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

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Advanced Energy Storage Solutions

Faradion: Introduction

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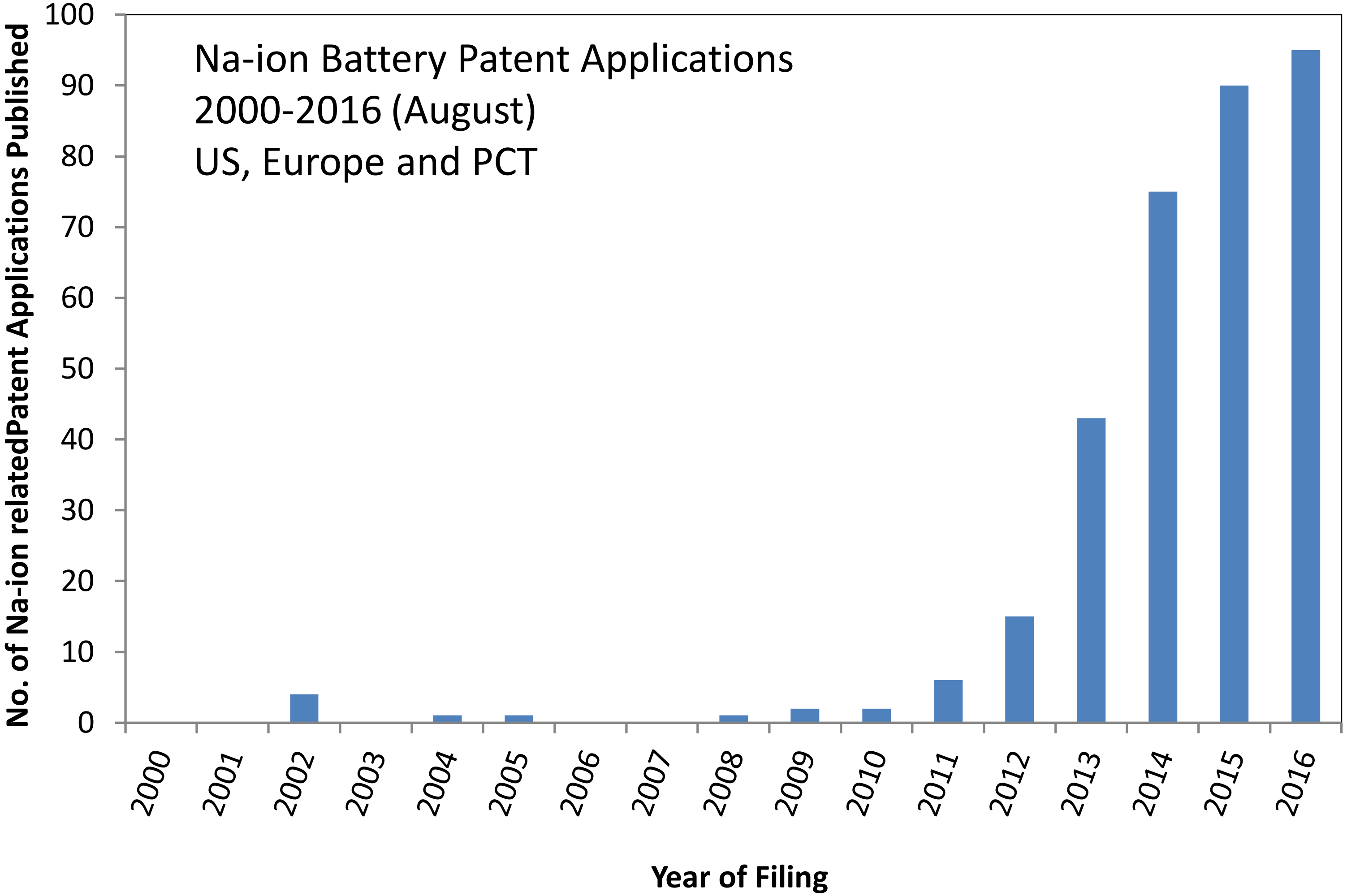
Why Na-ion Batteries?

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

IP Landscape



Sources: US-PTO, EPO and WIPO (PCT)

Faradion: IP

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
- 2 EP Patent Issued (Dec. 2016)
- 6 EP Patent Applications Granted
- 2 CN Patent Applications Granted
- No significant opposition on any current application

(19) Europäisches Patentamt / European Patent Office / Office européen des brevets

(11) **EP 2 761 687 B1**

(12) **EUROPEAN PATENT SPECIFICATION**

(45) Date of publication and mention of the grant of the patent: **03.02.2016 Bulletin 2016/05**

(21) Application number: **12769157.4**

(22) Date of filing: **25.09.2012**

(51) Int Cl.:
C01B 25/38 (2006.01) *C01B 25/42* (2006.01)
C01G 45/00 (2006.01) *C01G 51/00* (2006.01)
C01G 53/00 (2006.01) *H01B 1/08* (2006.01)
H01M 4/58 (2006.01) *H01M 10/054* (2010.01)

(86) International application number: **PCT/GB2012/052363**

(87) International publication number: **WO 2013/045905 (04.04.2013 Gazette 2013/14)**

(54) **CONDENSED POLYANION ELECTRODE**
KONDENSIERTE POLYANIONELEKTRODE
ÉLECTRODE À BASE DE POLYANION CONDENSÉ

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR

(30) Priority: **30.09.2011 GB 201116877**

(43) Date of publication of application: **06.08.2014 Bulletin 2014/32**

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(56) References cited:
EP-A1- 2 752 925 EP-A2- 1 544 930
WO-A1-2012/024001 US-A1- 2004 206 938

- **ESSEHLI R ET AL: "Synthesis, crystal structure and infrared spectroscopy of a new non-centrosymmetric mixed-anion phosphate Na4Mg3(PO4)2(P2O7)", JOURNAL OF ALLOYS AND COMPOUNDS, ELSEVIER SEQUOIA, LAUSANNE, CH, vol. 493, no. 1-2, 18 March 2010 (2010-03-18), pages 654-660, XP026928421, ISSN: 0925-8388, DOI: 10.1016/J.JALLCOM.2009.12.181 [retrieved on 2010-01-04]**
- **FRANCISCA SANZ ET AL: "Crystal Structure, Magnetic Properties, and Ionic Conductivity of a New Mixed-Anion Phosphate Na 4 Ni 5 (PO 4) 2 (P 2 O 7) 2", CHEMISTRY OF MATERIALS, vol. 11, no. 10, 1 October 1999 (1999-10-01), pages 2673-2679, XP055049856, ISSN: 0897-4756, DOI: 10.1021/cm981105s**
- **KHIEM TRAD ET AL: "A Layered Iron(III) Phosphate Phase, Na 3 Fe 3 (PO 4) 4 : Synthesis, Structure, and Electrochemical Properties as Positive Electrode in Sodium Batteries", JOURNAL OF PHYSICAL CHEMISTRY C, vol. 114, no. 21, 3 June 2010 (2010-06-03) , pages 10034-10044, XP055049271, ISSN: 1932-7447, DOI: 10.1021/jp100751b**
- **UEBOU Y ET AL: "Electrochemical insertion of lithium and sodium into (MoO2)2P2O7", JOURNAL OF POWER SOURCES, ELSEVIER SA, CH, vol. 115, no. 1, 27 March 2003 (2003-03-27), pages 119-124, XP004414858, ISSN: 0378-7753, DOI: 10.1016/S0378-7753(02)00648-1**

Note: Within nine months of the publication of the mention of the grant of the European patent in the European Patent Bulletin, any person may give notice to the European Patent Office of opposition to that patent, in accordance with the Implementing Regulations. Notice of opposition shall not be deemed to have been filed until the opposition fee has been paid. (Art. 99(1) European Patent Convention).

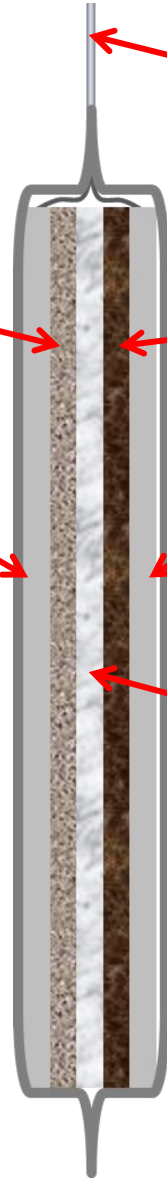
EP 2 761 687 B1

Cell Structure

Na-ion Cell Design

- All testing performed in full Na-ion pouch cells
- **Cells optimized for energy**
- Electrode loading
  - ~ 3+ mAh/cm²
- Cycling conditions
  - 1.0 – 4.3 V
  - CC, CV
  - C/10 to C Rate

ENERGY APPS



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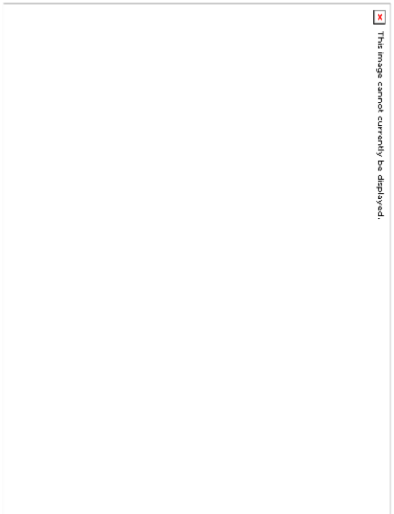
Faradion Cell Designs



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

WMG
THE UNIVERSITY OF WARWICK

Active Materials

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Cathode Materials

Database of Na Cathode Materials > 90 classes in total

Phosphates

$Na_7M_4(P_2O_7)_4PO_4$
$Na_7M_3(P_2O_7)_3$
$Na_4M_3(PO_4)_2P_2O_7$

$Na_3M_2XO_6$
$Na_2M_2X'O_6$

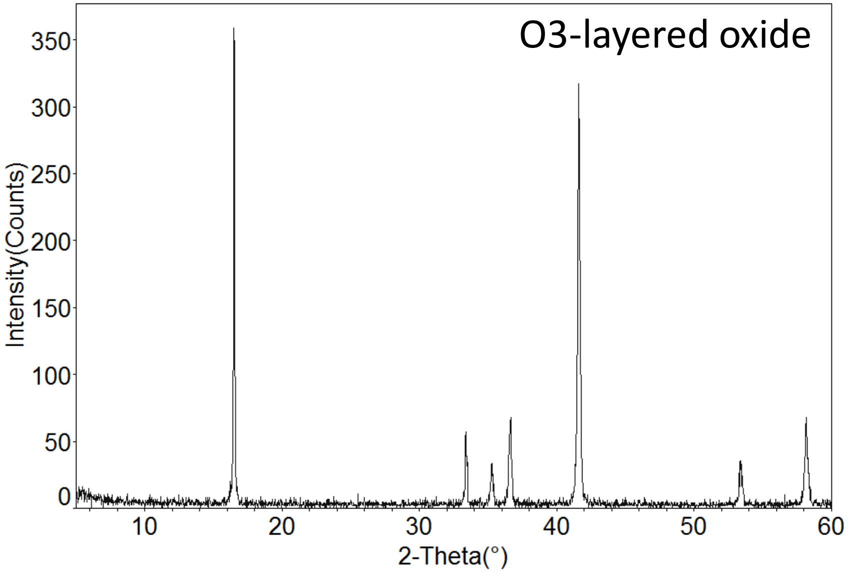
O3-$Na_3Ni_2SbO_6$
P2-$Na_2Ni_2TeO_6$

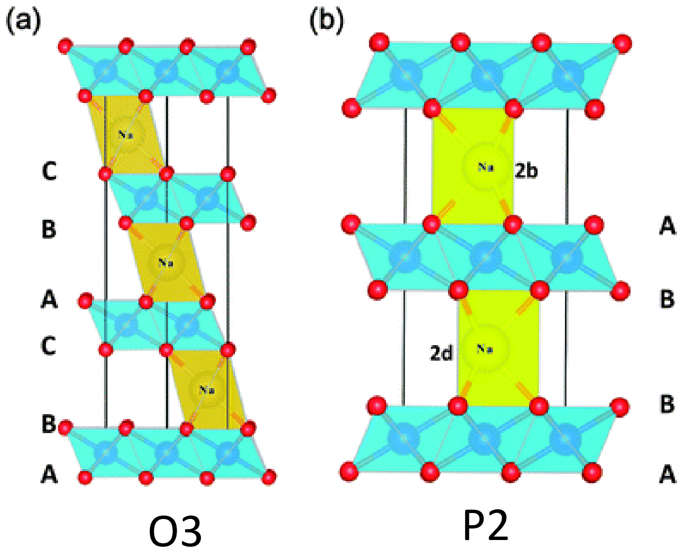
(O3,P2)
Layered Ni Oxides

$Na_aNi_{1-x-y-z}M^1_xM^2_yM^3_zO_2$

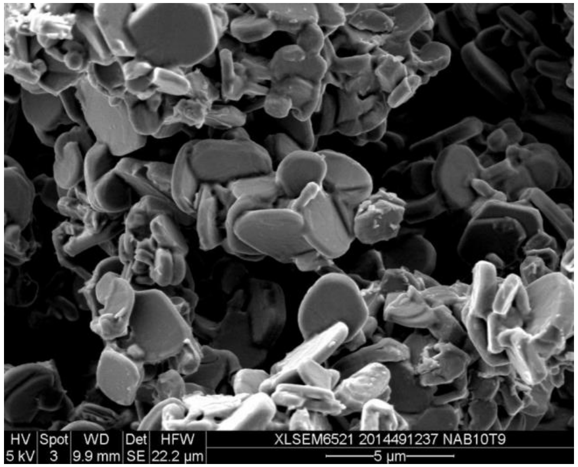
$Na_{1-x}Ni_{1-x-y-z}M^1_xM^2_yM^3_zO_2$

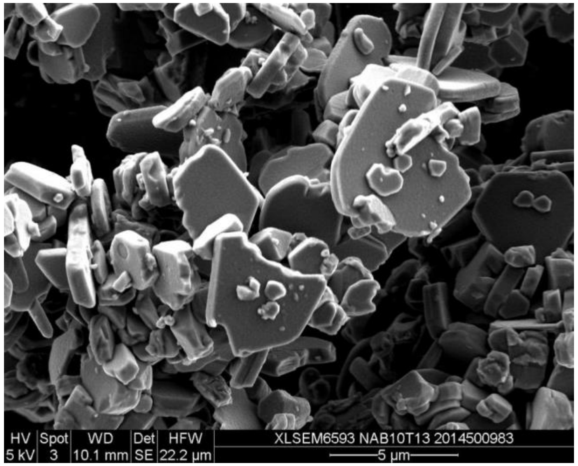
- **$Na_{1-x}Ni_{1-x-y-z}M^1_xM^2_yM^3_zO_2$: O3- and P2- type layered oxides**
- **Na ions in the interlayer space**





*Pan et al, Energy Environ Sci., 2013, **6**, 2338-2360*



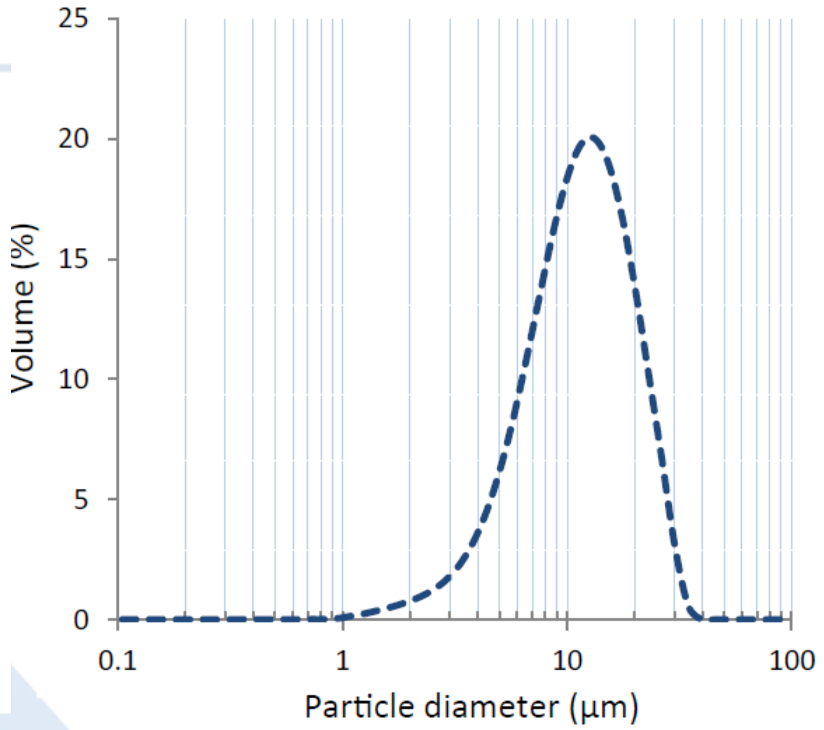


HT $Na_{1-x}Ni_{1-x-y-z}M^1_xM^2_yM^3_zO_2$

HALDOR TOPSØE

Particle size distribution

d_{10}	=	5.4 µm
d_{50}	=	11.6 µm
d_{90}	=	21.3 µm
d_{99}	<	33.4 µm



50-100 kg Cathode Batches

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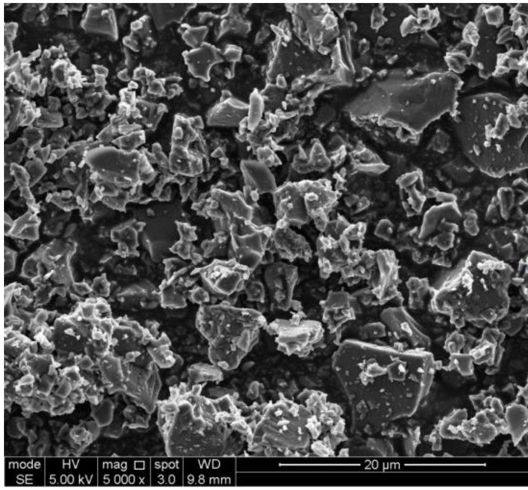
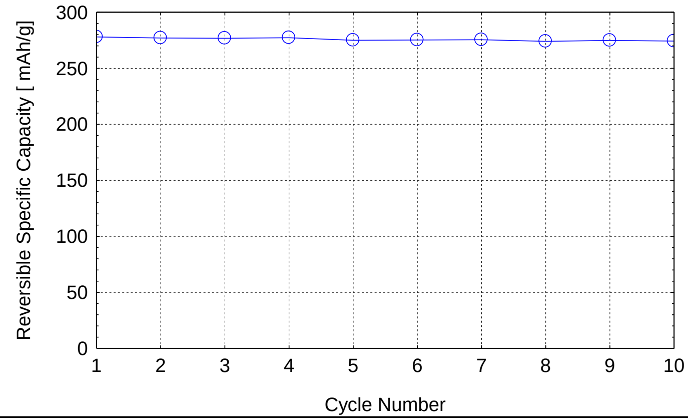
Hard Carbon: Faradion

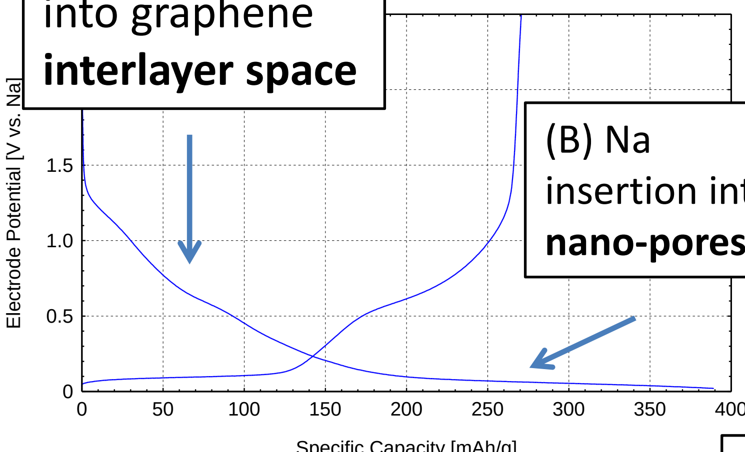


Typical particle sizes = 2-8 µm

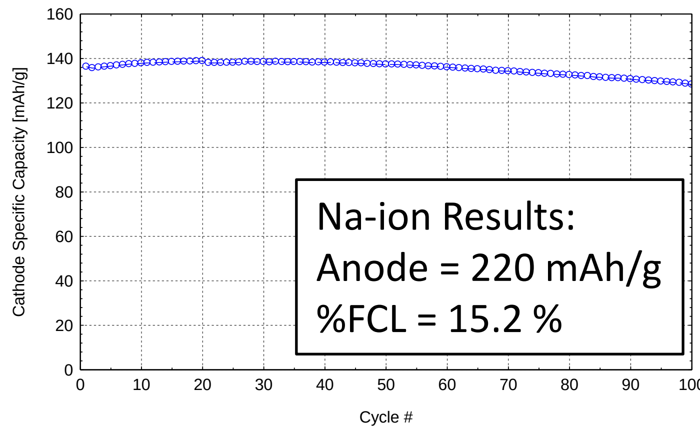


Faradion Hard Carbon vs. Na = 280 mAh/g

(A) Na insertion into graphene **interlayer space**



(B) Na insertion into **nano-pores**



Na-ion Results:
Anode = 220 mAh/g
%FCL = 15.2 %

Capacity fade = 5.9 % in 100 cycles - 0.059 %/cycle

Electrolyte

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

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Na-ion Cells: Performance

Voltage Profile: Gen#2

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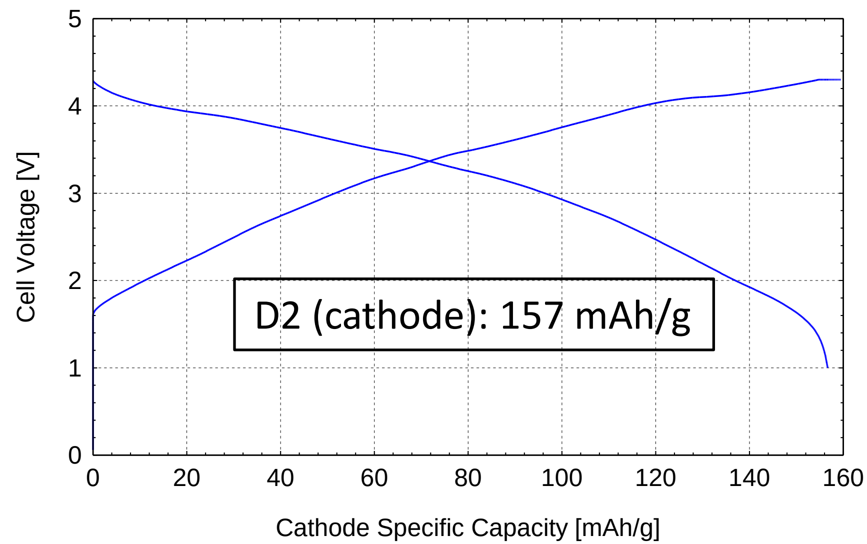
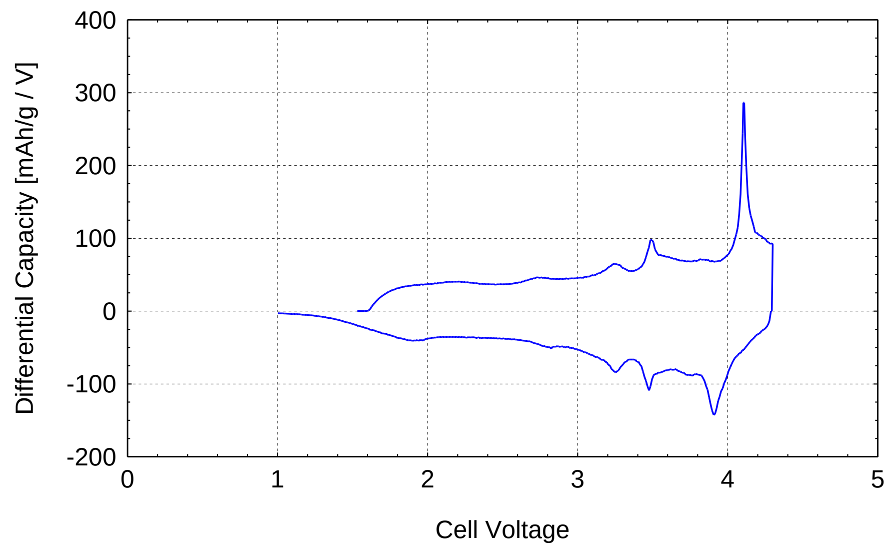
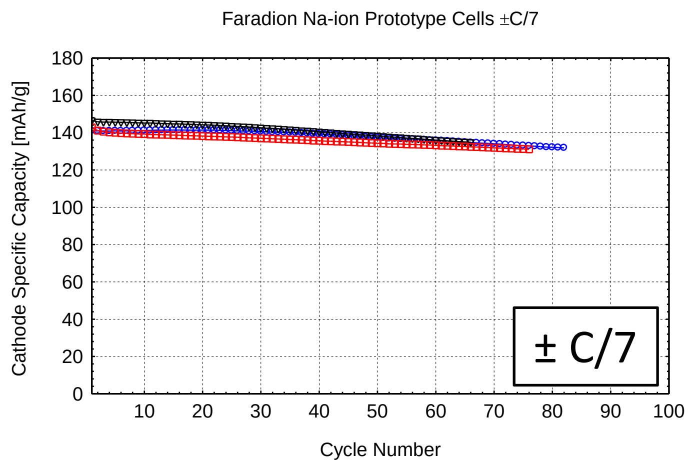
- Reversible cathode specific capacity = **157 mAh/g**
- Average discharge voltage = **3.20 V**
- Cathode specific energy = **500 Wh/kg**
- Round trip energy efficiency **> 91 %**
- Low polarization

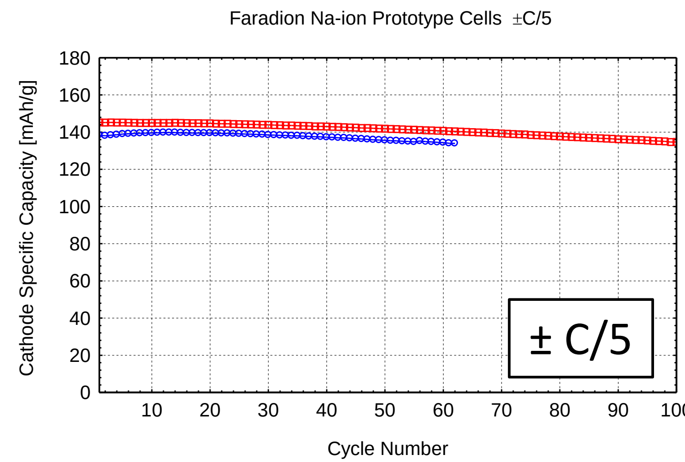


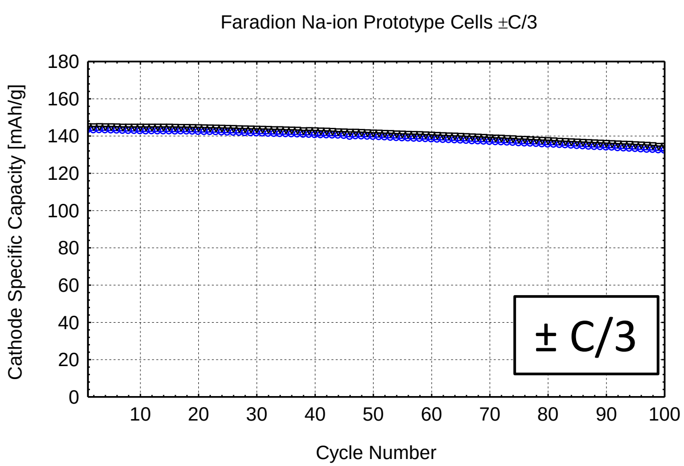


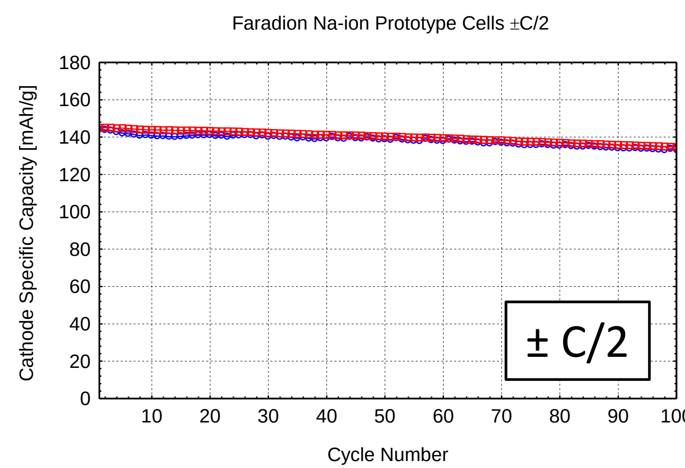
Cycle#2

Prototype Cells

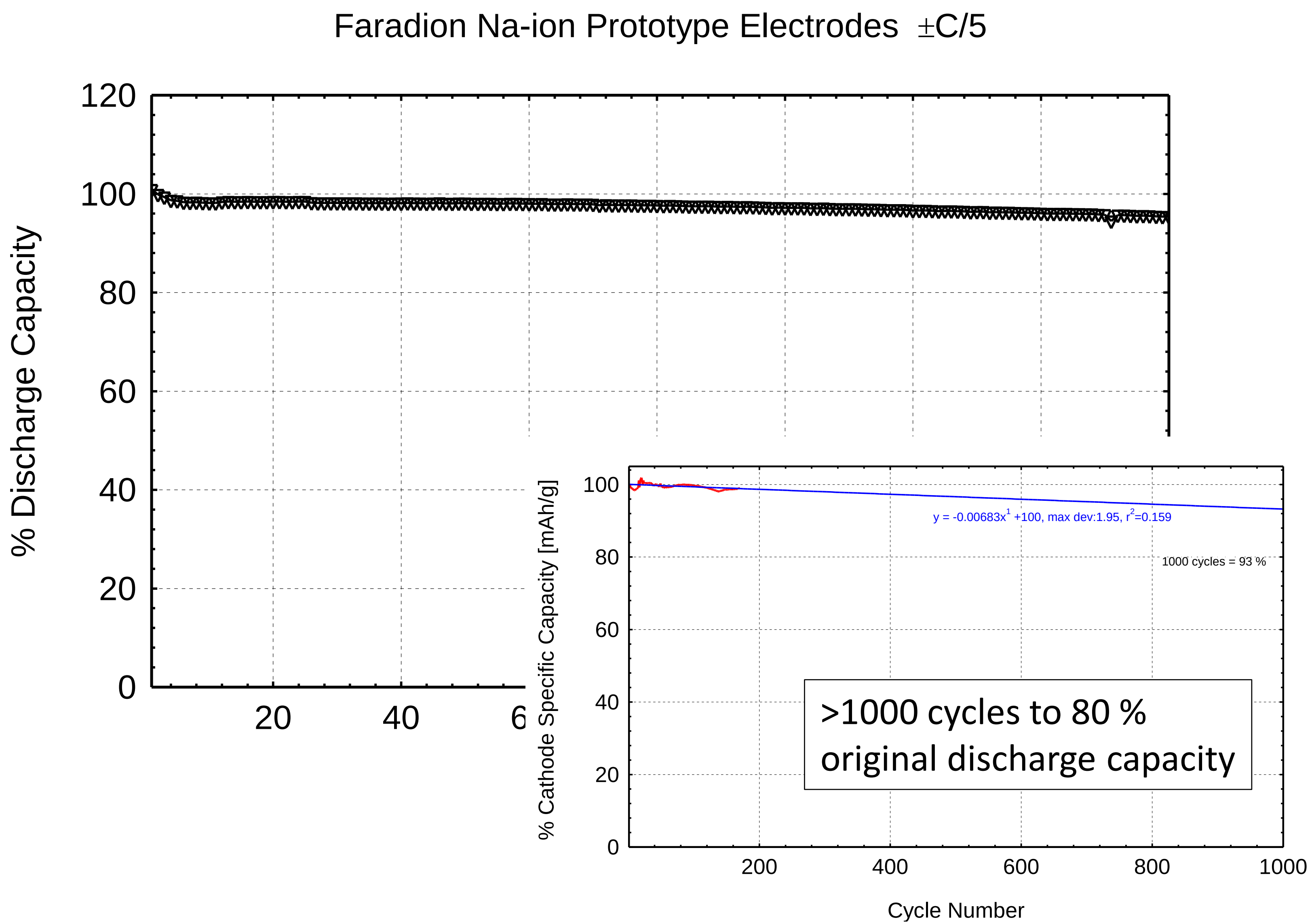




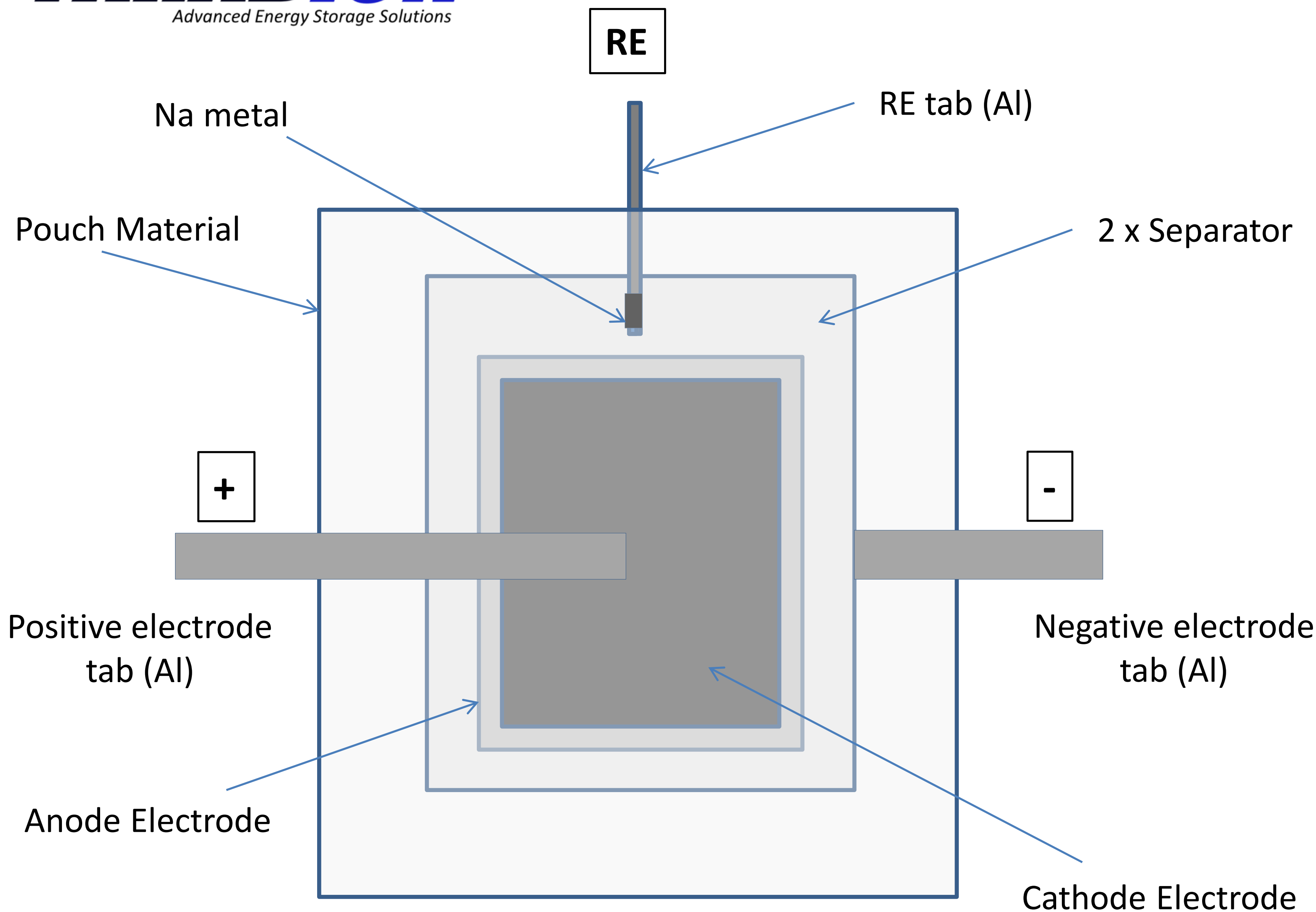




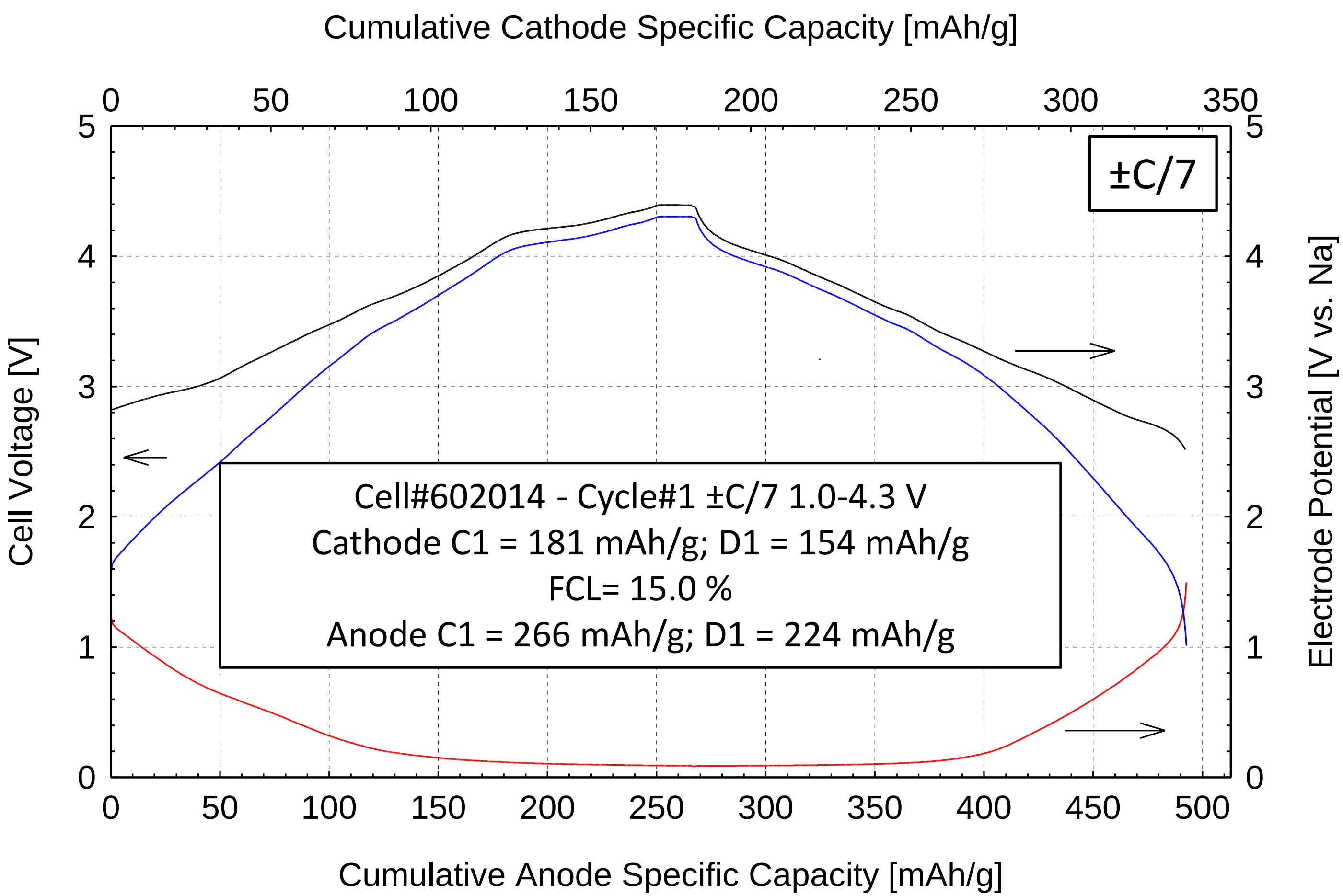
80 % DOD Cycling



3-Electrode Cell Design



Formation Cycle



✓ Very low levels of both cell and electrode polarization at this charge/discharge rate

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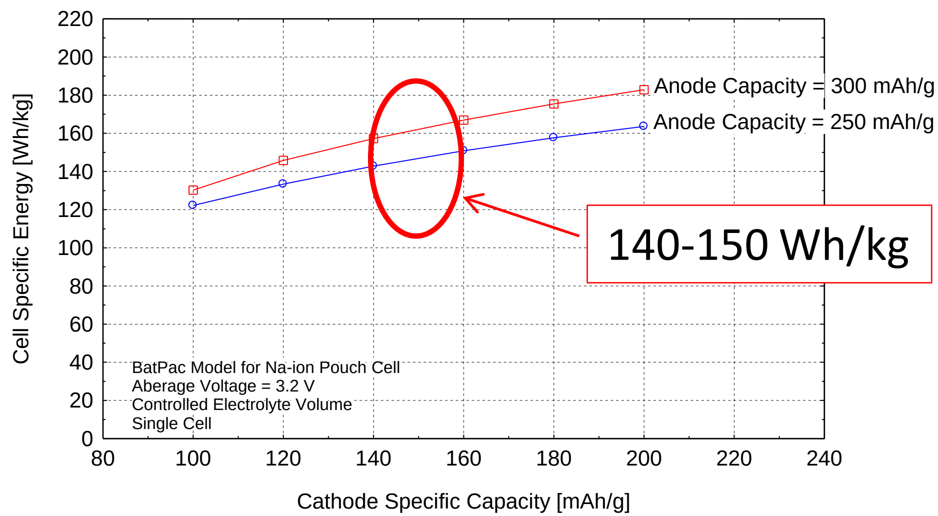
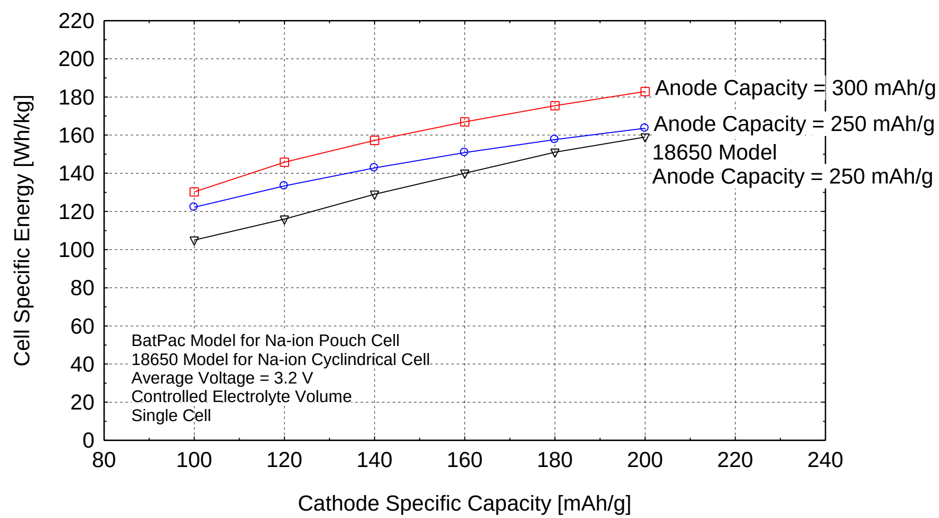
Specific Energy

Cell Specific Energy Model

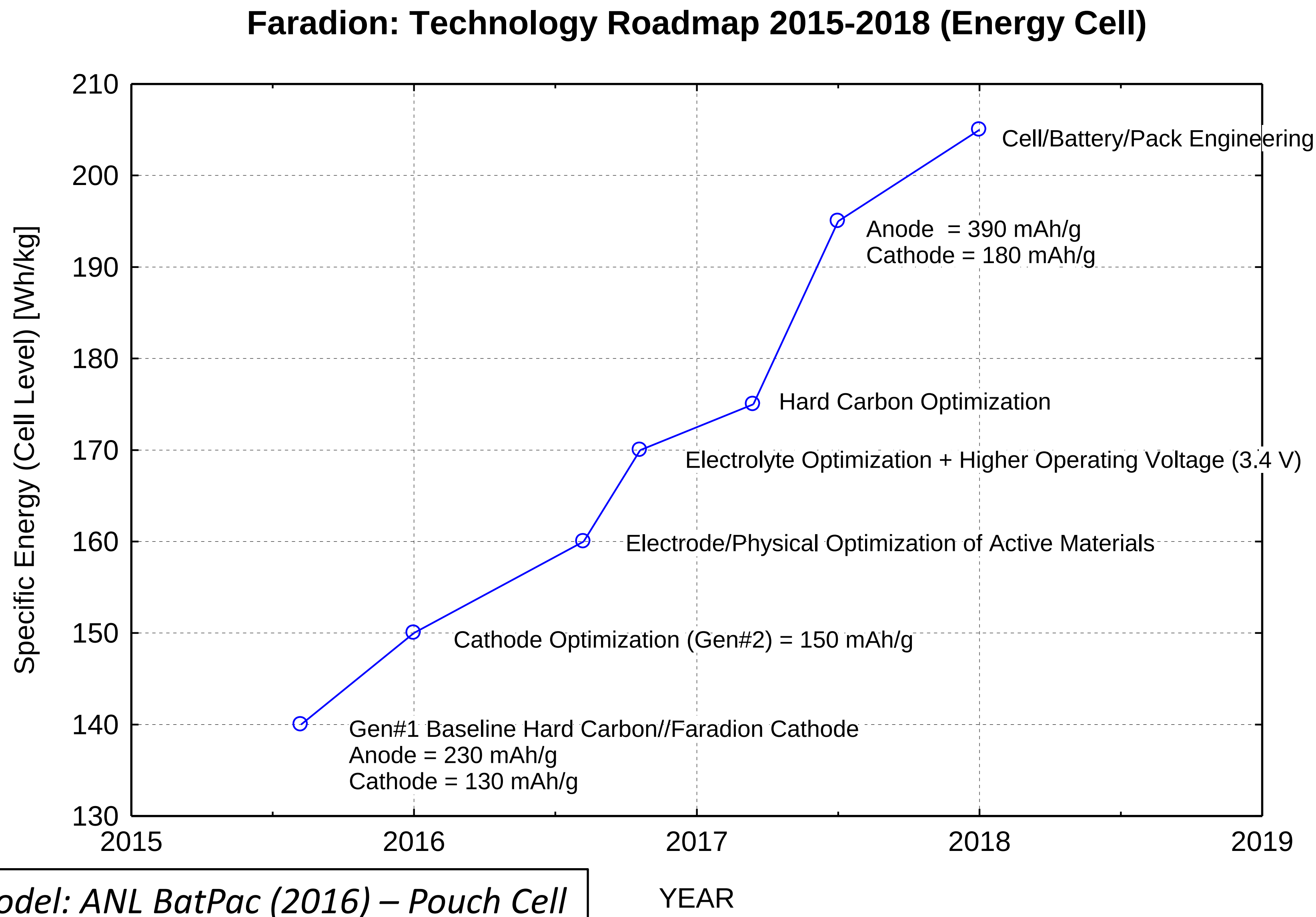
ANL BatPac Model
3.2 V Average Voltage
Pouch Cell - stacked design
Energy Design



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



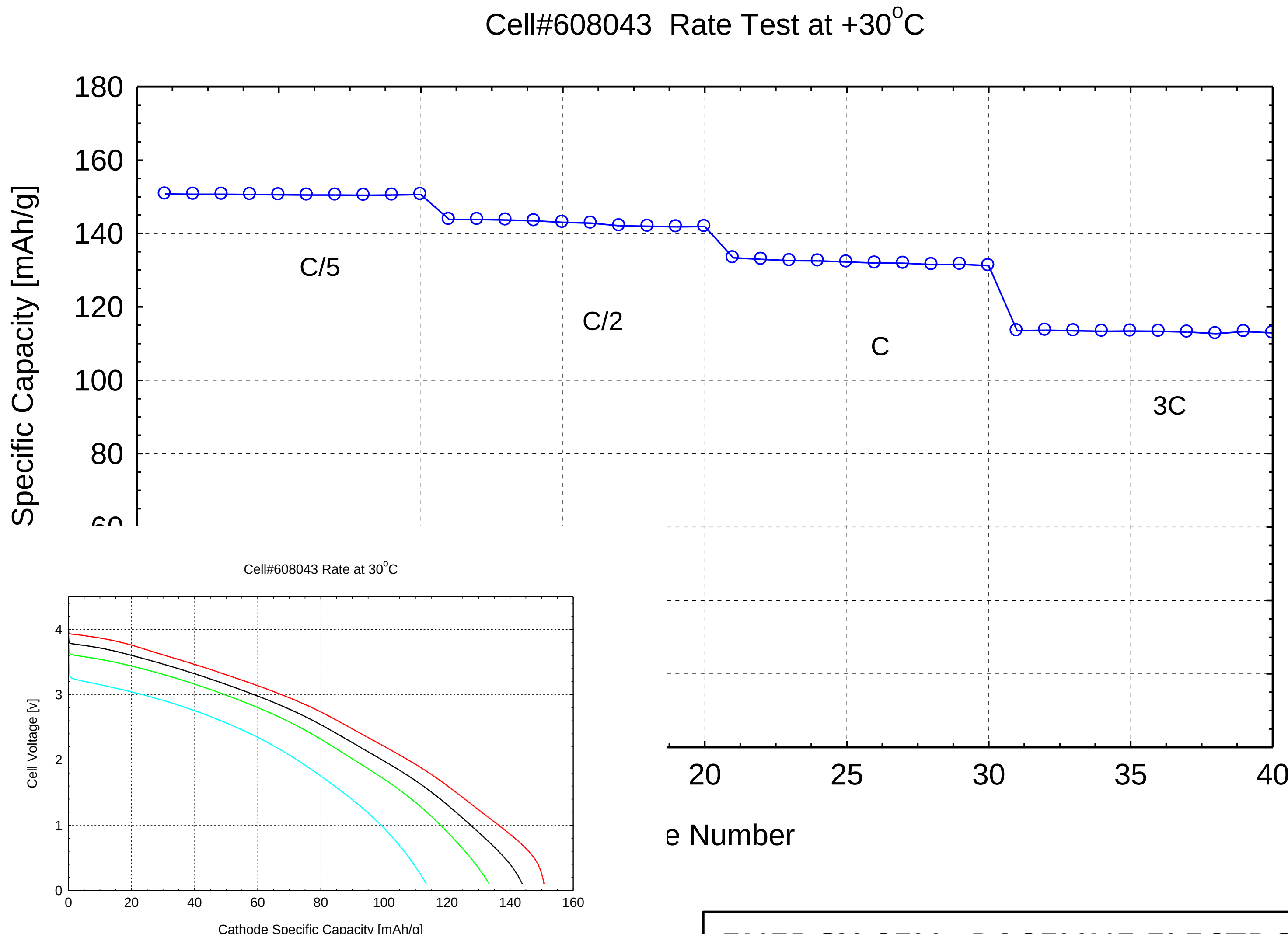
Technology Roadmap



Model: ANL BatPac (2016) – Pouch Cell

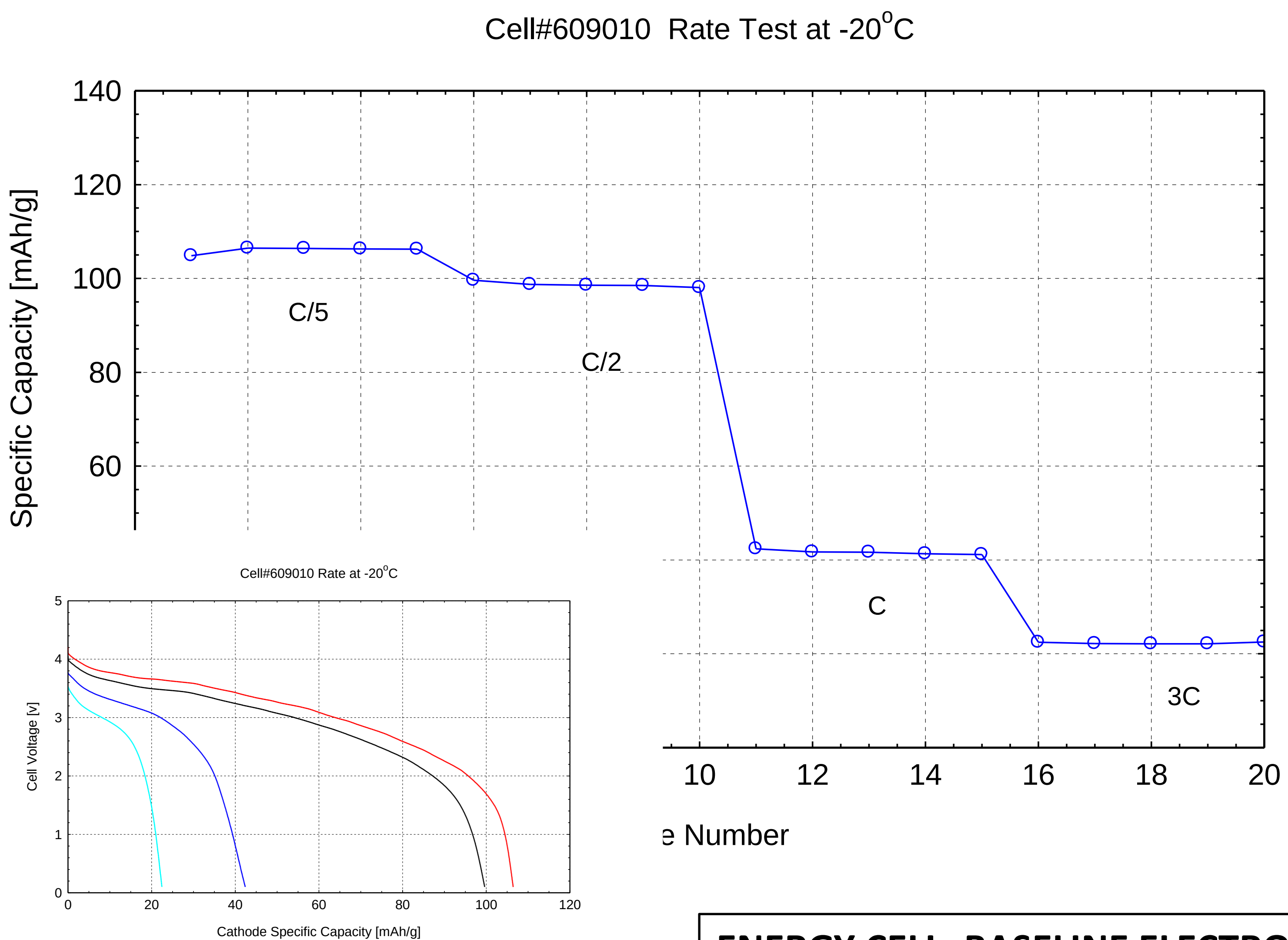
Temperature Performance

Rate Performance at +30ºC



ENERGY CELL; BASELINE ELECTROLYTE

Rate Performance at -20ºC



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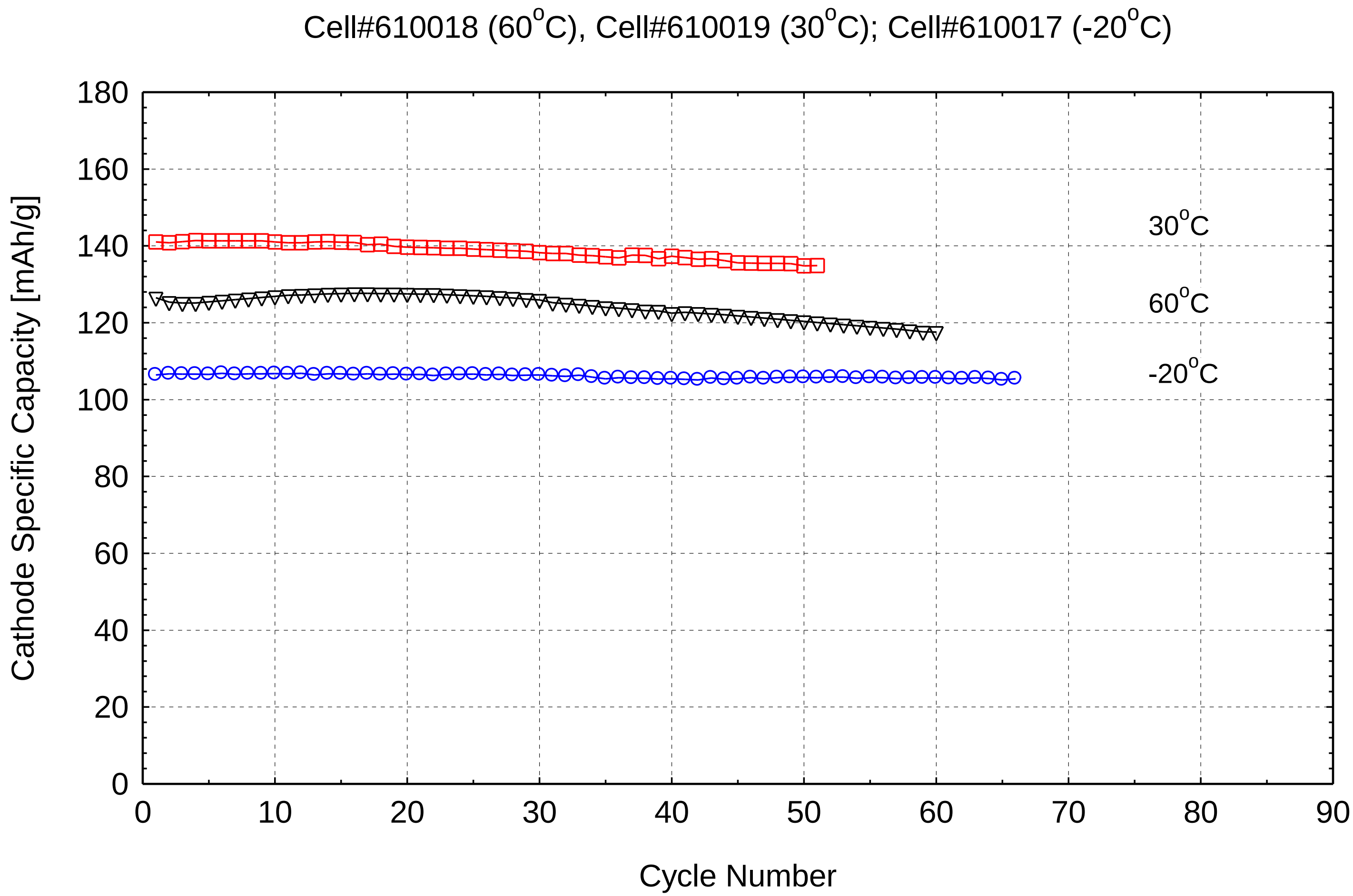
Temperature Performance



ENERGY CELL; BASELINE ELECTROLYTE

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Na-ion Cells: Safety

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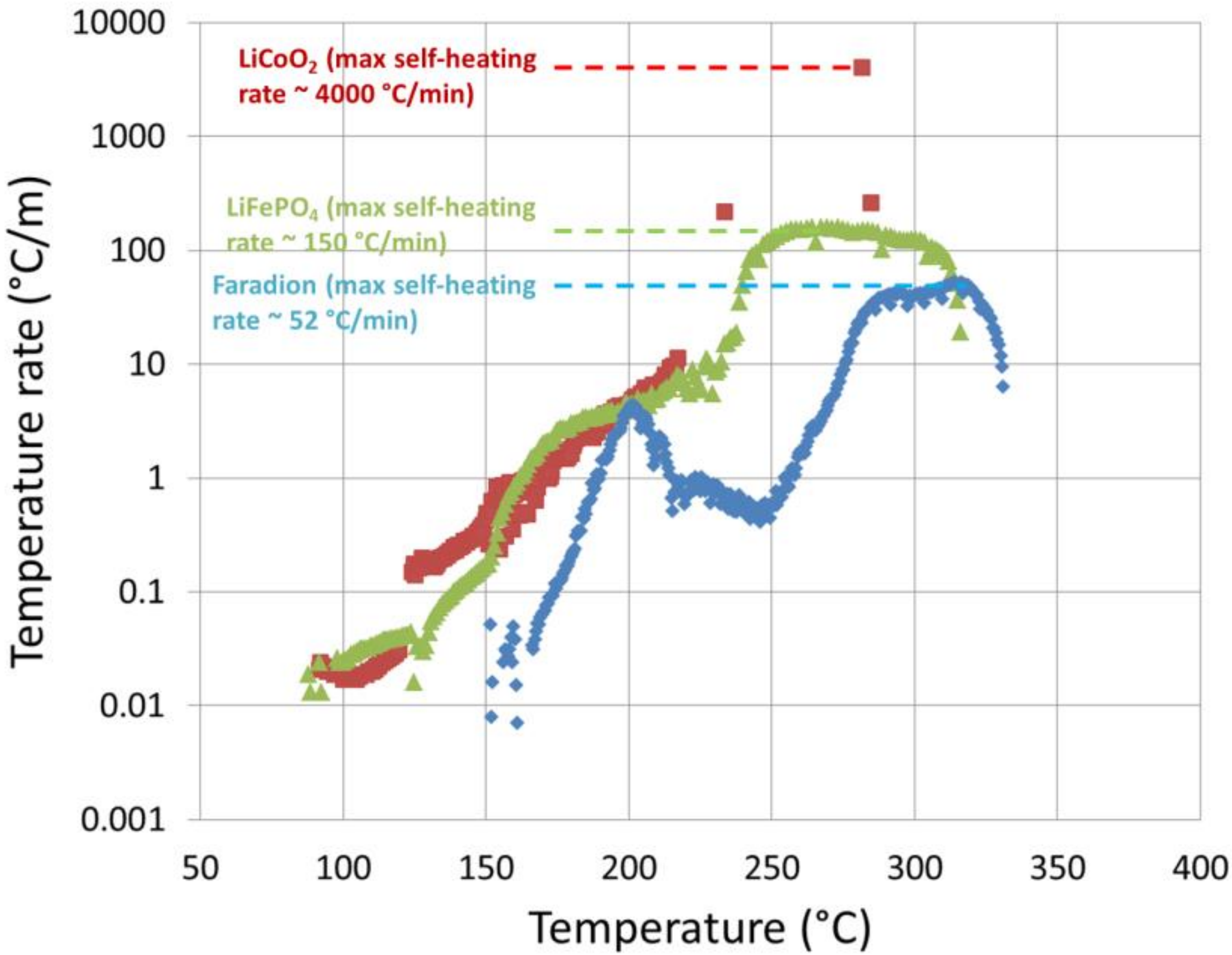
ARC: Self-heating Rate



ARC: Safety Summary

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Cell	Onset T (°C)	Max Self-Heating Rate (°C/min)
$LiCoO_2$	90	~ 4000
$LiFePO_4$	100	~ 150
Faradion	150	~ 52

- 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

Zero Energy Transportation

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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.

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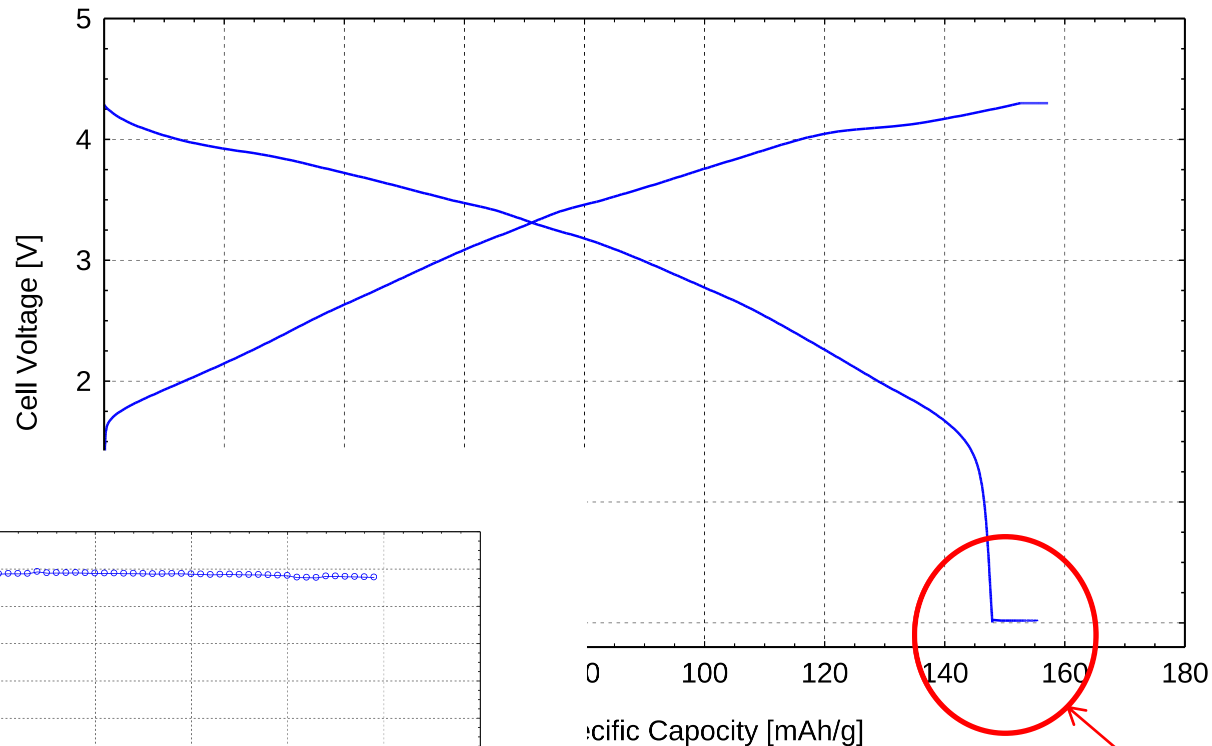
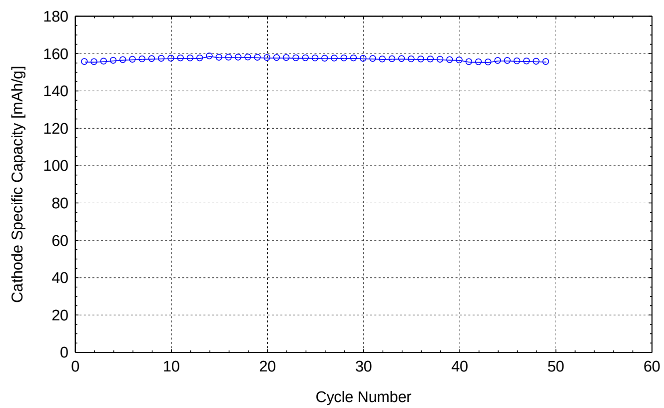
0 V Storage: 24 h





0 V Voltage Hold

Medical & Transportation Applications

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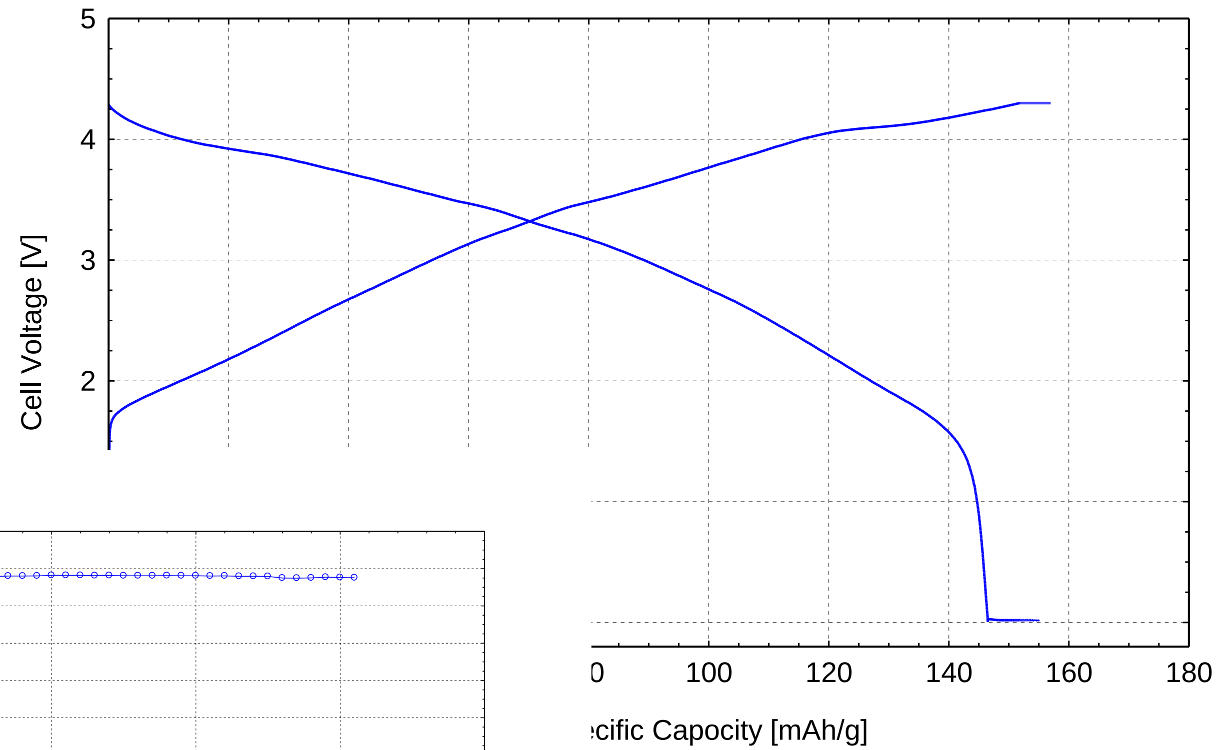
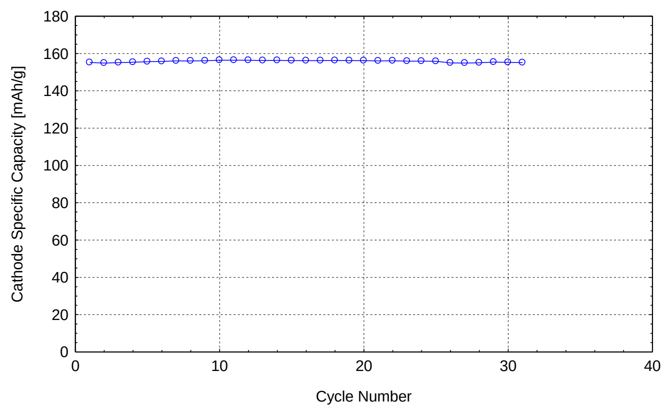
0 V Storage: 48 h





Max: 6 months at 0 V = no degradation

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Scale-up

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Prototype Facility

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.

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418 Wh E-Bike Pack

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

Summary & Conclusions

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- 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: **-20ºC to +60ºC**
- 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)