2	12333

Battery selection criteria

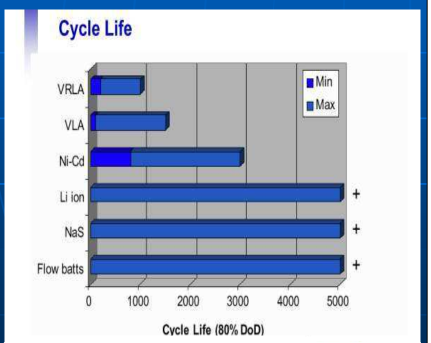
- Power and energy density



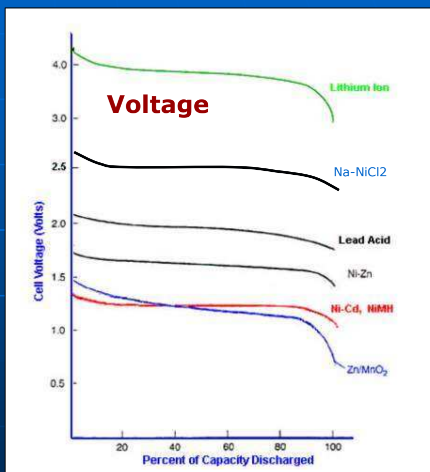
Status & prospects for zero emissions vehicle technology – Report of the ARB independent expert panel, 2007
http://www.arb.ca.gov/msprog/zevprog/zevreview/zev_panel_report.pdf

Battery selection criteria

- Voltage
- Life



From " Role of Energy storage for distributed energy resources", 2006
Thomas Key (tkey@epri.com).



Modified from "Types of batteries & differences in energy & power",
B. Fultz, 2007

Lead acid batteries

Overall cell reaction:

$PbO_2 + Pb + 2H_2SO_4 \Leftrightarrow 2PbSO_4 + 2H_2O$

Overcharge reaction:

$2H_2O \Rightarrow 2H_2 + O_2$ (water loss)

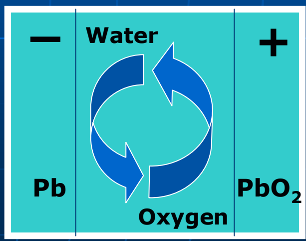
Oxygen recombination cycle:

$2Pb + 2H_2SO_4 + O_2 \Rightarrow 2PbSO_4 + 2H_2O$

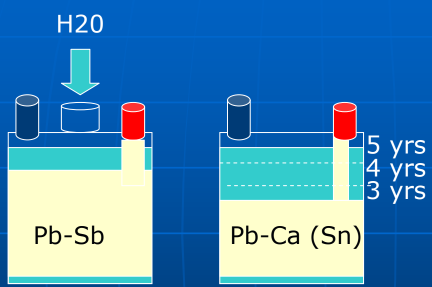
$2PbSO_4 + 4H^+ + 4e^- \Rightarrow 2Pb + 2H_2SO_4$

$O_2 + 2H_2 \Rightarrow 2H_2O$

(water preserved)



Types of lead acid batteries

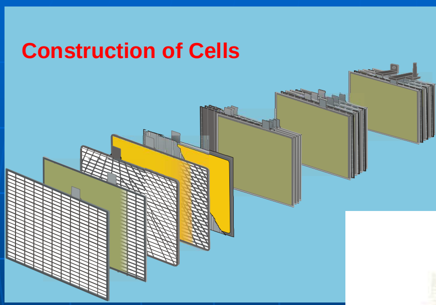


Conventional flooded or hybrid. High gas rate. Water added

Maintenance free. “Sealed”, flooded. Minor gas vented through lid. Excess water determines life

VRLA (AGM or GEL). “Sealed”, no excess electrolyte. Water retained by oxygen recombination cycle. Gas may be released through valve

SLI battery

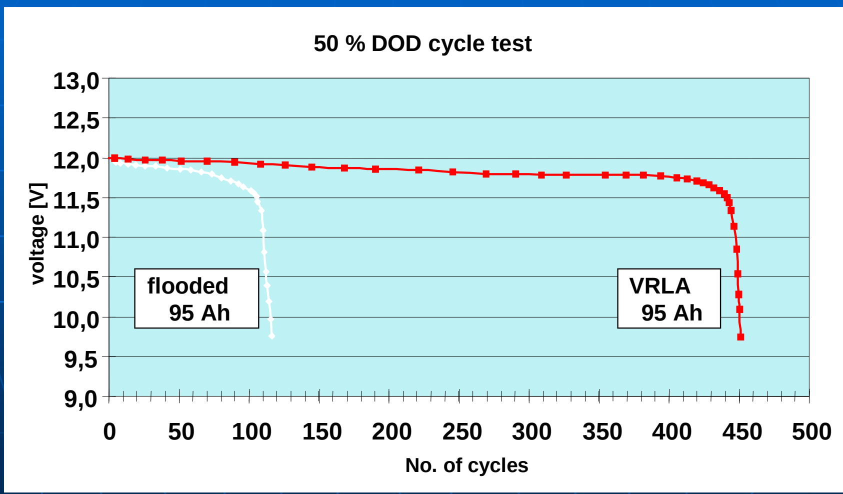


1. Maintenance free battery
2. Positive plate
3. Separator
4. Negative plate
5. Strap
6. Heat sealed lid
7. Central venting system
8. Intercell weld
9. Terminal
10. Mud rib

SLI (Starting, lighting & ignition) batteries

- Starter motor
- Ignition
- Head Lights
- Side Lights
- Fog Lights
- Rear Lights
- Reverse Lights
- Brake Lights
- Hazard Lights
- Dashboard Lights
- Interior Lights
- Direction Indicators
- Horns
- Electronic Voice Synthesizer
- Wipers
- Screen Washer
- Fuel Pump
- Heater/Demister/Blower
- Rear Window Heater
- Rear Window Wash/Wipe
- Cigarette Lighter
- Radio/Cassette Player
- Electric Aerial.
- CB Radio
- Burglar Alarm
- Seat Belt Warning Light
- Central Locking System
- Catalyst Heater
- Electric Windows
- Electric Sun Roof
- VHF Radio Telephone
- Air Conditioning
- Electric Mirrors
- Electric Seat Adjustment
- Electric Seat Heater
- Air Damper Compressor Unit
- Water Injection System
- Electronic Fuel Injection
- Electronic Instrument Displays
- Headlamp Wash/Wipe

SLI battery - VRLA vs flooded



Advantages of VRLA

- **Extremely low water loss**
- **Increased cycle life & energy throughput**
- **Improved cold cranking**
- **Increased capacity for same size**
- **Improved shelf life**
- **Leakproof battery**
- **No acid stratification**

Flooded lead acid batteries

Plante battery

Thick electrodes

20 year life

Applications: Power stations, telecoms etc.

Flooded tubular plate battery (OPzS)

Applications: Traction, solar and load leveling.

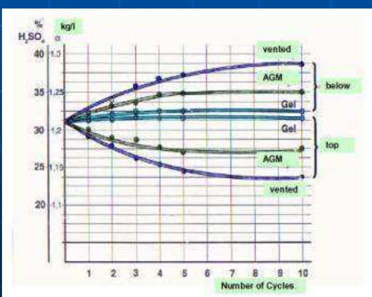
Flooded flat plate battery (OGi)

Applications: Telecoms and UPS.

http://www.battery.co.za

VRLA batteries

- Valve regulated (AGM & GEL)
  - OPzV - VRLA/GEL (sealed) tubular plate
    - Applications: Telecommunications and solar
  - OGiV – VRLA/AGM (sealed) flat plate batteries
    - Applications: UPS and high rate requirements



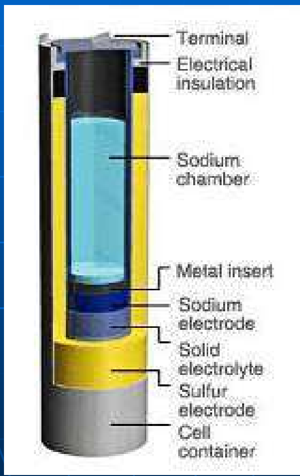
Acid stratification in lead-acid battery systems. www.exide.com

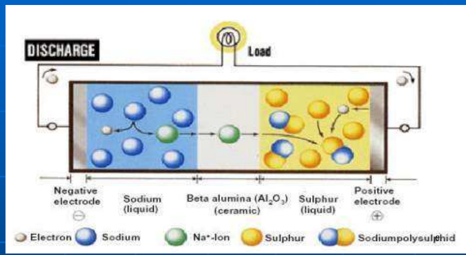
Sonnenschein A600

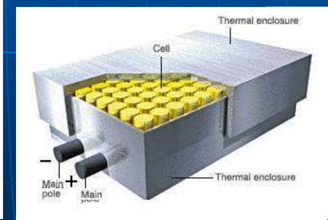
200 – 3000Ah (C10) 15-18years (20 C)

Telecommunications (www.exide.com)

Sodium sulphur battery







Cell = 2.0 V
T= 350 °C
120 Wh/kg
260 W/kg
Traction, UPS & load levelling

Illustrations: www.ngk.co.jp

Zebra Battery

$$2\ NaCl + Ni \underset{discharge}{\overset{charge}{\rightleftharpoons}} NiCl_2 + 2\ Na$$

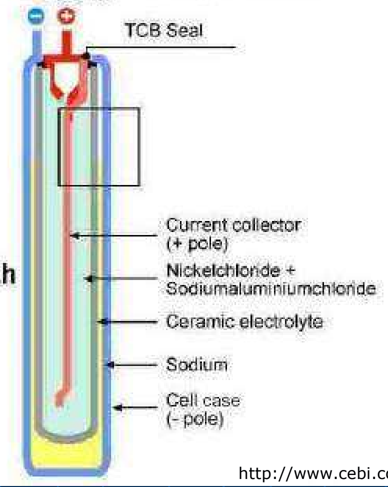
OCV 2.58 at 300°C,

Operating range

270°C to 350°C,

Typical capacity 38Ah

100% Ah-efficiency

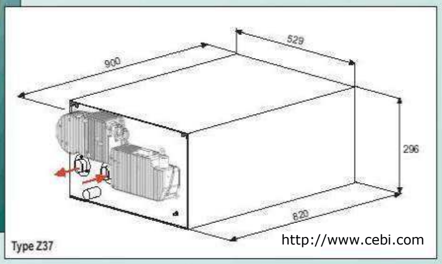


http://www.cebi.com

Zebra Battery

Each battery is composed of series and parallel connected cells (example Z37 has 240 cells)
Battery: 120 Wh/kg, 180 W/kg (310V or 619V)
Cycles 3500 (80% DOD) Application: Traction

The information contained herewith is subject to change without notice



Zebra Battery

Technical data ZEBRA® Battery

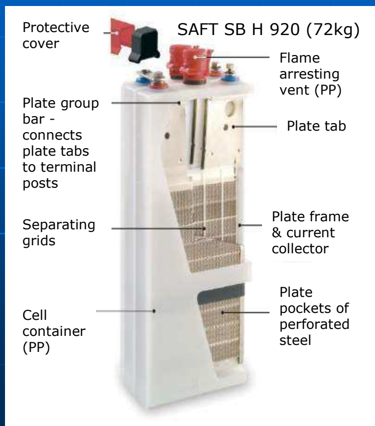
Type		Z37		
		Z37-310-ML3X-64	Z37-620-ML3X-32	Z37-310-ML3X-76
	Id.	30x00167	30x00153	30x00268
	unit			
Capacity	Ah	64	32	76
Rated Energy	kWh	19.8	19.8	23.5
Open circuit voltage 0 - 15% DOD	V	310	619	310
Max. regen. voltage	V	348	696	372
Min. op. voltage	V	206	413	206
Max. discharge current	A	224	112	224
Cell Type / N° of cells		ML3X / 240		ML3X/240
Weight with BMI	kg	201		201
Specific energy without BMI	Wh/kg	101		119
Energy density without BMI	Wh/l	154		183
Energy 2 h discharge	kWh	18		20
Specific power	W/kg	171		170
Power density	W/l	261		261
Peak power 2/3 OCV, 30s,335°C	kW	35.5 DOD 80%		33.5 DOD 70%
Abient temperature	°C	-40 to +50		
Thermal loss at 270°C internal temperature	W	< 105		
Cooling		air		
Heating time	h	24 h at 230 VAC		
Periphery		BMI, Fan		
		HEV Application		EV Application
On board generator MAX voltage, up to 70%SOC	V/Cell	2.7		n.a.

System design recommendation:
- MES-DEA Charger
- Min. discharging time: 120 min.
Max. degree of discharge: 80%

http://www.cebi.com

Nickel cadmium

- $2NiOOH + 2H_2O + Cd = 2Ni(OH)_2 + Cd(OH)_2$ ($E^0 = 1.29V$)
- Temperature: -40C to 50 C
- Electrolyte: 32% KOH
- PAM: $Ni(OH)_2$ +C +$Co(OH)_2$
- NAM: $Cd(OH)_2$ +Fe +(C)
- Grid: Ni plated steel
- Separators: PP, or nylon
- Cell (plate) designs:
  - **Vented** - pocket, plastic-bonded, fiber, foam or sintered
  - **Sealed** – smaller cells, cylindrical or rectangular with recombination
- Applications: UPS, telecoms, PV, HEV, EVs, satellite, aircraft, trains
- Performance:60Wh/Kg, 200W/kg, 2000 cycles

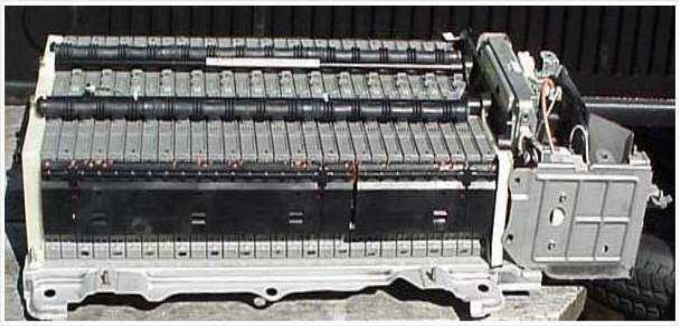


H, M, L for high, medium & low rates (www.saftbatteries.com)

Nickel metal-hydride

- $NiOOH + MH = 2Ni(OH)_2 + M$ ($E^0 = 1.35V$)
- Positive electrode like NiCd (plus ZnO & La_2O_3)
- Cell design same as sealed NiCd foam plates
- Separator: Non woven polypropylene
- Negative electrode: MH slurry on perforated foil (Ni, Cu or steel)
- Negative electrode - two types of metal hydride used:
  - AB_5 ($LaNi_5$, A=Mischmetal,La,Ce,Ti and B=Ni,Co,Mn,Al). Most used (300 Ah/kg)
  - AB_2 ($TiNi_2$, A=Ti,V and B=Ni,Zr (Cr,Co,Fe,Mn) Used by Ovonic (400Ah/kg)
- Applications: Smaller cells than NiCd. Large batteries: EV's (e.g. Toyota Prius)
- Performance:60-70Wh/Kg, 250W/kg, 2000 cycles (80% DOD)

Nickel metal-hydride



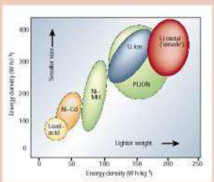
www.eaaev.org/CurrentEvents/pdf/2008/CurrentEvents200807.pdf (Photo courtesy of the Automotive Career Development Center.)

Toyota Prius (2nd generation): NiMH battery – Panasonic

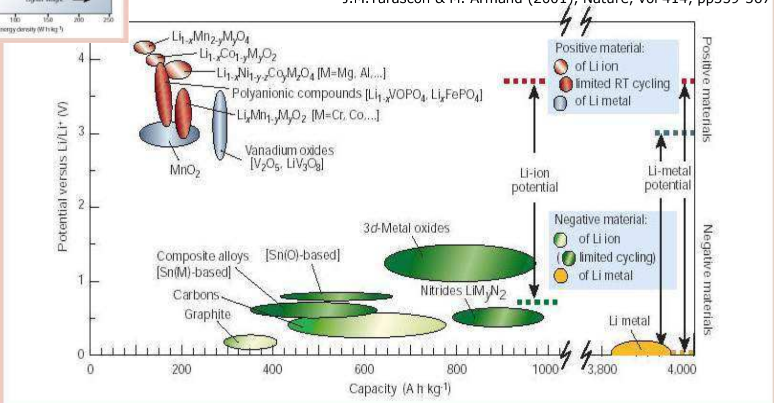
28 modules x 6 = 168 cells, 202V, 20kW (50% DOD)

Air cooled & computer controlled thermal management system

Lithium batteries

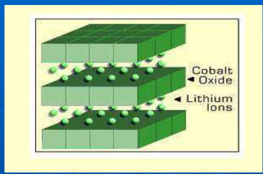


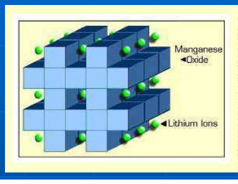
J.M.Tarascon & M. Armand (2001), Nature, vol 414, pp359-367

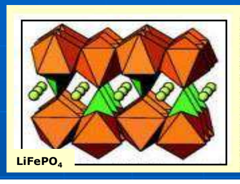


Voltage versus capacity for positive and negative electrode materials for Li cells. The cell potential is represented. Note the huge difference in capacity between Li metal and other negative electrodes, hence the interest in solving the problem of Li dendrite growth.

Lithium batteries



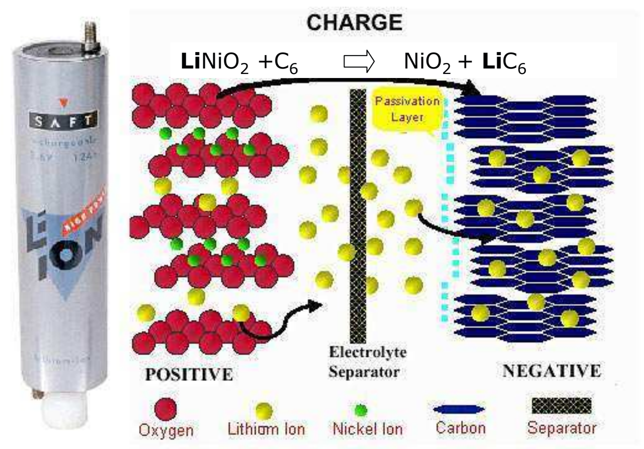




Chemistry	Nominal Voltage (V)	Charge limit (V)	Charge & discharge C-rates	Energy density (Wh/kg)	High T stability & SoC	Active material cost ($/kWh)	Application / comment
Cobalt $LiCoO_2$	3.60	4.20	1C	110-190	Fair - good	57-75	Since 1990's (Sony) Laptops.
Mn spinel $LiMnO_2$ "LMS"	3.80	4.20	10C cont. 40C pulse	110-190	Very good	25	Low energy density, high power Power tools
Li (Ni,Co,Mn) "NCM"	3.70	4.10	5C cont 30C pulse	95-130	good	30-50	$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ Power tools
Li (Ni,Co,Al) "NCA"	3.60	4.20	5C cont 30C pulse	110-190	Fair-good	50	$Li(Ni_{0.85}Co_{0.1}Al_{0.05})O_2$ Power tools
$LiFePO_4$ (A123)	3.30	3.60	35C cont	90-130	Very good	35	Lower capacity, high power

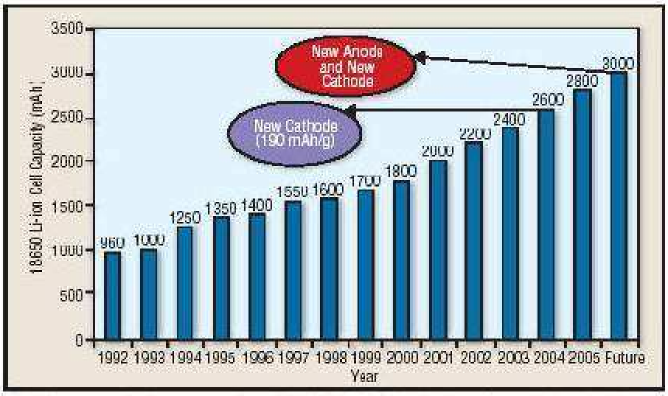
Modified from: www.BatteryUniversity.com and Wittingham, M.S. Chemical Rev, 2004 Vol 104, No 10 p4294

Lithium batteries



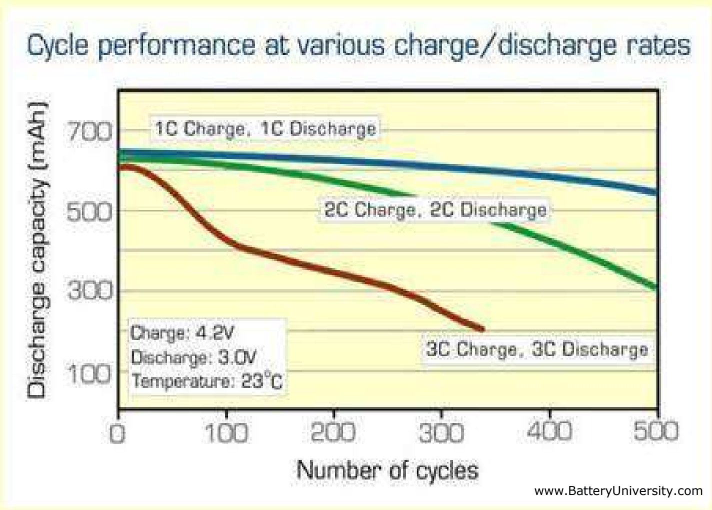
http://www.saftbatteries.com

Lithium batteries



The increase in the capacity of 18650 cells illustrates how Li-ion battery energy density has steadily risen since this battery technology was first commercialized in the early 1990s. **David Morrison**, Editor, *Power Electronics Technology*

Lithium batteries



Lithium batteries

SAFT
VL 45 E Cell
3.6v, 45Ah (C/3)
149 Wh/kg
664 W/kg
1.07 kg

Features
- Very high specific energy
- Light and compact
- Maintenance free
- Excellent cycle and calendar life
- Integrated liquid cooling
- Easy integration into customized battery systems

Applications
- Electric and hybrid vehicles
- Telecommunication networks
- Stationary
- Space and defence

http://www.saftbatteries.com

High energy lithium-ion module
VLE Module

	VLE 22-42	VLE 11-84
Electrical characteristics		
Nominal voltage (V)	21.6	10.8
Minimum capacity at c/3 after charge to 4.0 V/cell (Ah)	42	84
Specific energy (Wh/kg)	110	111
Energy density (Wh/dm³)	158	158
Specific power (30s peak/50% DOD) (W/kg)	533	533
Power density (30s peak/50% DOD) (W/dm³)	753	753
Mechanical characteristics		
Height (mm)	242	242
Width (mm)	190	190
Lenght (mm)	123	124
Typical weight (kg)	8	8
Volume (dm³)	5.66	5.66
Voltage limits		
Charge (V)	4.0 (4.1 for peak)/cell	
Discharge (V)	2.7 (2.3 for peak)/cell	
Current limits		
Max continuous current (A)	100	200
Max 30s peak current (A)	250	500

Lithium batteries

SAFT – VL 34P Cell - High Power cell

Graphite anode, Ni alloy oxide cathode
3.6v, 33Ah (C rate)
2000 cycles (100 DOD)
120 Wh/kg
Max. Discharge: 500 A cont,
1900 A 2 sec pulse
Mass =0.94 kg
Diameter = 54 mm
Length = 195 mm
Charge CCCV TO 4.1 V (0.04)
Charge current = C/2
Temp D = -30 to 60 C,
Temp C = 5 to 35 C

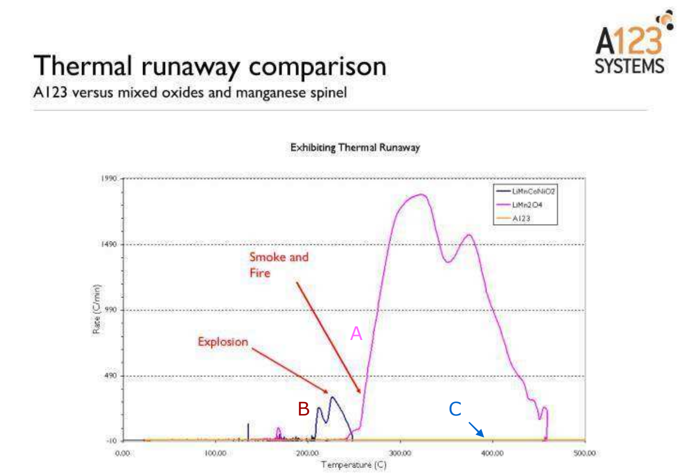
Applications
- Electric and hybrid vehicles
- Telecommunication networks
- Stationary
- Space and defence

http://www.saftbatteries.com

VL 34 P module

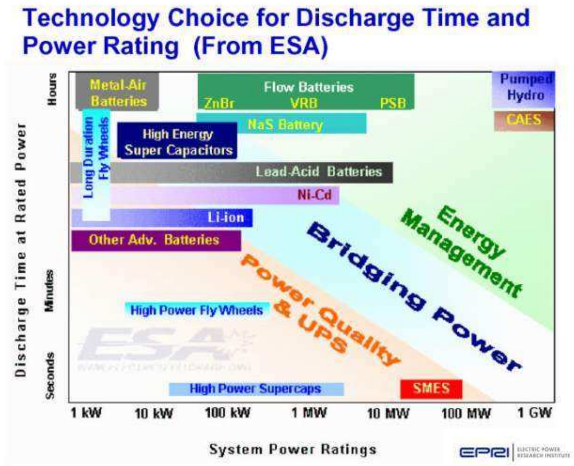
Electrical characteristics	
Nominal voltage	43.2 V
Maximum continuous current at 25° C	200 + A
Continuous power at 50% SOC	20 kW
Energy density at C rate	139 Wh/l
C rate energy	1.3 kWh
Capacity at C rate	31.5 Ah
Specific energy at C rate	75 Wh/Kg
Specific power (continuous from 100% SOC)	1100 W/Kg
Impedance at 5 sec (250 A discharge)	10 mΩ
Mechanical characteristics	
Length	14.6 in /371 mm
Width	4.4 in /112.8 mm
Height	8.3 in / 211.8 mm
Weight	35 lbs /16 kg
Operating conditions	
Operating temperature range	- 30° C to + 60° C
Transport or storage temperature range	- 40° C to + 65° C
Voltage limits	
In charge	49.2 V
In discharge	30 V

Lithium batteries



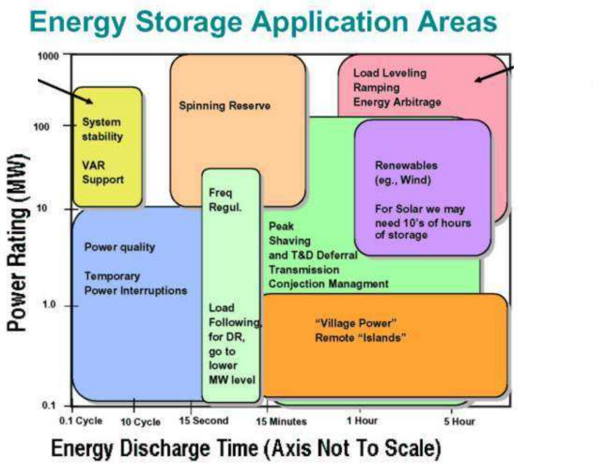
Thermal runaway comparison. A) LiMnCoNiO2,, B) LiMn2O4 and C) LiFePO4 (A123).
http:/www.aircraft-world.com/prod_datasheets/hp/A123/A123.pdf

Standby battery applications



From " Role of Energy storage for distributed energy resources", Thomas Key (tkey@epri.com).

Battery applications



All boundaries of regions displayed are 'approximate, from EPRI Program Planning

From " Role of Energy storage for distributed energy resources", Thomas Key (tkey@epri.com).

Applications – Lead acid

Battery systems installed between 1986 & 1997

Technology		Power MW	Energy MWh	Year Operation	Purpose
Lead Acid	Berlin(D)	17	14	1986 - 1995	Power Quality Spining reserve
Lead Acid	Tatsumi(J)	1	4	1986	Multi-purpose Demonstrator
Lead Acid	Chino(USA)	10	40	1988 - 1997	Multi-purpose Demonstrator
Lead Acid	South Africa	4	7	1989	Peak Shaving UPS
Zn-Br	Kyushu(J)	1	4	1991	Multi-purpose Demonstrator
Lead Acid	Puerto Rico	20	14	1994	Power Quality Spining reserve
Lead Acid	Vernon(USA)	3.5	3.5	1996	Peak Shaving UPS
Lead Acid	Metlakatla	1	1.3	1997	Grid stabilization Power Quality

www.cambridgeenergy.com/archive/2005-06-22/CEF-Tarrant.pdf

TGT energy

Applications - NaS & NiCad

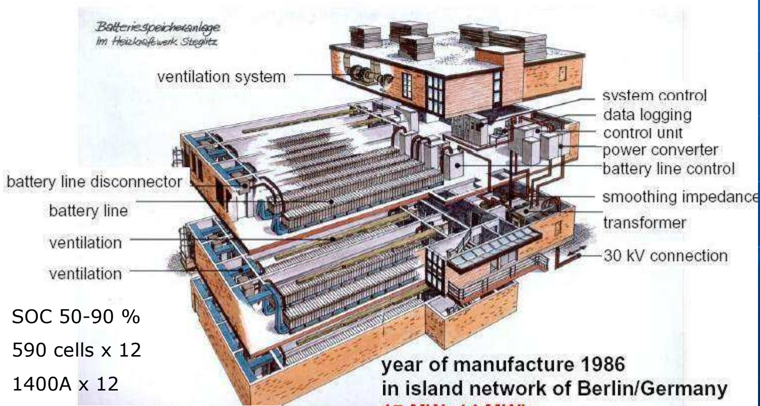
Systems Installed 1998 to 2004

Technology	Location	Power MW	Energy MWh	Year Operation	Purpose
NaS	Tsunashima Substation	6	48	1998	Load Levelling Spinning reserve
NaS	Ohito Substation	6	48	1999	Load Levelling
NaS	Saitama	2	12	1999	Load Levelling
NaS	Odaka	1	8	2000	Load Levelling
NaS	Tsunashima	2	14.4	2000	Load Levelling
NaS	Shinagawa	2	14.4	2001	Load Levelling
NaS	Kanagwana	1	7.2	2001	Peak Shaving UPS
NaS	Ebina	1	7.2	2001	Peak Shaving UPS
NaS	Chichibu Semicond pl	1	7.2	2002	load levelling UPS
Ni-Cad	Fairbanks Alaska(USA)	40	10	2003	load levelling UPS

www.cambridgeenergy.com/archive/2005-06-22/CEF-Tarrant.pdf

Applications – Pb acid

Battery system of BEWAG for frequency regulation



SOC 50-90 %
590 cells x 12
1400A x 12

year of manufacture 1986
in island network of Berlin/Germany
17 MW, 14 MWh
7080 cells with 2V / 1000 Ah

Wagner R, J of Power sources 67 (1997) 163-172
batteries@isea.rwth-aachen.de

Applications - NiCd

Golden Valley Electric's Battery Energy Storage System (Alaska)

27 MW for 15 minutes
13760 NiCd cells (SAFT SBH 920 cells)
35 Mio $
commissioning: Aug. 2003

batteries@isea.rwth-aachen.de

Applications - NaS

- NaS-battery system for "load leveling" in Tokyo
- Performance characteristics
  - 2 MW
  - 1,165 V DC
  - 40 modules (12,800 cells)
  - weight > 136 tons

batteries@isea.rwth-aachen.de (NGK / TEPCO)

Applications – Li-ion

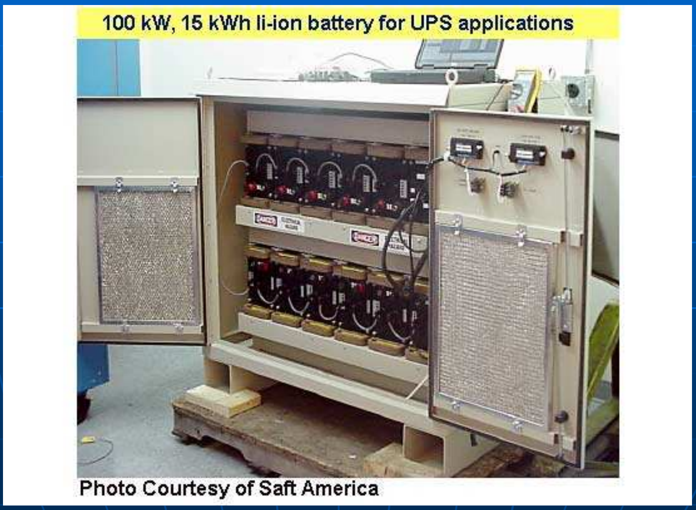


Photo Courtesy of Saft America

Conclusions

- There are pros and cons of every battery system which should be weighed up against the intended application
- Lead acid batteries are good for float applications, have a low initial capital cost, proven technology with high recycling efficiency and future potential for improvements in life
- Nickel cadmium and nickel metal hydride batteries have good cycling and power capabilities at increased cost. They have a memory effect and high self discharge. Metal hydride batteries have higher energy density with no toxic metals but poor charge acceptance at high temperatures and require thermal management
- Sodium metal chloride batteries have high energy density & are promising for traction and stationary applications. Disadvantages are the high temperatures, limited manufacturing facilities & lack of high power cell designs.
- Li-ion batteries are starting to enter the telecoms markets in larger cell sizes where weight & space is a criteria but at increased cost. Each cell requires electronics to control C/D voltage. Safety will remain a key issue