Current technology for Space
Li-Ion is now a reality for Space Use

VES100  VES180  VES140  VL48E  MPS  VL8P  Power Cell
GEO 10 Real Time Life Test: 14 seasons so far...

- Energy increased by 5% close to mid-life
Schematic of post-life analyses DPA

1. Cell discharged to ≤3.3V OCV
2. Recovering of gas generated
3. Recovering of electrolyte
4. Composition analyses

- Analysis, Cell Pressure
- Recovering of gas generated
- Recovering of electrolyte
- Composition analyses

Compositions analyses:
- Cell dismantling inside glove box
- SEM observations ≠ points per electrode
- BET surface area ≠ points per electrode
- Photographs during dismantling
- Sampling of electrodes in ≠ lengthwise locations and three axial locations

- Quantification of Li content in negative electrode on the ≠ locations
- Quantification of Ni/Li ratio in positive electrode on the ≠ locations
- Coin cells with both electrodes in ≠ points
- Low current cycling + C pulses cycling
- 3-electrodes cells with both electrodes
- IES at 0, 50 and 100% SOC
- Transient voltage measurement
- XPS, TEM, AFM, TOF-SIMS and Raman analyses on electrode samples
More than 20 cells have been fully DPA’ed:
- After storage at various temperature
- After GEO and LEO cyclings
- After long term cycling: 95 GEO seasons (GEO9)

DPA’s have allowed to:
- To determine the degradation phenomena that occur during life at both electrode.
- To set-up models for life evolutions for the model
Saft Life prediction model: SLIM

Energy vs Temperature

Energy vs Power

Year Eclipse Duration

Ri vs SOC

Resistance increase vs T and time

Time vs Lithium Loss %

End of Charge: End Of Discharge VOLTAGES and Rint: 61 % DOD; T=20 °C

Total negative capacity vs T

End of Charge; End Of Dicharge VOLTAGES and Rint; 61 % DOD; T=20 °C
SLIM Model correlation with GEO10

Real Time ESA GEO10

Seasons

Voltage

Cell 1
Cell 2
Cell 3
Mod Min
Mod Av
Battery 701 cell-module voltage min. and max
From launch (March 2004 up to October 2007)
EADS-ASTRIUM E3000 satellite

![Graph showing cell-module voltage and bus current over time.](image-url)
In Orbit Status

- 19 Satellites have been launched with Saft Li-Ion batteries
- 15 GEO commercial communication satellites using VES140 including 5 military communication satellites
  - Up to 18 years
  - Up to 85 % DOD
- 2 LEO Satellites with VE100 (Callipso launched in April 06)
- 2 LEO satellites launched with MPS cells (Agile in April 07)
- 7th GEO season (3.5 years) finished on W3A (8.5 kW GEO Satcom)
- More than 28 Million hour*cell in orbit
What’s about tomorrow?
Research programs per Technology

- Research actions are grouped under sub-programs:
  - NCA/graphite
    - Automotive HEV
    - Automotive EV
    - Stationary, including telecom
    - Aviation (gliders, drones, aircrafts)
    - Space and defense
  - LiCoO$_2$/graphite
    - Military
    - Space
    - Telecom
    - Medical
    - Professional power tools
  - New families of materials:
    - NMC Li(NiCoMn)O$_2$
    - LiFePO$_4$
    - Li$_4$Ti$_5$O$_{12}$
Major technology trends for Li-ion

- Li-ion technology is being explored in many sizes, shape and stack construction.

- Proven to be suitable both for high energy or high power, long life.

- Next improvements to come from materials study with principal aims:
  - More energy
  - More power
  - Lower cost
  - Better life duration
  - Better safety
  - Thermal performance

- Goal: +30% energy increase in the coming years (up to 250 Wh/kg)

Search for the optimum compromise related to a given application
Future of current technologies

Applications

technical requirements

More power

Super capacitors

Lead acid spirally wound

Ni-Cd

Ni-MH

Li-Ion Very High Power

Na / NiCl2

Li-Ion High Power

Li-Ion High Energy

LiM-Polymer

More energy

specific power W/kg

specific energy Wh/kg

Lead acid

High Power

High Energy

High Power

High Energy
The Fun Stuff…

- Recent Developments
  - Ultra High Power Li-ion
  - LiFePO$_4$ Technology
  - High Energy cells
High Power Cells
Progression of Li-ion Power Cell

| Progress in Specific Power of Saft technology on a cell level (2 sec pulse) |
|---------------|-------------------|-------------------|
| 2.5 kW/kg       | 8 kW/kg           | 20 kW/kg         |

- Saft has used its Very High Power cells to deliver complete batteries to various customers within Department of Defense

350V Emergency Battery
(89lb)
Used in F-35 Aircraft
TRL7

<table>
<thead>
<tr>
<th>Specific Power, kW</th>
</tr>
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<tbody>
<tr>
<td>0.2 sec</td>
</tr>
<tr>
<td>2 sec</td>
</tr>
<tr>
<td>5 sec</td>
</tr>
<tr>
<td>Continuous</td>
</tr>
<tr>
<td>320</td>
</tr>
<tr>
<td>225</td>
</tr>
<tr>
<td>200</td>
</tr>
<tr>
<td>175</td>
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</tbody>
</table>
High Power Cell Products

- Three cell sizes available – VL8P, VL16P and VL34P

- VL8P cell is used on Thruster Vector Control battery for VEGA European launcher

- VL34P cell is used in military vehicle applications

- This cell combines good power capability with decent energy content

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>Value</th>
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<tbody>
<tr>
<td>Mass</td>
<td>kg</td>
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<tr>
<td>Volume</td>
<td>L</td>
<td>0.41</td>
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<tr>
<td>Charge Voltage</td>
<td>V</td>
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<tr>
<td>Nominal Capacity</td>
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<tr>
<td>Specific Energy</td>
<td>Wh/kg</td>
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<tr>
<td>Energy Density</td>
<td>Wh/l</td>
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<tr>
<td>Terminal-to-Terminal Length</td>
<td>mm</td>
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</tr>
<tr>
<td>Diameter</td>
<td>mm</td>
<td>54</td>
</tr>
<tr>
<td>Max Discharge Current @ 25°C Continuous</td>
<td>A</td>
<td>500</td>
</tr>
<tr>
<td>Max Discharge Current @ 25°C 2 sec pulse</td>
<td>A</td>
<td>1900</td>
</tr>
<tr>
<td>1kHz AC Impedance</td>
<td>mΩ</td>
<td>0.45</td>
</tr>
</tbody>
</table>
SAFT is working on Ultra High Power

- Applications: Directed Energy, Launchers, Applications with Tight Voltage requirements

- Also, low impedance performance results in smaller battery size due to optimized thermal and voltage performance
# Very High Power Li-ion

<table>
<thead>
<tr>
<th></th>
<th>VL4V</th>
<th>VL8V</th>
<th>VL12V</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity</strong>, Ah</td>
<td>6</td>
<td>8.5</td>
<td>12.5</td>
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<tr>
<td><strong>Energy</strong>, Wh</td>
<td>22</td>
<td>31</td>
<td>45.5</td>
</tr>
<tr>
<td><strong>Power (100% SOC), W</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200 milli-seconds</td>
<td>3800</td>
<td>5650</td>
<td>9000</td>
</tr>
<tr>
<td>2 seconds</td>
<td>2500</td>
<td>3800</td>
<td>5500</td>
</tr>
<tr>
<td>15 seconds</td>
<td>2000</td>
<td>3000</td>
<td>4000</td>
</tr>
<tr>
<td><strong>Weight</strong>, grams</td>
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<td>470</td>
<td>600</td>
</tr>
<tr>
<td><strong>Diameter</strong>, mm</td>
<td>34</td>
<td>41</td>
<td>47</td>
</tr>
<tr>
<td><strong>Length</strong>, mm</td>
<td>156</td>
<td>156</td>
<td>156</td>
</tr>
</tbody>
</table>

**Kanban**

**POWER** = **SIZE**

*Image of the battery workshop and product images are also included.*
Very High Power Delivered by VL4V Cell used in 270V JSF Battery

- **Standard VL4V cells can:**
  - Be completely discharged at 500A in room temperature (30 sec)
  - Deliver 2 second long pulses at currents exceeding 1500A
  - Deliver over 2000A in 200msec long pulses

- Performance at temperature
  - VL4V cell delivers power at -40°C for emergency loads on board aircraft
  - The technology can operate at temperatures as low as -70°C
Long Life Test Results of the VHP Li-ion

Cycle Life
- Stability is a major advantage of LiNiCoAlO₂ based Li-ion system
- Simulated Airborne Active Denial cycling

Calendar Life
- Data presented by Jeff Belt from Idaho National Laboratory at AABC’07
- Graph based on 6 years of actual storage in 5 temperatures at 50% SOC
- SAFT VL12P cells supplied out of Cockeysville in 2001 timeframe

Graph:
- Discharge Impedance at 50% SOC
- Calendar Life vs. Temperature (°C)

Equation:
y = 481475x² - 954334x + 473191
R² = 0.9919
LiFePO$_4$ cells
VL10Fe Cell Based On LiFePO₄ Cathode

- Cell optimized for Very High Power applications
- VL25Fe also available
- SAFT is using licensed supplier for the Iron Phosphate cathode material
**LiFePO₄ Large Cell Development: Life**

- Very little loss of low temperature power after cycling at high temperature
Specific Energy increasing
New materials: a lot of candidates ...
(and more announcing their intent every day)
Li-ion of the future?

Today …

LiNi$_{1-x}$M$_x$O$_2$ ; LiCoO$_2$ ; 4V-LiMn$_2$O$_4$

5V-spinel + coatings (4.7V vs Li discharge)

Separator – electrolyte - specific additives

Si-C, Sn-C, Sn intermetallics

Graphite, carbons

Phosphides

Nano

Nanotubes

4.3V Emass. (+30%) Evol. (+40%)

3.6-3.7V Emass. Evol.

4.6V Emass. (+10%) Evol. (+10%)?
Increase of cell energy

- High energy MPs & Ds objective: energy > 210 Wh/kg
  - 4.4 V end-of-charge voltage (+30 % capacity)
    - Adapt electrode materials to such demanding EOCV

![Graph showing cycling performance at 4.4V]
Advanced Li-ion technologies

- Lithium titanate based negative electrode for high charge power
  - Lower voltage per cell but no risk of Li plating
  - Ex. Li$_4$Ti$_5$O$_{12}$ based Li-ion cells with very high charge rate capability

![Graph showing normalized capacity vs C/5 RT %, with DoD (%) on the x-axis and Max. power (mW/cm²) on the y-axis.](image)

- Charge C/5 pulse 9C 2s - discharge C/5 pulse 18C 10s

Legend:
- Uc=1.5V
- Uc=2.75V
- Uc=3.4V

4/5A prototypes

Vaughan Technologies

Charge C/5 pulse 9C 2s - discharge C/5 pulse 18C 10s
Space Cell Development RoadMap
New Ni-based Oxide “low capacity” MP Cell dedicated for LEO

- Existing MP cells use Cobalt Oxide that provides limited life time (calendar)

- Specific development for space application based on MP cells with already proven Nickel based Oxide:
  - for small and mid size LEO satellites
  - Increase of the specific energy
  - Increase of the life time over 10 years in LEO
  - Extension of temperature range with specific electrolyte

- Available End 2008
Nickel-based MP cell design

- VES Nickel based electrochemistry
- Middle range MP aluminum case

- Capacity: 4.25 Ah
- Energy: 15.5 Wh
- Mass: 100 g
- LEO Cycle Life: 12 years

MP HD “High Drain” Negative electrodes

HE electrode thickness
Battery assembly.

Figure 1: Twin modules assembly structure.

Figure 2: 3 modules assembly structure.

Figure 3  Unit rack structure.

- s-p Configuration.
- Individual cell balancing system
- Power range from 300 W to 1.2 kW.
Optimized LEO Development

- Saft, in response to some applications needing 10 years @ high DOD (~40%) initiated specific cell development

- Different parameters have been investigated

<table>
<thead>
<tr>
<th>Chemistry</th>
<th>Cell Design</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negative Recipe</td>
<td>Electrical busing</td>
<td>Rests are beneficial</td>
</tr>
<tr>
<td>Positive Recipe</td>
<td>Winding options</td>
<td>De-rated method</td>
</tr>
<tr>
<td>Electrolyte choice</td>
<td>Electrode thickness</td>
<td>Temperature</td>
</tr>
<tr>
<td>Additives</td>
<td>Electrode porosity</td>
<td></td>
</tr>
<tr>
<td>+/- Ratio</td>
<td>Separator</td>
<td></td>
</tr>
</tbody>
</table>

- Results after 2+ years, VL44EL cell capable of 33 % DOD performance predicted for 10 years and has good 40% performance to-date
Optimized LEO 40% DOD Testing

- Currently 19 cells are on various different LEO Test methods

- Early on, a sampling at 40% DOD shows excellent stability on this high a DOD. Orbital time is 35min discharge @ 30.17A, 61 min charge starting at 19.5A

![Graph showing EODV vs Cycle Number](image)

**Equations:**

- $E_{ODV763-55} = -6.60E-06x + 3.56E+00$
  - $R^2 = 7.26E-01$

- $E_{ODV763-54} = -4.60E-06x + 3.55E+00$
  - $R^2 = 8.35E-01$
Next Space cell Generation

- Based on research on active material on going: “5V positive” and “Si-C negative”

- Main Objectives:
  - Specific energy target: 250 Wh/kg
  - Industrial cell qualification planned in 2010
  - Space cell (mainly for GEO) development starting in 2010 and qualification expected in 2012
Saft. Energy unlimited