Commercialization of Faradion’s High Energy Density Na-ion Battery Technology

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Faradion: Introduction
1. **Sustainability.** Na is abundant, so a Na-ion battery manufacturing facility may be established virtually anywhere in the world with local supplies. Focus on low cathode materials (Mn, Ti, Fe etc.).

2. **Performance.** We believe we can match best Li-ion in terms of cycle life, rate capability, energy density and specific energy.

3. **Cost.** Lower cost of precursor materials, use of aluminium cc etc. Overall we predict a ~30% decrease in $/kWh at cell level.

4. **Safety.** Improved safety, storage and transportation characteristics.

5. **Existing Infrastructure.** We can use existing Li-ion cell manufacturing lines – for pouch, prismatic and cylindrical cells. Unlike other new battery technologies we do not have to re-define cell manufacturing approaches.

6. **IP Landscape.** By comparison, Li-ion technology is a minefield – it is far easier to secure ‘definitive’ IP for Na-ion technology. Plenty of scope for improvements as we move forward - we are not limited to incremental enhancements - large-step improvements possible for Na-ion technology.

A good licensing opportunity for existing Li-ion producers
Na-ion Battery Patent Applications
2000-2016 (August)
US, Europe and PCT

Sources: US-PTO, EPO and WIPO (PCT)
Current Status (December 2016):

- 22 Patent Application Families Filed
  - Cathode Active: 14
  - Anode Active: 1
  - Preparative Methods: 4
  - Cell Infrastructure: 2
  - Safety & Transportation: 1

- GB - PCT - National Phase
- Europe, China, Korea, Japan, US

- 6 EP Patent Applications Granted
- 2 CN Patent Applications Granted

- No significant opposition on any current application
Cell Structure
• All testing performed in full Na-ion pouch cells

• Cells optimized for energy

• Electrode loading
  • $\sim 3+ \text{ mAh/cm}^2$

• Cycling conditions
  • 1.0 – 4.3 V
  • CC, CV
  • C/10 to C Rate

Na$_a$Ni$_{(1-x-y-z)}$Mn$_x$Mg$_y$Ti$_z$O$_2$
Faradion Cell Designs

Faradion Energy Cell
Stacked
A5 Format
14.8 x 21.0 cm
4-5 Ah
12-16 Wh

Faradion Energy Cell
Power Cell
Stacked
Varying Footprint
1-4 Ah
3-14 Wh

Faradion Energy Cell
Power Cell
Wound
Varying Footprint
1-3 Ah
3-10 Wh
Active Materials
Database of Na Cathode Materials > 90 classes in total

Phosphates

Na₃M₂XO₆
Na₂M₂X’O₆

(O3,P2)
Layered Ni Oxides

Na₇M₄(P₂O₇)₄PO₄
Na₇M₃(P₂O₇)₃
Na₄M₃(PO₄)₂P₂O₇

O3-Na₃Ni₂SbO₆
P2-Na₂Ni₂TeO₆

NaₐNi₁₋ₓ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ₋ₙ_-
Na$_{1-x}$Ni$_{1-x-y-z}$M$_1^x$M$_2^y$M$_3^z$O$_2$

- Na$_{1-x}$Ni$_{1-x-y-z}$M$_1^x$M$_2^y$M$_3^z$O$_2$: O3- and P2- type layered oxides
- Na ions in the interlayer space

Pan et al, Energy Environ Sci., 2013, 6, 2338-2360
HT Na\(_{1-x}\)Ni\(_{1-x-y-z}\)M\(^1\_x\)M\(^2\_y\)M\(^3\_z\)O\(_2\)

Particle size distribution

- \(d_{10}\) = 5.4 \(\mu\)m
- \(d_{50}\) = 11.6 \(\mu\)m
- \(d_{90}\) = 21.3 \(\mu\)m
- \(d_{99}\) < 33.4 \(\mu\)m

50-100 kg Cathode Batches
Typical particle sizes = 2-8 μm

Faradion Hard Carbon vs. Na = 280 mAh/g

(A) Na insertion into graphene interlayer space

(B) Na insertion into nano-pores

Capacity fade = 5.9 % in 100 cycles - 0.059 %/cycle
Electrolyte
- Proprietary formulation selected based on a combination of cell performance and lowest cost
- Low volatility solvents to assist safety characteristics, significant PC component
- Na electrolytes more conductive than Li so use molarity < 1.0 M for most applications (typically 0.5 M)
- Mixed carbonate-based solvents; NaPF$_6$ salt
- Commercial separator grades
Na-ion Cells: Performance
• Reversible cathode specific capacity = 157 mAh/g

• Average discharge voltage = 3.20 V

• Cathode specific energy = 500 Wh/kg

• Round trip energy efficiency > 91 %

• Low polarization

Cycle#2
Prototype Cells

Faradion Na-ion Prototype Cells ±C/7

Faradion Na-ion Prototype Cells ±C/5

Faradion Na-ion Prototype Cells ±C/3

Faradion Na-ion Prototype Cells ±C/2

Cathode Specific Capacity [mAh/g]

Cycle Number
80% DOD Cycling

Faradion Na-ion Prototype Electrodes ±C/5

% Discharge Capacity vs. Cycle Number

% Cathode Specific Capacity [mAh/g] vs. Cycle Number

>1000 cycles to 80% original discharge capacity

y = 0.00683x + 100, max dev:1.95, r²=0.159

1000 cycles = 93%
3-Electrode Cell Design

- Na metal
- Pouch Material
- 2 x Separator
- RE tab (Al)
- Positive electrode tab (Al)
- Negative electrode tab (Al)
- Anode Electrode
- Cathode Electrode

3rd International Conference on Sodium Batteries
Geelong, December 2016
Formation Cycle

Cell#602014 - Cycle#1 ±C/7 1.0-4.3 V
Cathode C1 = 181 mAh/g; D1 = 154 mAh/g
FCL = 15.0 %
Anode C1 = 266 mAh/g; D1 = 224 mAh/g

✓ Very low levels of both cell and electrode polarization at this charge/discharge rate
Specific Energy
ANL BatPac Model
3.2 V Average Voltage
Pouch Cell - stacked
design
Energy Design

18650 Model
3.2 V Average Voltage
Cylindrical 18650 -
Wound Cell
Energy Design

Cell Specific Energy Model
Faradion: Technology Roadmap 2015-2018 (Energy Cell)

- **Anode = 390 mAh/g**
- **Cathode = 180 mAh/g**
- **Hard Carbon Optimization**
- **Electrolyte Optimization + Higher Operating Voltage (3.4 V)**
- **Electrode/Physical Optimization of Active Materials**
- **Cathode Optimization (Gen#2) = 150 mAh/g**
- **Gen#1 Baseline Hard Carbon/Faradion Cathode**
  - Anode = 230 mAh/g
  - Cathode = 130 mAh/g

**Model: ANL BatPac (2016) – Pouch Cell**
Temperature Performance
Rate Performance at +30°C

Cell#608043 Rate Test at +30°C

Specific Capacity [mAh/g]

Cell Voltage [V]

Cathode Specific Capacity [mAh/g]

C/5

C/2

Cell#608043 Rate at 30°C

C

3C

Energy Cell; Baseline Electrolyte
Cell#609010 Rate Test at -20°C

Specific Capacity [mAh/g]

C/5
C/2

C
3C

Cell#609010 Rate at -20°C

ENERGY CELL; BASELINE ELECTROLYTE
Cell#610018 (60°C), Cell#610019 (30°C); Cell#610017 (-20°C)

Cathode Specific Capacity [mAh/g]

Cycle Number

ENERGY CELL; BASELINE ELECTROLYTE
Na-ion Cells: Safety
ARC: Self-heating Rate

- **LiCoO₂**: (max self-heating rate ~ 4000 °C/min)
- **LiFePO₄**: (max self-heating rate ~ 150 °C/min)
- **Faradion**: (max self-heating rate ~ 52 °C/min)
The ARC test generates an accurate prediction of the safety/abuse tolerance of the battery technology under test.

For a safe cell – need a combination of:
- (a) high onset temperature for self-heating
- (b) low self-heating rate

Preliminary tests indicate Faradion Na-ion cells are significantly safer than either Li-ion LCO or Li-ion LFP.

Full safety/abuse testing on prototype cells is underway.
Zero Energy Storage and Transportation
Transport issues with Lithium-ion

- Transportation of lithium-ion batteries is inherently hazardous.
- Lithium-ion cells have to be stored and transported in a charged state, i.e. a state that is less stable and more prone to fire.
- Numerous incidences of charged lithium-ion batteries producing smoke, extreme heat, catching fire or exploding.
- A major concern, particularly to airlines and there are very stringent controls on the bulk air transportation of lithium-based cells
- Controls on both the size as well as the number of batteries allowed in each consignment.

Faradion’s solution

- Faradion's sodium-ion batteries solve the problem of air transport.
- Sodium-ion cells use safer and lower cost active materials than Lithium-ion cells and low volatility electrolyte.
- Sodium-ion batteries can be discharged to 0 Volts and stored and transported in this discharged state (unlike Lithium-ion batteries).

Associated IP

- Faradion has patented a method for the transportation and storage of sodium-ion cells
- Cells can be safely transported without any risk of overheating, catching fire or exploding.
0 V Storage: 24 h

Medical & Transportation Applications
0 V Storage: 48 h

Max: 6 months at 0 V = no degradation
Scale-up
Faradion has established a full Na-ion prototype facility in Sheffield, England. This is based at the Innovation Centre and contains the same equipment as that used in Li-ion cell production. The facility has the facility to produce stacked and wound cells and is currently producing 3 Ah (9 Wh) demonstrator cells.
Total Pack Weight = 5.1 kg – 82 Wh/kg; fully packaged
Pack Dimensions: 36 cm (L) x 14 cm (W) x 5 cm (D); Volume = 2.5 litres
• Faradion has demonstrated **industry-leading Na-ion battery technology**

• Significant **IP** secured

• Battery performance is comparable with commercial Li-ion technology - SE ~ **140-150 Wh/kg** at cell level; **cycle life, rate, temperature** etc.

• Temperature of operation: **-20°C to +60°C**

• Significant **cost** (30 % cheaper at cell level) and **safety benefits** over commercial Li-ion batteries, including **0 V storage and transportation**

• Scaled-up to the **5 Ah (16 Wh)** prototype cell size

• Demonstrated (May 2015) successfully in an **E-Bike (> 400 Wh pack)** and **E-Scooter** applications (> 800 Wh pack)