DE LA RECHERCHE À L'INDUSTRIE

cea

Perspectives of Li-Ion technology developments

Florence Fusalba
Sebastien Martinet

www.cea.fr

ASPROM - December 3rd and 4th 2013

Presentation of CEA & LITEN

ASPROM
OPTEZ POUR L'INNOVATION

French Atomic and Renewable Energy Commission

CEA : 10 R&D Centers in France

4 main research priorities

- Defense & Global Security
- Energy
- Health and Information Technology
- Fundamental Research

Key figures (2011-12)

- Staff : 15 982
- Budget : 4,2 b€
- 613 priority patents applications field

« Laboratory for Innovation in New Energy Technologies and Nanomaterials »

LITEN R&D

⇒ Solar energy & smart building
⇒ Transport technologies
⇒ Energy sources for portable electronics
⇒ Nanomaterials
⇒ Biomass & Hydrogen Technologies

- Staff : 1200
- Budget : 170 M€ (140M€ turnover)
- 840patents
- >250 p on batteries

http://www.cea.fr/
http://www-liten.cea.fr
@

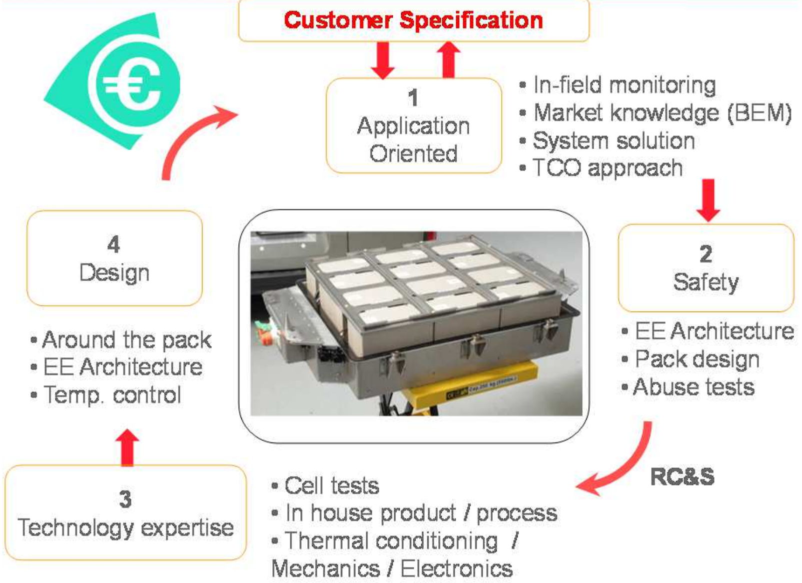
Li-Ion Cell Pilot Line: Production representative environment

Semi Industrial Line: Dry room ~ 1000m² (Dew points: -20°C & -40°C)

All materials & components electronically tracked during the process thanks to bar codes

- **A stabilized design to investigate chemistries** with capability to produce prototypes **in a production relevant environment**
- Stable Prototypes Performances, Manufacturing process definition established, Process flow validated… Manufacturing yield compatible with an industrial transfer…

Battery System from TRL3 to TRL6-8



Electrical test benches:
High power ~300 channels
Low power (Includes formation) 480 channels

Battery Modules & pack assembly with e-management
Semi automatic assembly with full components tracking

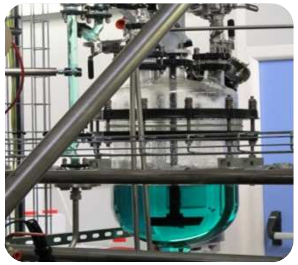
Li-Ion Active Material Up-scaling platform

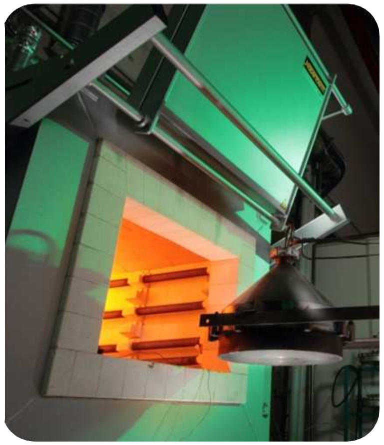
Upscale of Material Synthesis (solid-state route, solvothermal route…)

- **Production of ~1Kg batches**
- **Process Optimization (cost, perfs…)**
- Differentes synthesis routes possibles

Reminder – Rough Estimation of AM per device:
Cellular Phone 5-10g – EV pack 20-60kg







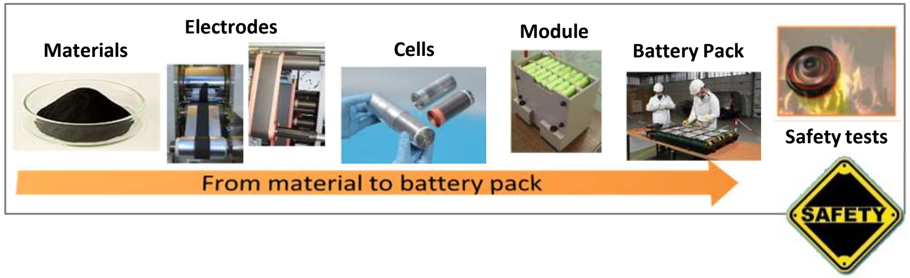
Embedded Energy : Specific Batteries

ASPROM
OPTEZ POUR L'INNOVATION

Customized battery development to stand drastic conditions

CEA Tech Competences

➦ CEA LITEN has an **integrated approach** from **materials** to **system** dedicated to **battery** developments :



➦ CEA LITEN develops customized **Li-ion technologies** and **designs** depending on technical specifications, for example :

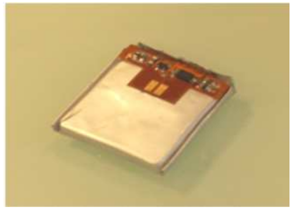
- Safe & Stable energy or Power batteries integrating $LiFePO_4$
- High Energy Li-ion cells integrating high capacity electrodes
- Costs care

Applications

➦ Prototyping (TRL 3-6) have been realized in several application fields :

Military application

Si-C Technology
3.4V - 1.25Ah 260Wh/kg cells
Reduced cyclability
For 70Wh 13.6V Si Battery pack
Higher autonomy at 20°C (+60%) & -20°C (+180%) versus commercial
For Energy Efficient Soldier…

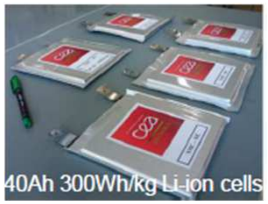


Security (beacons)

NMC/Si-C Technology
3.4V – 1.2Ah, 250-270Wh/kg
Operating from -20°C to 55°C
In a power mode
Cospas-Sarsat approval
UL1642-qualified

Spatial Sensor

NCA/G Technology
3.6V - 450mAh
Cell mechanical design to sustain extreme environment (vibration, acceleration, vacuum…)



Aeronautic Large Capacity/High Energy Li-ion cells

Si-C Technology
3.4V – 40Ah
300Wh/kg (C/10 @45°C)

Micro Hybrid – Start & Stop

High Power
Fast charge
24V – 15Wh
Bipolar Architecture

EVs, Buses, other large vehicles, stationary

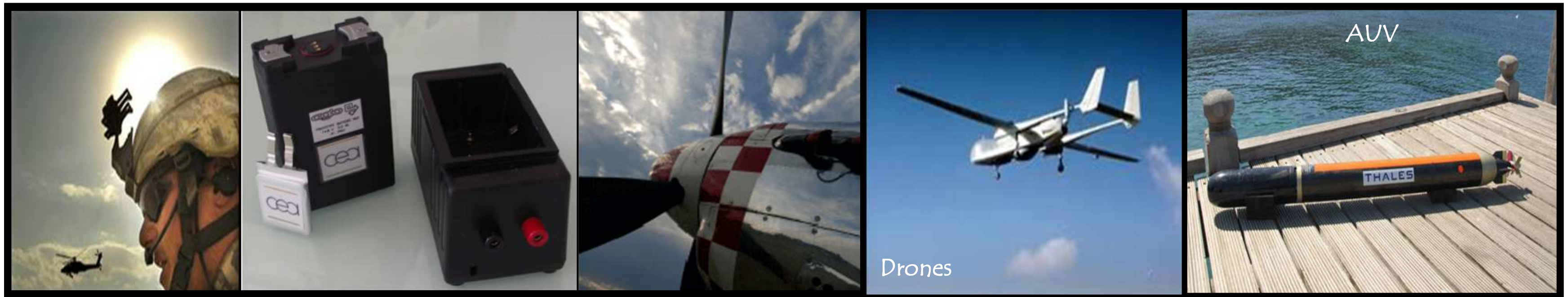
Various P/E ratio
3.3V – 10Ah $LiFePO_4$ Technology
1.9V – 11Ah $Li_4Ti_5O_{12}$ Technology
Designed electrolytes, components…

Contact : florence.fusalba@cea.fr

OUTLINE

- **Brief Introduction of Li-Ion Technology**
- **Introducing High Energy >250Wh/kg**
- **High Power Systems**
- **Perspectives**

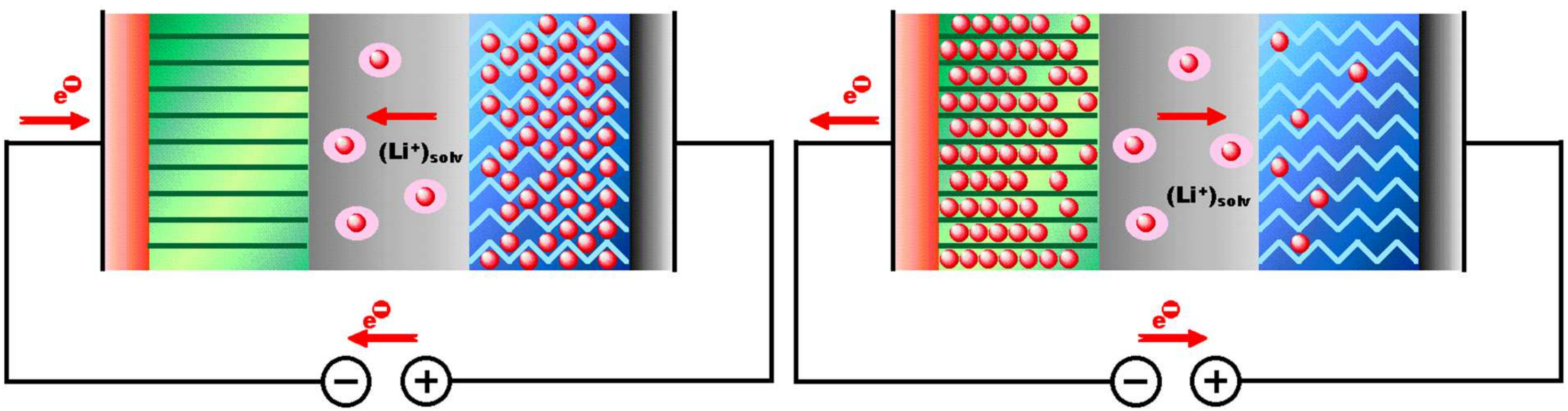
Electric Mobility, Stationary Applications



Professional, security, military, defense, aerospace applications

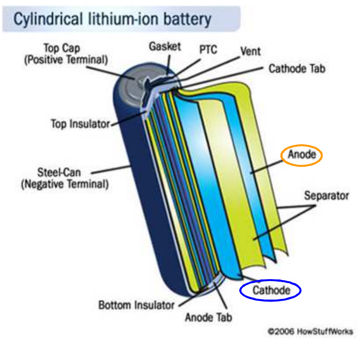
Basic Principles of Li-Ion Cells

Charge **Décharge**



<H> + Li⁺ + e⁻ → <HLi> <HLi> → <H> + Li⁺ + e⁻

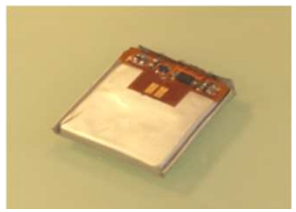
<MLi> → <M> + Li⁺ + e⁻ <M> + Li⁺ + e⁻ → <MLi>



First Commercialized Li-Ion:
(-) Graphite / (+) $LiCoO_2$ (18650 Cell - LapTop) Sony (1991)
Today >250Wh/kg and 600Wh/L

Main limits:

- Cost (Co – Electrolyte – Separator)
- Safety (Co – G - Electrolyte)
- Low T° performances especially in charge (G)



Li-ion- A generic technology !
Not only One System

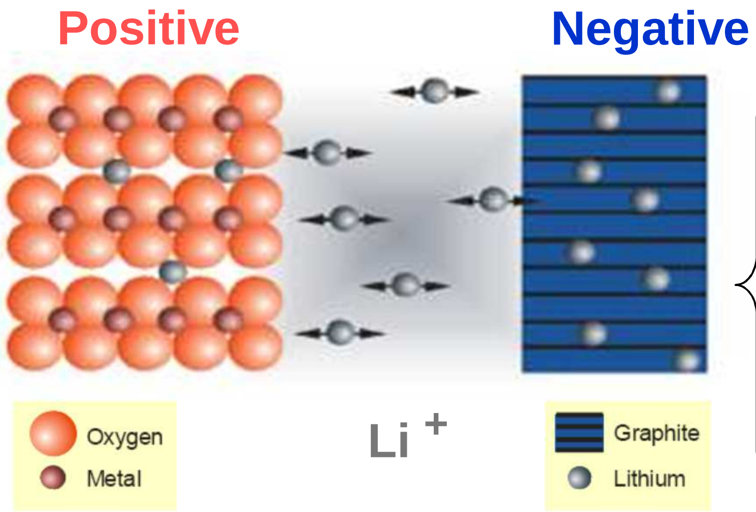
Lithiated Metal Oxide :

Commercial Grades

- *LCO ($LiCoO_2$)*
- **NCA** ($LiNiCoAlO_2$)
- **LMO** ($LiMn_2O_4$)
- **NMC** ($LiNiMnCoO_2$)
- « 3V » **LFP** ($LiFePO_4$)

Dev.

- « 4V » Li-Rich LO
- « 5V » (Spinel…)



- *Graphite (Std)*
- Ti-Based (LTO)
- Li-Alloy (Si, Sn…)

➢ Positive Side: Tendency to Suppress Cobalt for Safety / Cost

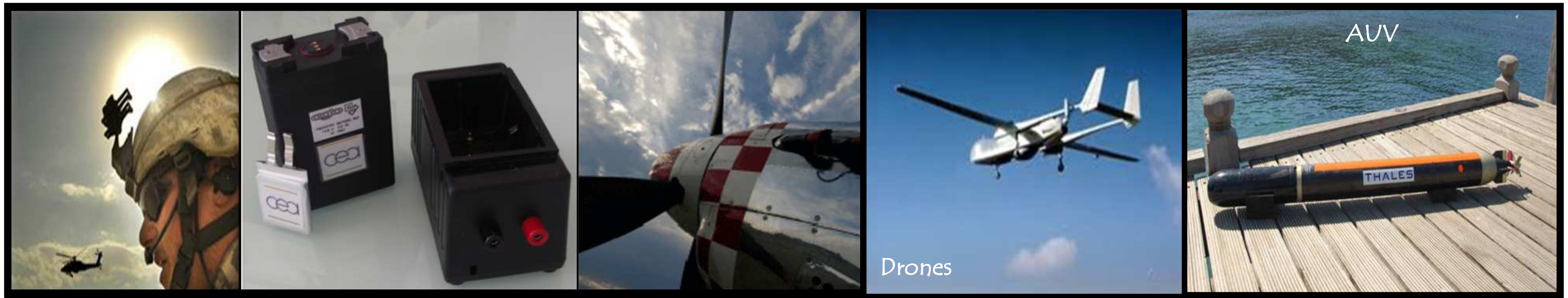
➢ Negative Side: Replacement of Graphite by Titanium Oxides for Safety/Cyclability or Si-C for Energy Density

⇒ With new Li-Ion systems, more than 10,000 full cycles achievable

OUTLINE

- Brief Introduction of Li-Ion Technology
- **Introducing High Energy >250Wh/kg**
- High Power Systems
- Perspectives

Electric Mobility, Stationary Applications



Professional, security, military, defense, aerospace applications

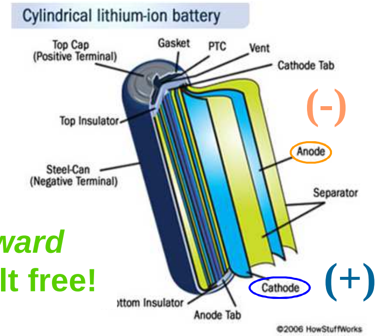
CEA Li-ion Technology (Chemistries) for High Energy Status at Cell Level

ASPROM OPTEZ POUR L'INNOVATION

Applied Research mostly to increase specific energy, to improve autonomy…

Technology (+)/(-)	Gravimetric Energy Density / $Wh.kg^{-1}$	Status
LFP/Graphite	120 to 155 TRL 6	✔
NMC or NCA or $LiMn_2O_4$/Graphite	180 to 220 TRL 6	✔
5V Spinel/Graphite	200 to 240 TRL 3-4	✔
HE-LMO/Graphite	220 to 250 TRL 3-4	✔
LFP/Si-C	155 to 180 TRL 3-4	✔
NMC or NCA/Si-C	250 to 270 TRL 4-5	✔
HE-LMO/Si-C	280 to 320 TRL 3-4	Under development

Increase of voltage and/or capacity of positive electrode



Toward Cobalt free!

… Manufacturing full cell prototypes

Increase of voltage and capacity of positive electrode + Use of a high capacity negative electrode

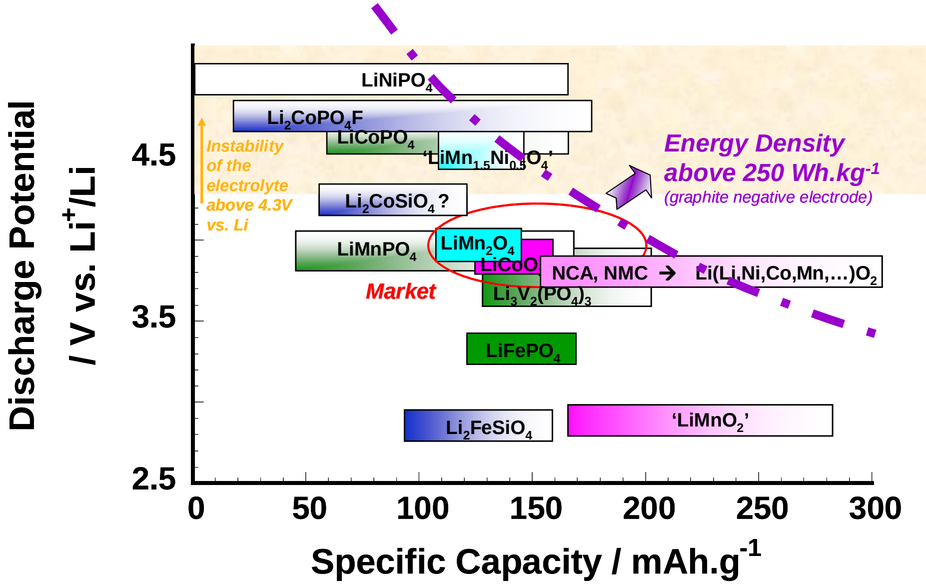
State of the art in 18650 *ca. 3Ah (3,6V) Li-ion cells: ~230-240$Wh.kg^{-1}$

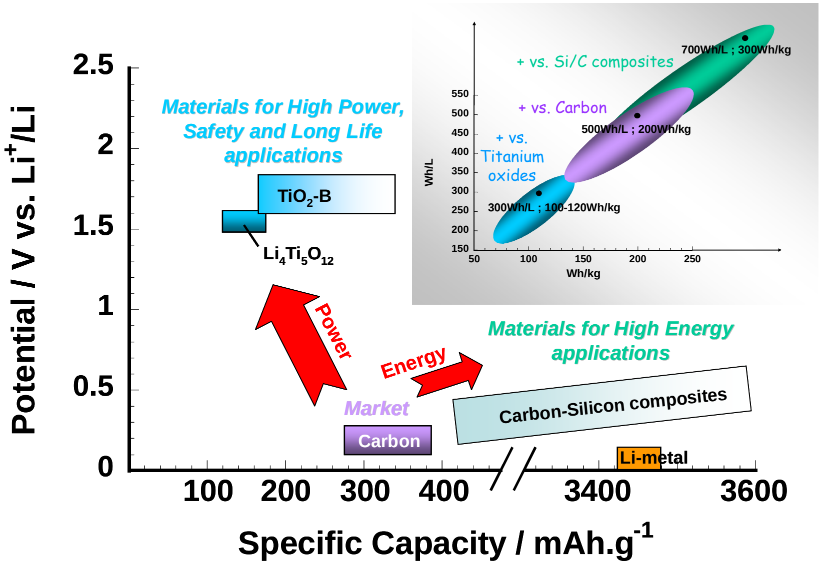
* commercial

The technology selected for Energy >250Wh/kg

Positive Electrode – 2 possibilities:
- **Commercial NMC – 170mAh/g or NCA – 190mAh/g**
- **HE-Lamellar Oxide - 250mAh/g (Dev.)**

Negative Electrode:
- **Si-C composite (500 to 1000mAh/g)**





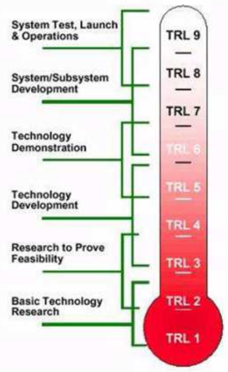
In soft packaging

- NMC / Si-C ➔ 300 Wh/Kg — **A**
- HE-LMO /Si-C ➔ 400Wh/Kg — **B**

In rigid casing

- HE-LMO/Si-C ➔ > 250 Wh/Kg — **B**

High Energy with High Capacity Negative Electrode



TRL 4-5

NCA / Si-C lab prototypes

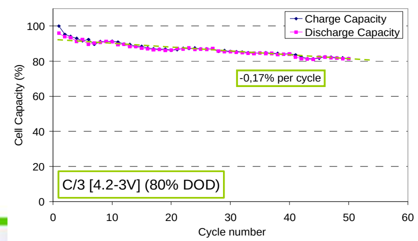
- Positive : NCA (NiCoAl Oxide)
- 3.2 x 3.6 x 0.5 cm core
- Mixed carbonate electrolyte

- Wound Configuration

1000+ cells manufactured and assembled in dry room

Graphite prototypes
- 850 mAh
- **200 Wh.kg^{-1}**
- 450 Wh.L^{-1}

Si-C prototypes
- 1250 mAh
- **260 Wh.kg^{-1} (+30%)**
- 600 Wh.L^{-1}
- Reduced cyclability for niche market (< 50 cycles)



High Energy Li-ion Battery for Energy Efficient Military/Soldier

Acknowledgements to Rockwell Collins Building trust every day, aglo

Table legends:
Italic= Calculated value
Bold = Corrected value due to additional interface resistance at electrical test bench (Pressure connection for the commercial battery not for HE battery)
*only between 80-50% SoC

Battery	HE (4S)	Competitor (3S)	Δ
Capacity @C/5 20°C (Ah)	5	*4.2*	+20%
Weight (g)	371	370	+0.3%
Nominal voltage @C/5 20°C (V)	13.6	10.8	+25%
Energy @C/5 20°C (Wh)	68	45	+50%
Gravimetric energy @C/5 20°C (Wh/kg)	183	120	+50%
Volumetric energy @C/5 20°C (Wh/L)	285	225	+25%
Internal resistance (mΩ)	220	330	-33%
Specific Autonomy 20°C (h) (µcycles 4,5A (6s) – 0,1A (54s))	8h30	7h20	+15%
Specific Autonomy 20°C (h) (µcycles of 45W (6s) – 1W (54s))	**12**	**8**	+50%
Specific Autonomy -20°C (h) (µcycles 4,5A (6s) – 0,1A (54s))	7h15	3h50*	+85%
Specific Autonomy -20°C (h) (µcycles of 45W (6s) – 1W (54s))	**10**	**3h30***	+185%
Specific Energy density 20°C (Wh/kg)	163	103	+60%
Specific Energy density -20°C (Wh/kg)	136	48*	+180%

Test protocol: Repeated 1min µ-cycles, made of 4.5A-6s pulses corresponding to radio emission followed by CC 100mA-54s for reception or stand-by

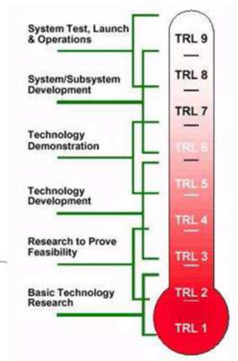
-**Higher autonomy** at 20°C (+60%) & -20°C (+180%) compared to commercial battery
-**Specific pack design** developed by AGLO-DEV for this « breathing » technology with high reproducibility in term of weight (<0.5%) and resistance (<0.5%)

Si-based technology at low T° in power mode for Beacons/Security

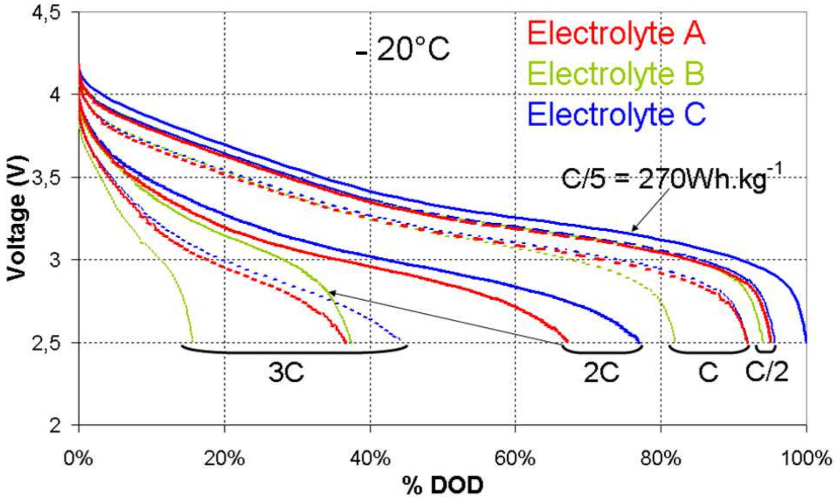
ASPROM
OPTEZ POUR L'INNOVATION

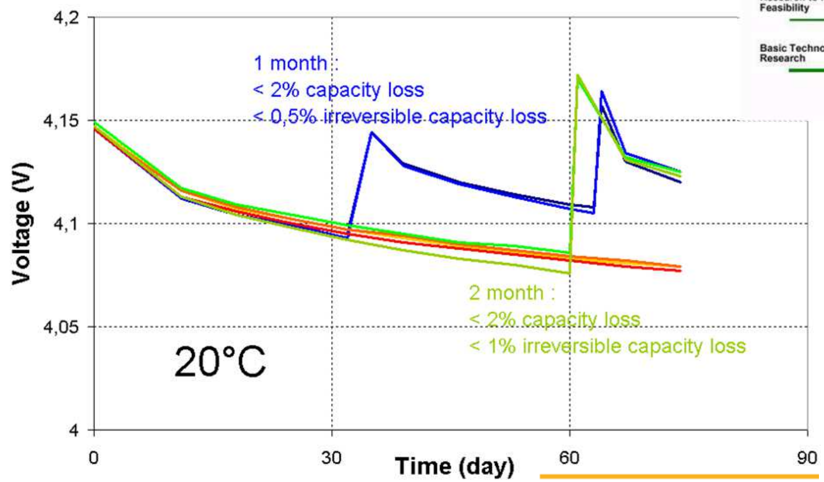
NMC / Si-C lab prototypes (~1Ah)

TRL 5-6



53734 ELEMENTS OF 270WH/KG AT 20°C AND C/5 RATE





PROLLiON

+ Cycle life, self-discharge and power tests from -40 to +55°C

1000+ cells manufactured in dry room to evaluate silicon materials, electrode formulations, electrolyte compositions, separators

Development of the NMC/Si technology

Research of electrolyte for low temperature applications (-20°C) in power mode

Development of batteries which can be stored at full charge

- At -20°C, high performances up to 2C rate
- 70% of the capacity recovered at -20°C
- UL1642 standard compatibility under progress

2012: Si-C 40Ah Prototypes Under Progress for Aerospace

Development of 35-40Ah cells, NMC & HELMO/Si-C for E > 250Wh/kg

NMC electrode High energy density

Separator

Si-C electrode High energy density

Specifications aimed:

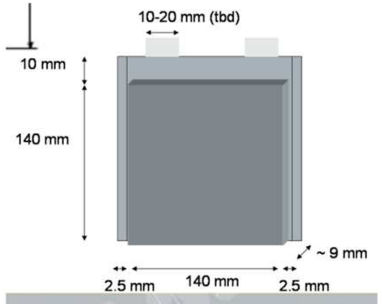
-For Spatial: Aluminum hard casing
C ~ 35Ah, E > 250Wh/kg BOL at cell level
Loss < 0.07% per cycle (80%DOD)

-For Aeronautic: Soft pouch
C ~ 40Ah, E ~ 300Wh/kg BOL at cell level
Loss ~ 0.7%/cycle (100%DOD)

TRL 3-4

Winding

Assembly

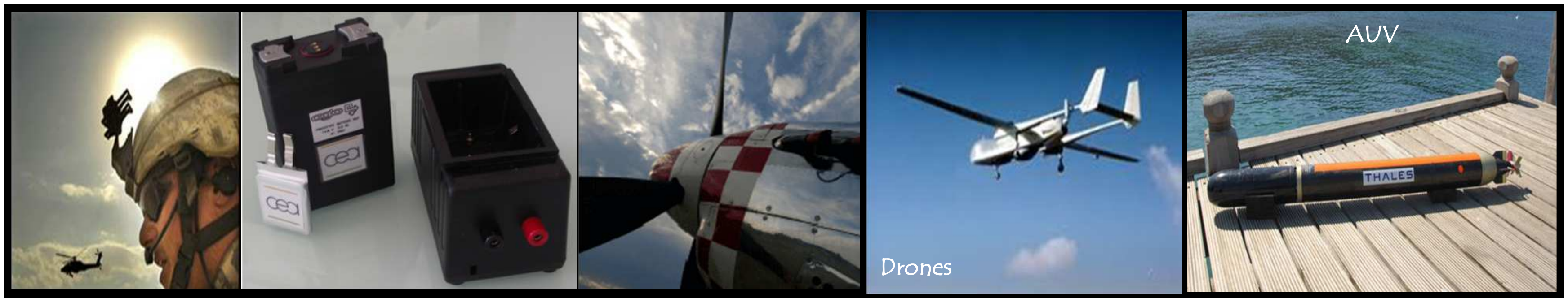


ca. 300Wh/kg (C/10 @45°C)
40Ah Prismatic shape
10 x 140 x 140 mm; NMC/Si-C technology

OUTLINE

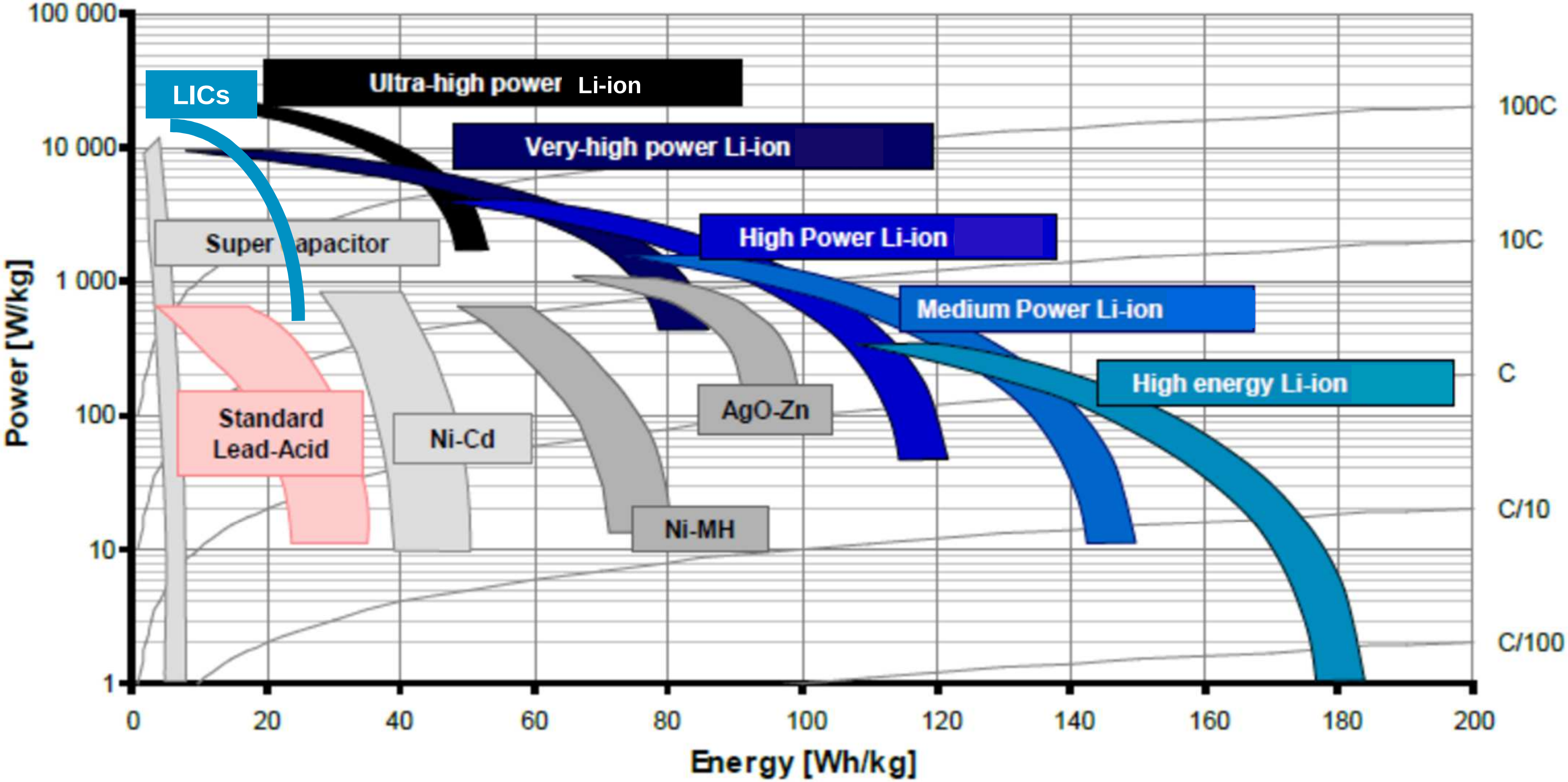
- Brief Introduction of Li-Ion Technology
- Introducing High Energy >250Wh/kg
- **High Power Systems**
- Perspectives

Electric Mobility, Stationary Applications



Professional, security, military, defense, aerospace applications

Ragone Diagram: High Power Cells



✓ **Missing data : Cycle Life, Discharge rates, Pulses or Continuous, Temperatures…**

Electrochemical Storage Technologies Candidates for Power Applications

	Supercapacitor	LIC	Energy LIB
Cell voltage	2.3 to 2.75V	2.2 to 3.8V	2.75 to 4.2V
Specific Energy (Wh/kg)	5 (typical)	10 (typical)	100 to 200
Specific Power (W/kg)	Up to 10000	Up to 3500	1000 to 3000
Charge T°	-40 to 65°C	-30 to 70°C	0 to 45°C
Discharge T°	-40 to 65°C	-30 to 70°C	-20 to 60°C
Cycle life	1 million to 30000h	100 000	500 and higher
Service life	10 to 15 years	?	5 to 10 years
Cost per Wh	20$ (typical)	?	0.50 to 1$ (large system)

- ✓ **Suppliers Data**
- ✓ **Lack of experience on LICs**
- ✓ **Self-Discharge data ? (supercapacitors: 50-100% /month)**
- ✓ **LIBs not High Power Sized here**

CEA Pilot Line LFP Cells Developments – GEN1

EXAMPLE : Power-Sized versus Energy-Sized LFP chemistry

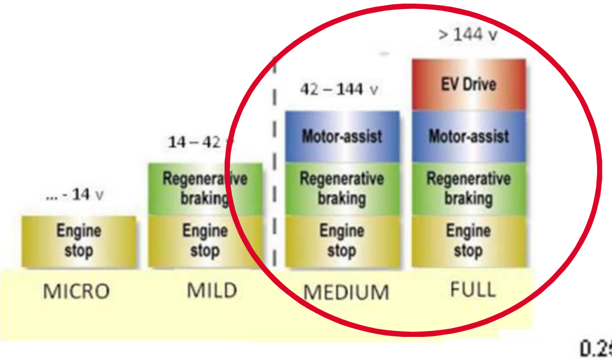
	LFP/G Energy V1	LFP/G High Energy E0	LFP/G Power PG0	LFP/LTO Power P0
Performances assesments started	Q2/12	Q3/12	Q4/12	Q4/12
Specifications	16.5Ah – 3.3V 112Wh/kg-220Wh/L C-2C* Charge 2C-5C* Discharge	19Ah – 3.3V 130Wh/kg-250Wh/L C/2-C* Charge C-2C* Discharge	10Ah – 3.3V 70Wh/kg-135Wh/L 3C-5C* Charge 10C-30C* Discharge	11Ah – 1.9V 50Wh/kg-100Wh/L 10C-30C* Charge 10C-30C* Discharge
#Customers	4	2	1	1

LTO Negative Electrode: LFP/LTO Power P0

Graphite Negative Electrode: LFP/G Energy V1, LFP/G High Energy E0, LFP/G Power PG0

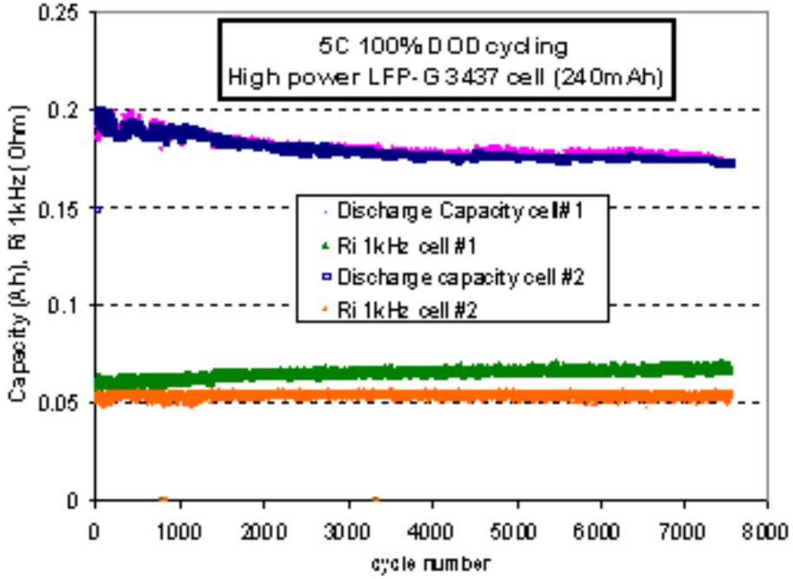
*Continuous-Pulsed

GEN1: LFP for High Power Discharge



LFP/G

Cylindrical Hard Casing (Al)
Wound cell
Dimensions :125 mm Height – 50mm Diameter
Practical Capacity : 16Ah [3,6V-2,5V]
120Wh/Kg – 3C Rate
Mean Discharge Voltage: 3.2V

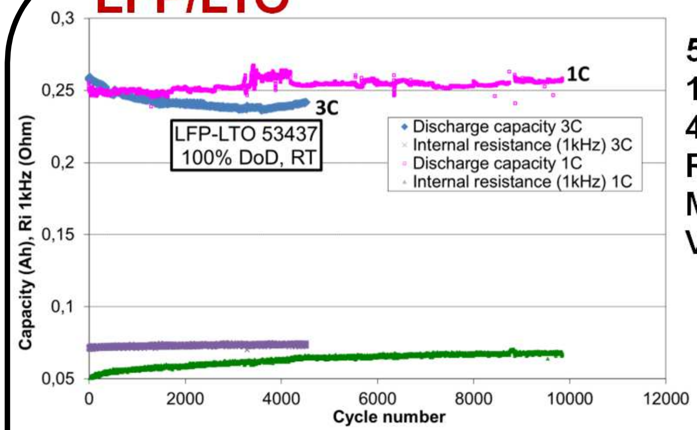


beLife by Umicore & Prayon

Lithium Iron Phosphate Technology – Cycle Life in a power mode (5C charge-discharge rates) exhibits only -0.0017% capacity loss per cycle upon 7500cycles…

CEA Li-ion Power Cells GEN1

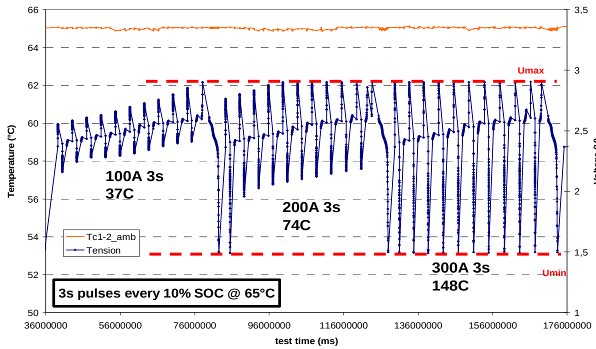
LFP/LTO



50125 Capacity : 11Ah
45-50Wh/Kg 15-30C Rate
Mean Discharge Voltage: 1.9V

- ⇒ **Extended cycle life**
- ⇒ **No Capacity Loss after 10000 cycles 100%DOD@C-Rate (RT)**

LMO/LTO



High Power Short Pulses Li-ion for F1 KERS: 150C charge-discharge max limit

Lithium Titanate Technology

- ⇒ **Fast charge / Ultra High Power**
- ⇒ Long cycle life
- ⇒ Low self-discharge
- ⇒ Stable/Safe behavior
- ⇒ Very good low temperature capability

✓ **NMC/LTO also possible for higher energy density (~90Wh/kg)**

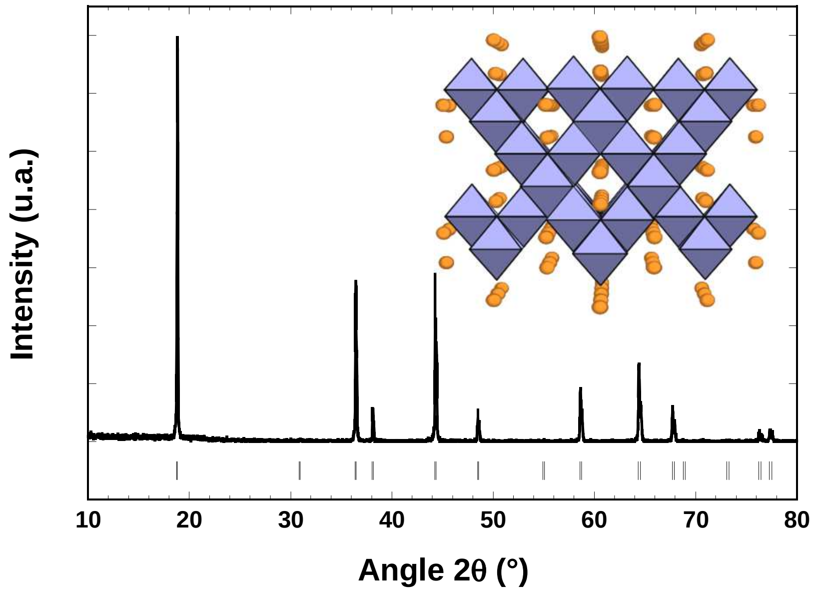
LTO Technology competitive for Power modes if C-rates >15C

GEN2: Interest in High Voltage Spinel Oxides

"5V Spinel"

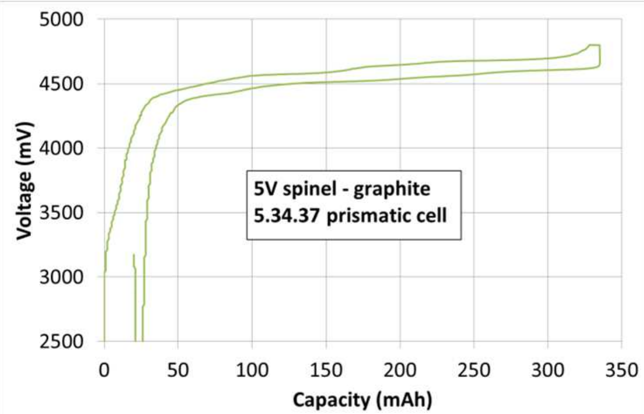
- **Generic composition is $LiNi_{0.5}Mn_{1.5}O_4$**
- **Theoretical capacity = 146.7 mAh/g at ~4.7 V vs. Li^+/Li (Ni^{4+}/Ni^{2+})**
- **High cycle life, High rate capability, Energy density increase strategy**

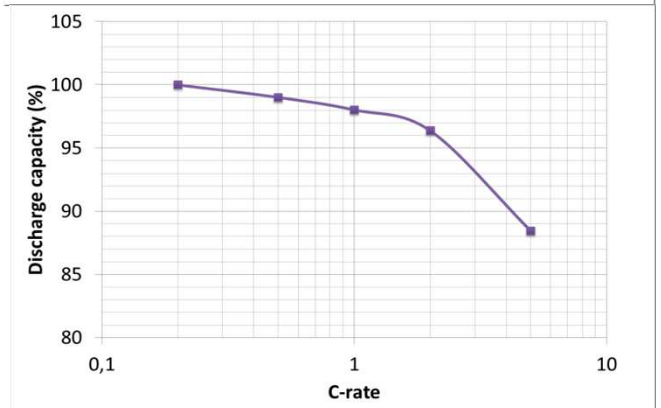
Spinel structure with a ~ 8.18Å



Medium power design

Target ~150 Wh/kg in hard casing

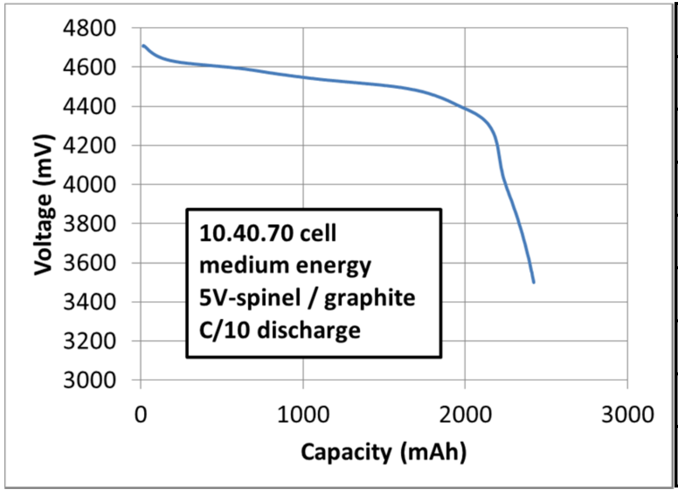




CEA High Voltage Spinel Oxide: $LiNi_{0.4}Mn_{1.6}O_4$

ASPROM OPTEZ POUR L'INNOVATION

5V Spinel/Graphite prototype:



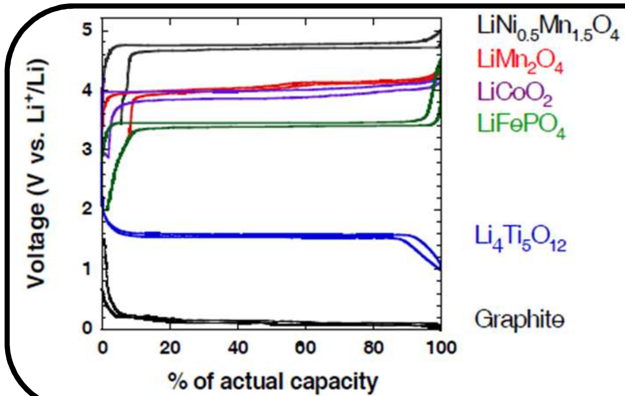
Cell design	Soft Prismatic 40x70mm
Cell capacity	2,4 Ah
Electrodes loading	3 mAh/cm²
Positive electrode	$LiNi_{0.4}Mn_{1.6}O_4$
Negative electrode	Graphite
Electrolyte	**$LiPF_6$ in carbonates +** additives
Separator	2500-type Celgard®
Potential at equilibrium	4.6 V
Specific energy	**200Wh/kg**

***Target:* Similar Energy Density to current commercial Power sized cells but with Higher Power rate capability due to higher cells voltage (4.6V versus 3.6V) and lower battery oversizing due to higher discharge rate capability especially at low Temperature**

By replacing Graphite by

Lithium Titanate Technology

⇒ Fast charge / Ultra High Power
⇒ Higher low temperature capability



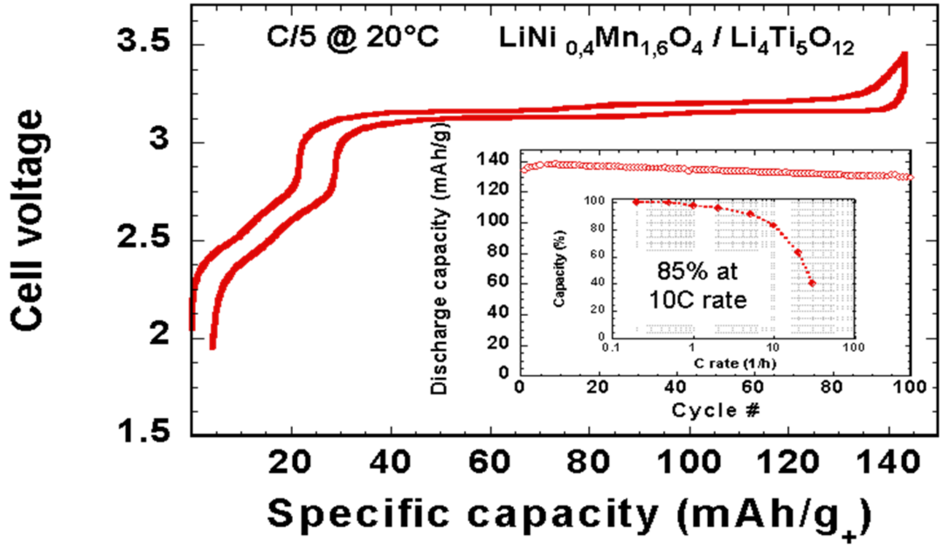
Versus LTO:

- ✓ **LFP: 1.9V**
- ✓ **LCO, NMCs: 2.1V**
- ✓ **$LiMn_2O_4$: 2.4V**
- ✓ **5V Spinel : 3.2V**

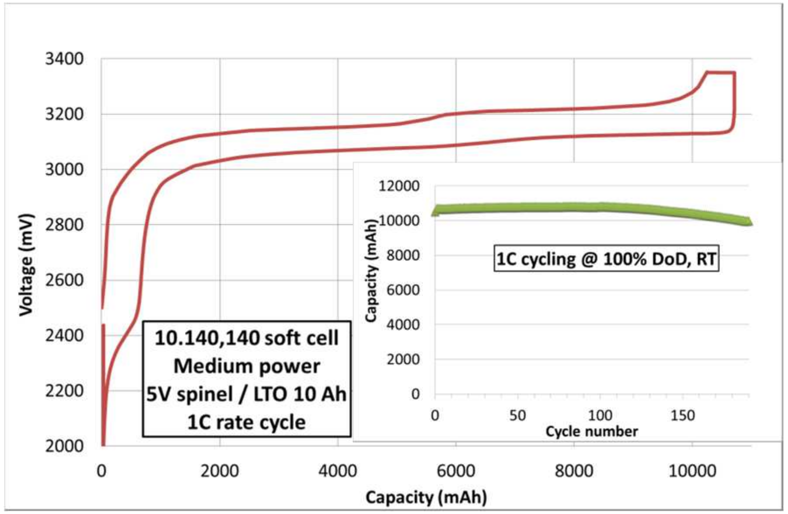
CEA PROPRIETARY

CEA Li-ion Power Cells GEN2

'3V' Li-ion Cell by coupling of 5V Spinel with LTO



Target: 10kW/kg



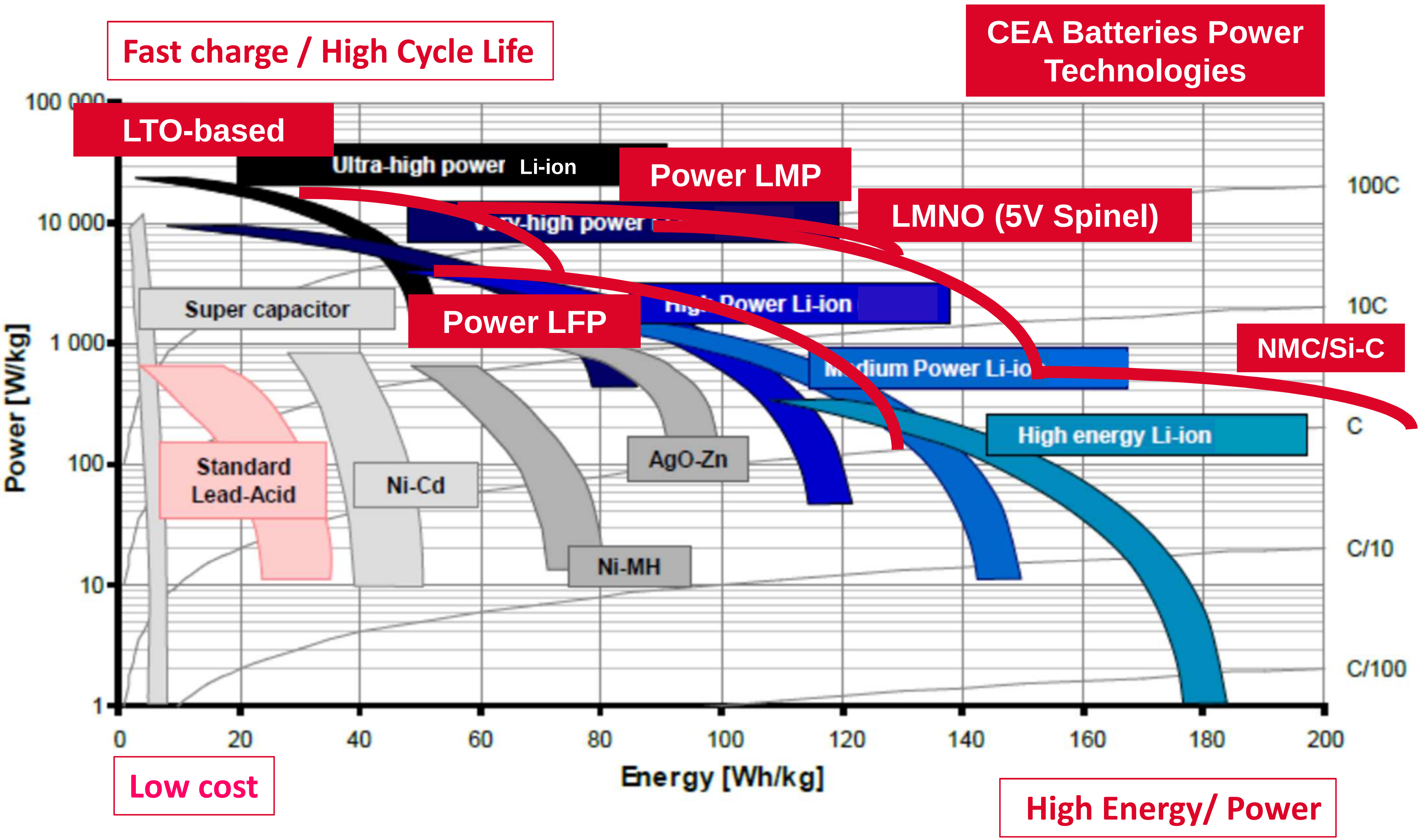
5V Spinel versus LTO

- ✓ Higher Power capability at low temperature
- ✓ Higher DOD (higher useful capacity or lower oversizing)
- ✓ No Li plating event (safer)
- ✓ Lower Self-discharge (compared to graphite)

BUT (Compared to Graphite)

- ✓ More cells in series to increase battery voltage
- ✓ Lower energy density <100Wh/kg

CEA POWER TECHNOLOGIES

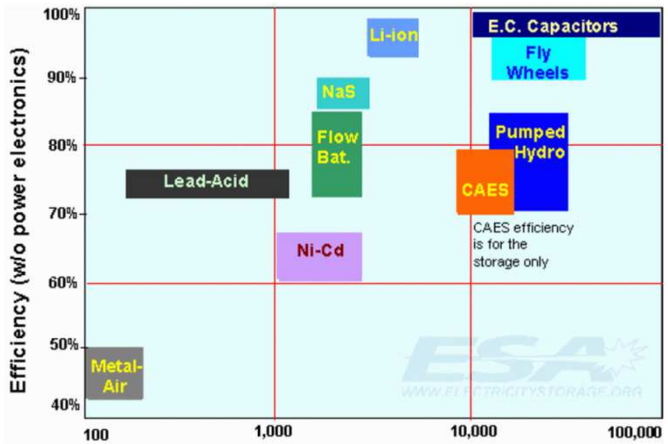


Power Technologies versus Applications Examples

- eBUS >200kW, 10-20kWh
- Start & Stop: 2-3kW, 250Wh
- Autonomous Heavy Duty Vehicles >500kW, >20kWh

Study of Case

- Stationary ESS: Other targeted application field (*not discussed here*)



Source: ESA (RT Efficiency versus Cycle Life)

LFP/G TECHNOLOGY IN POWER MODE

e-BUSES
Electric Energy Storage with Power Capability

Demonstrating Project under progress (**ElLiSup**)
Round trip : Battery pack charged at the end of the bus line. Lifetime of the bus : 15 years (ca. **15000 cycles**)
Embedded energy 12 kWh (Mini) discharged in 26min. Charge Max Power :
180 kW, 4 min (at least 20% of capacity). Voltage of the battery : between 400V and 600V

CEA Work:

- ✓ Design and manufacturing of packs
- ✓ Key issues : end of bus line charge = 250 kW in 5mn => cooling / mechanical integration and validation
- ✓ System integration tests on the CEA test bench. Bus integration.
- ✓ In use tests

CEA Grenoble Scale 1 Demonstration

LFP/G TECHNOLOGY IN POWER MODE

e-BUSES
Electric Energy Storage with Power Capability

Battery Design
- ✓ 4 battery packs, their cooling system and BMS
- ✓ 480 kW DCDC converters for the main power
- ✓ Power box (fuses, contactors)
- ✓ 4 inverters (for communication) and 1 motor for power
- ✓ 2 DCDC converters for the 24V auxiliaries bus
- ✓ Vehicle central unit

CEA Battery Modules

Station Design
- ✓ Key issues : harmonics, noise, perturbation on the grid, 250 kW safe interface with the bus
- ✓ Electrical and thermal architecture
- ✓ Power electronics definition
- ✓ Manufacturing by sub-contractor
- ✓ System tests with the bus

250kW charging station

12V Li-ion Starter Battery for Stop & Start Vehicles

ASPROM
OPTEZ POUR L'INNOVATION

Concern

- Exemption Risk on Lead Starter Batteries reviewed in 2015
- Lead : Today 25-27kg (full display)
- Average current life time = ca. 5 years (i.e. : 80% of French users)

=> Take advantage of Li-ion in term of charge sustaining (CO_2 reduction)

Goal: decrease embedded capacity

Performances requirements are summarized below:

Current Design with Lead-Acid Battery

Energy C(20h)= 70 Ah

Power 760A (EN)

Working Temp [-30°C ; 75°C]

12Vnet Fully compatible with 12V network

Battery Target Design with Li-ion

Typical requirement: C(20h)= 70 Ah

Typical requirement: 760A (EN)

Typical requirement: [- 30°C ; 75°C]

Fully compatible with 12V network

Li-ion Starter Battery Specifications:

Unom = 12V

Imax = 760A, 10s @-18°C 100% SOC
475A, 10s @-30°C 100% SOC
988A, 1s @23°C 80% SOC

Umin = 7.5V 10s -18°C @Imax

Charge acceptance: 100A @0°C & 50%SOC
200A @25°C & 70%SOC

Capacity: 10Ah min EOL

Weight: 10kg max Volume: 9.14L max

Max Operating T°: 80°C (Mean 50°C)

Max Calendar T°: 100°C

Energy: 120Wh EOL (12Wh/kg min)

Pmax: 11856W

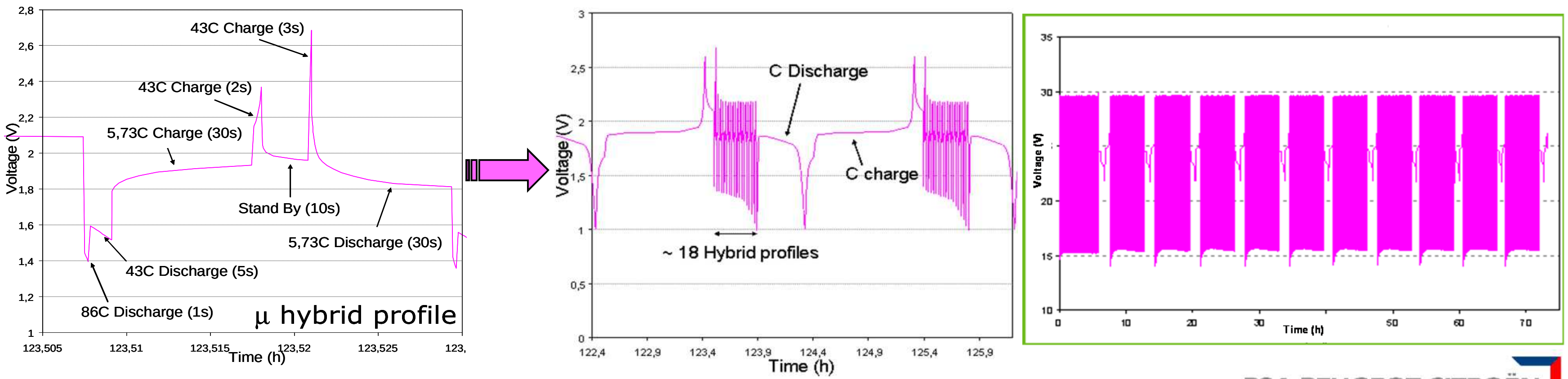
CEA PROPRIETARY

12V Li-ion Starter Li-ion Proposed Solution

⇒ **LFP/LTO solution allows responding to the needs with weight < 10kg**

⇒ **Best chemistry in SAFETY and CYCLE LIFE for such charge & discharge rates**

⇒ **Demonstrated by CEA under Start & Stop mission profiles with 0.7Ah 24V cells :**



PSA PEUGEOT CITROËN

1 HEV profile = An accelerated duty profile built from the succession of these micro cycles (100 µcycles ~ 1 week of actual operation):

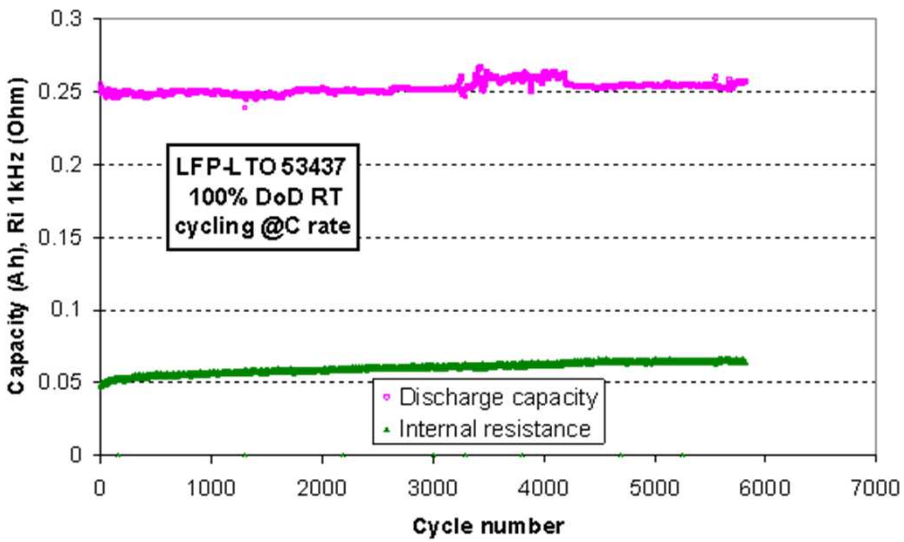
A **discharge** at max. current 60A and 6V cut-off voltage 60A (1s) ⇔ **80C rate**

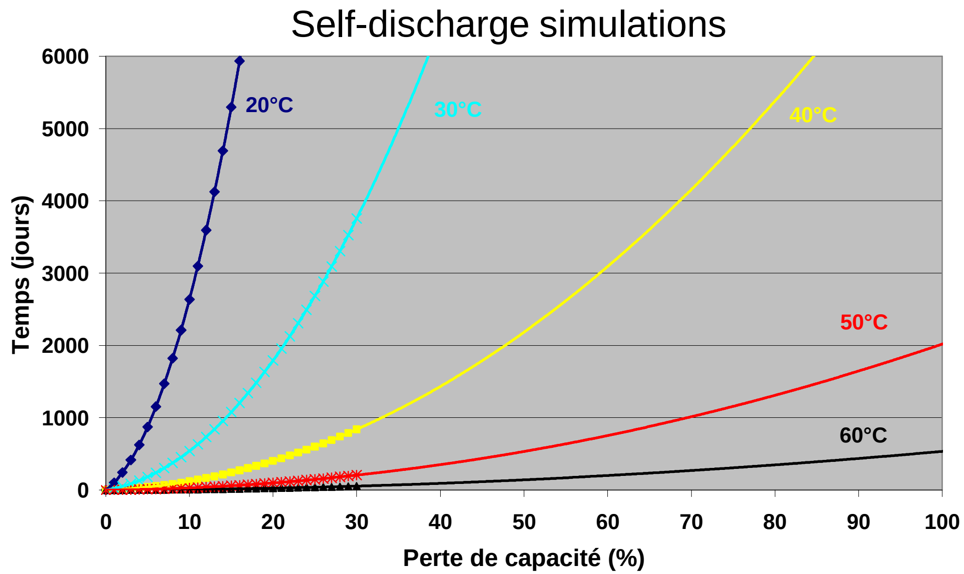
A **charge** at max. current 30A and 30V cut-off voltage 30A (3s) ⇔ **40C rate**

Start & Stop Experimental Data

⇒ **LFP/LTO** accumulator allows to restitute **ca. 30000 times more than 40% of its total capacity** at very high rates (>>50C) in both charge and discharge modes

WHY LFP/LTO TECHNOLOGY?





=> Extrapolated Data following 6 months testing at 3 different temperatures (25, 40 et 55°C)

- ⇒ **Extended cycle life**
- ⇒ **No Capacity Loss after 6000 cycles 100%DOD@C-Rate (RT) with 20% increase of Internal Resistance**
- ⇒ **Very low self-discharge : 10% capacity loss extrapolated after 6 years at 20°C or ca. 20% after 3 years at 35°C**
- ⇒ **Safety Tests successfully passed w/o passive or active safety display**

LFP/LTO TECHNOLOGY FOR ULTRA HIGH POWER MARKETS

HEAVY DUTY VEHICLES
Autonomous between stations

Example of Required Specification :

-**Partial Cycling Hypothesis** for >100k Cycles with ability to sustain >200k peaks @15kWh Storage Systems Sizing w/o hybridization (Super Capacitors)
- Parameters of interest:
Charge power / Discharge maximum level
Available Energy and Restituted Energy/kWh

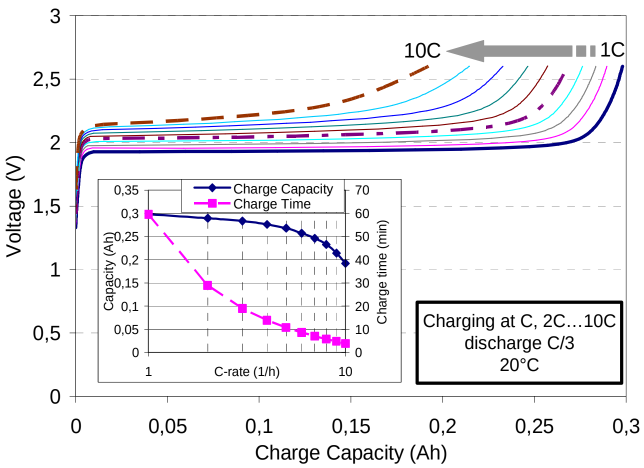
	CEA Pess	CEA Med	CEA Opt	Lipo	LFP-G	SC	
Energy density	60	60	60	142	107	5	Wh/kg
Max DOD for µcycles #	5	7,5	10	1	2	100	DOD %
Restituted Energy	7884	11826	15768	3731,76	5623,92	13140,00	Wh
Requested Mini Weight	1633	1089	817	3451	2290	980	kg
Embedded Energy	98,0	65,3	49,0	490,0	245,0	4,9	kWh

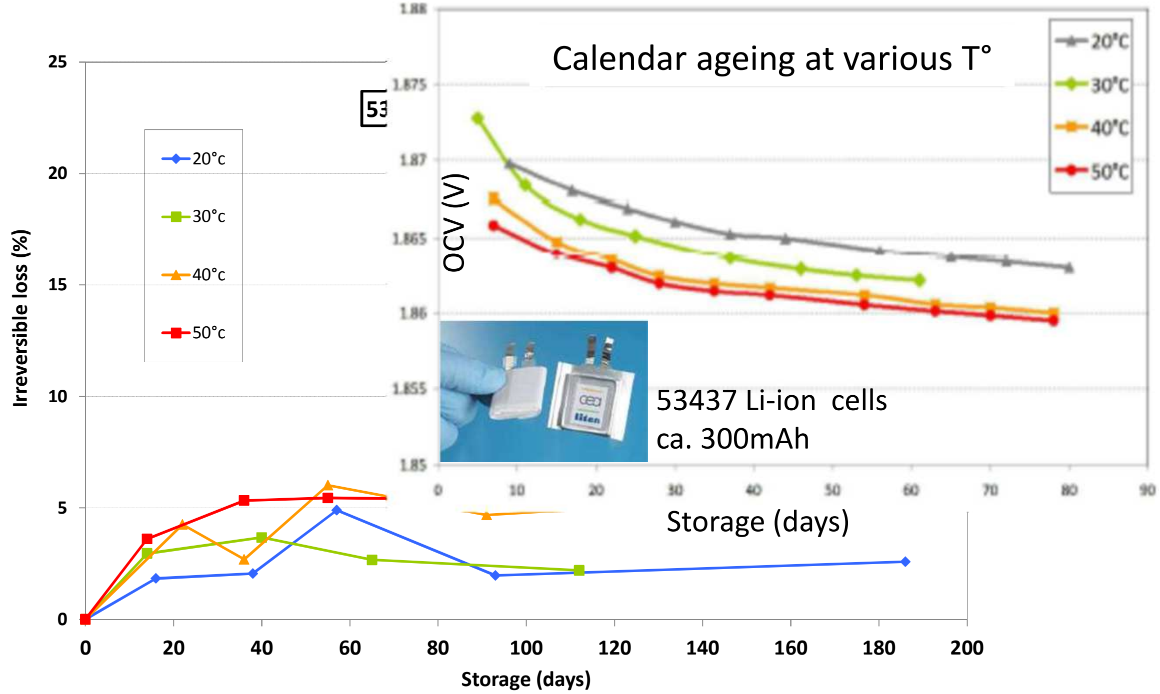
(Power peaks to sustain not taken into account…) Power peaks @500k-1MW

⇒ **LFP-LTO = End of life OK with needed DOD**
⇒ **Others = need SC hybridization for life cycle > 2 500 000 µcycles**

TECHNOLOGY DEMONSTRATION
EXPERIMENTAL RESULTS FOR LFP/LTO

LFP/LTO





⇒ **Power capability @+20°C** : 10C power available in charge/discharge modes quasi-stable over 20 to 90% SOC

⇒ **Cycling** : After 2.5 months cycling (customer profile), good IR stability no significant effect of DOD%. Expected > 100 000 cycles

⇒ **Calendar ageing** : Irreversible capacity loss < 6% upon 6 months storage at different T° (up to 40°C). Good OCV stability during storage

Cost of Battery Pack Analysis

Case n°1 : e-BUS Specifications

- Pack Energy > 20kWh
- Charge power ability = 260kW, 20s.

Techno	LFP / LTO	LFP / Graphite	LFP / Graphite
Type of cell	high Power	Energy	Power
pack config.	4P x 312S	8P x 192S	6P x 192S
Nbr of cells	1248	1536	1152
cell shape	50-125 cyl.	50-125 cyl.	50-125 cyl.
cell nominal Capacity (Ah)	11	16	10
cell nominal Voltage (V)	1,9	3,2	3,2
Pack total Energy (kWh)	26	78,6	36,9
Discharge Power (kW)	213	213	213
Cell Discharge Rate (equiv. xC)	9,1	3,0	6,4
Charge Power (kW) (duration= 20s)	260	260	260
Cell Charge Rate (equiv. xC)	**8,6**	3,0	6,4
Cost calculation , hypothesis= 500 packs/year			
Pack battery Global Cost (cells+ pack system) (k€)	100-110	100	65
Pack battery - Cost of Energy (k€ / kWh)	4,0	1,27	1,76
Pack battery - Cost of power (€ / kW)	**404**	**385**	**250**

- Cost of Power : LTO = about x 1,5 LFP/G power pack solution
- Pack Weight, Volume : nearly the same in case of using LFP/G power cells

Case n°2 : Simulation in the scope of a high power charge requested application

- Pack Energy > 20kWh = Unchanged
- Charge power ability = Power pick of ~900kW, up to 5-10s

Techno	LFP / LTO	LFP / Graphite	LFP / Graphite
Type of cell	high Power	Energy	Power
pack config.	4P x 312S	**24P** x 192S	**18P** x 192S
Nbr of cells	1248	4608	3456
cell shape	50-125 cyl.	50-125 cyl.	50-125 cyl.
cell nominal Capacity (Ah)	11	16	10
cell nominal Voltage (V)	1,9	3,2	3,2
Pack total Energy (kWh)	26	236	110,6
Discharge Power (kW)	213	213	213
Cell Discharge Rate (equiv. xC)	9,1	1,0	2,1
Charge Power (kW) (duration= 5-10 s)	**900**	**900**	**900**
Cell Charge Rate (equiv. xC)	**30**	3,5	7,4
Cost calculation , hypothesis= 500 packs/year			
Pack battery Global Cost (cells+ pack system) (k€)	**100-110** = unchanged	285	180
Pack battery - Cost of Energy (k€ / kWh)	4,0	1,21	1,63
Pack battery - Cost of power (€ / kW)	**117**	**317**	**200**

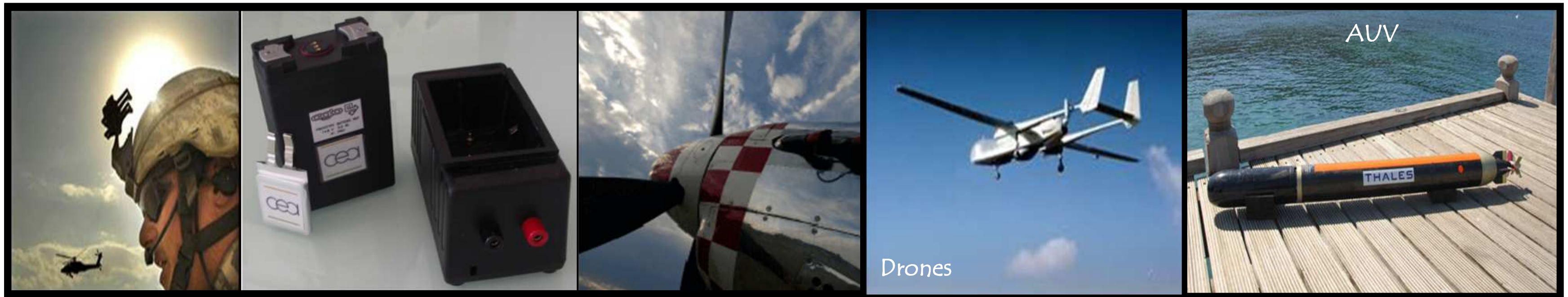
Optimistic

- Cost of Power : LTO = about divided by 2 vs. LFP/G power pack solution
- Pack Weight, Volume : about 3 times higher if using LFP/G power cells
- Use of LFP/G Energy cells is clearly not competitive !!

OUTLINE

- Brief Introduction of Li-Ion Technology
- Introducing High Energy >250Wh/kg
- High Power Systems
- **Perspectives**

Electric Mobility, Stationary Applications



Professional, security, military, defense, aerospace applications

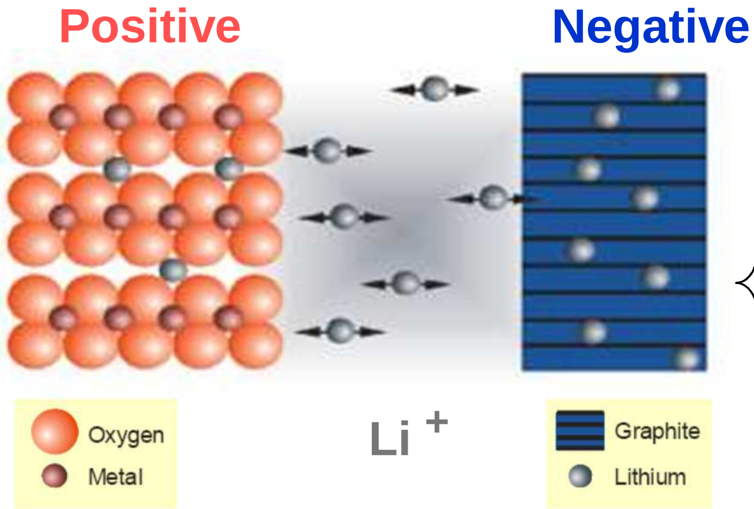
Conclusion

Remind that Li-Ion is a Generic Technology

ASPROM OPTEZ POUR L'INNOVATION

Lithiated Metal Oxide :

- *LCO ($LiCoO_2$)*
- NCA ($LiNiCoAlO_2$)
- LMO ($LiMn_2O_4$)
- NMC ($LiNiMnCoO_2$)
- « 3V » LFP ($LiFePO_4$)
- « 5V » (Spinel…)



- *Graphite*
- Hard Carbon
- Ti-Based (Titanate)
- Li-Alloy (Si, Sn…)

➢ 3 classes of Positive Electrodes: 3V (LFP) 4V (Std) or 5V (Dev)

➢ 3 classes of Negative Electrodes: Graphite (Std), Ti-Based (High Power, Durability), Si-based (High Capacity)

⇒ "easy" to adapt to customer's specifications

* Source GM

⇒ already five of the nine combinations are commercialized

⇒ **Perspectives at 400Wh/kg and 1000Wh/L – Volum. Energy Density >> Li-S and Li-Air ***

Still a place for significative improvement of Li-Ion Technology

ASPROM
OPTEZ POUR L'INNOVATION

- Positive Electrodes with 2 electrons per Transition Metal (Li-Rich Oxides or Polyanionic)
- Stabilized Si-Based Negative Electrode

⇒ **Perspectives at 400Wh/kg and 1000Wh/L – Volum. Energy Density >> Li-S and Li-Air** *

• Source GM Beyond Li-Ion 2012	Current Li-ion	Optimistic Li-ion*	Optimistic Li-Sulfur*	Optimistic Li-Air*
Specific Energy Density - Wh(total)/kg (cell)	250	530	550	710
Specific Energy Density - Wh(total)/kg (system)	**150**	**290**	**300**	**280**
Energy Density - Wh(total)/liter(cell)	520	1050	620	760
Energy Density - Wh(total)/liter(system)	**230**	**375**	**260**	**240**

*Assumes Li-Metal negative

High Power KPIs * / Markets / Perspectives

⇒ **2020 KPIs (Ref. STRATEGIC ENERGY TECHNOLOGY PLAN © European Union, 2011) :**

- ✓ **Li-ion Batteries KPI** = 10-year battery design life and 20-year power and balance-of-system design life; Charge-discharge T° range: -20°C to 70°C; Charge cycles: greater than 10 000 times at 70-80% DOD ; Fully installed system (All-in cost to install a step-up transformer) under 200€ per kilowatt-hour

- ✓ **Supercapacitors KPI =** Energy densities >15Wh/kg; A cost reduction down to maximum of 10 €/kW and a specific power > 30kW/kg

* **KPI: Key Performance Indicator**







High Power KPIs */ Markets / Perspectives

Large Volumes Markets:

- ✓ Start & Stop:
  2015 Market size $242.6M

- ✓ Grid Enhanced Energy Storage
  $16-35 Billions >2020
  (for 7 - 14 GW new installed capacities per year)

Small Volumes High Added Value Markets:

- ✓ Autonomous Heavy Duty Vehicles >500kW, >20kWh
- ✓ Aerospace (helicopters, launchers, radar satellites…),
- ✓ military…

Thank you !

End of lecture

Contact: florence.fusalba@cea.fr

Commissariat à l'énergie atomique et aux énergies alternatives
Centre de Grenoble | 38054 GRENOBLE Cedex 09
T. +33 (0)4 38 78 29 20 | F. +33 (0)4 38 78 51 98

Etablissement public à caractère industriel et commercial | RCS Paris B 775 685 019

Direction de la Recherche Technologique
Liten