# Energy density limit of Lithium ion Batteries

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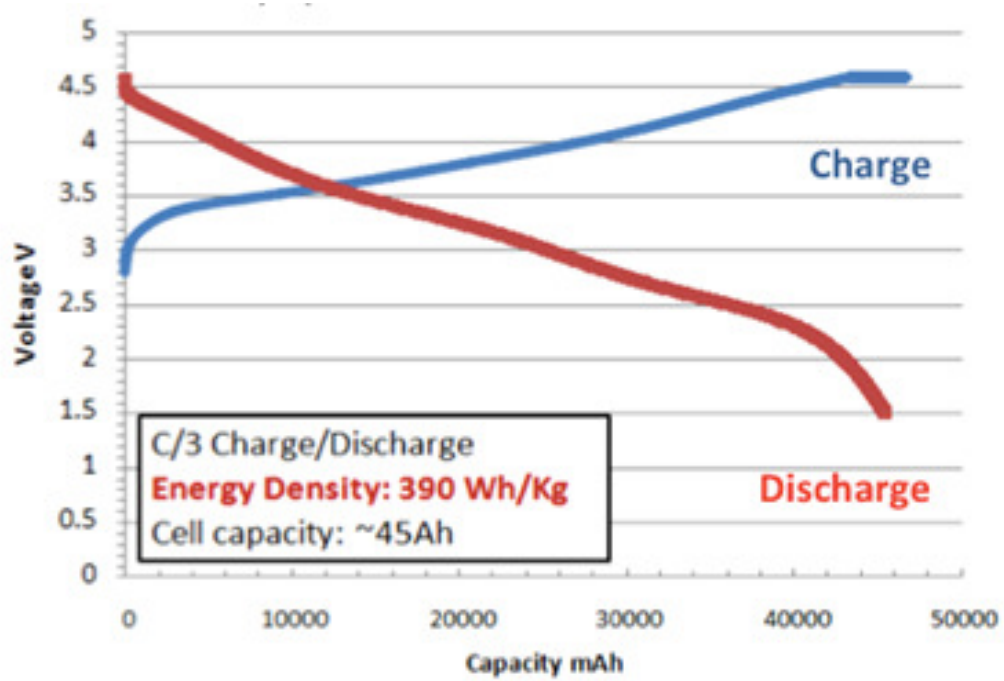
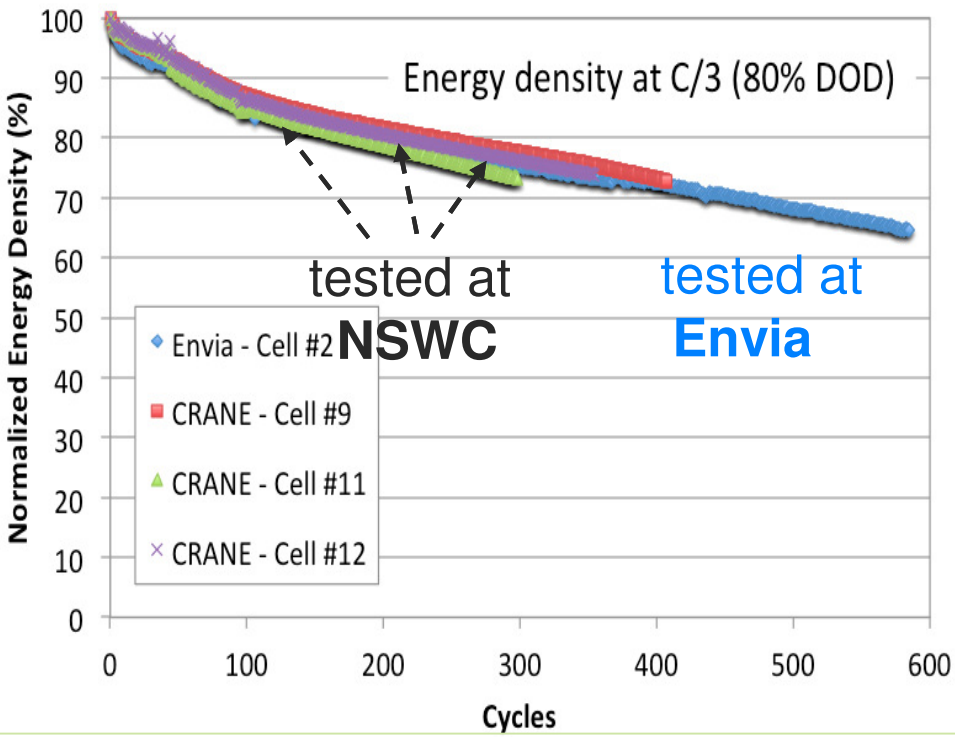
Richland, Washington

# Overview

- Founded in 2007. R & D center in Newark, CA and Cell Prototyping center in Jiaxing, China.
- High energy lithium battery technology
- Several funded joint product developments with industry leaders, with commercialization in 2017 and beyond
- Recipient of numerous DOE awards such as ARPA-E, ABR & USABC
- Multi $10B+ market coverage, including mobile devices, UAVs, and electric vehicles
- Strong IP with 23 issued patents & 20 pending applications

# Development of 400 Wh/Kg cell




45 Ah 400 Wh/Kg cell was fabricated by pairing lithium rich HCMR™ Cathode with silicon based anode.

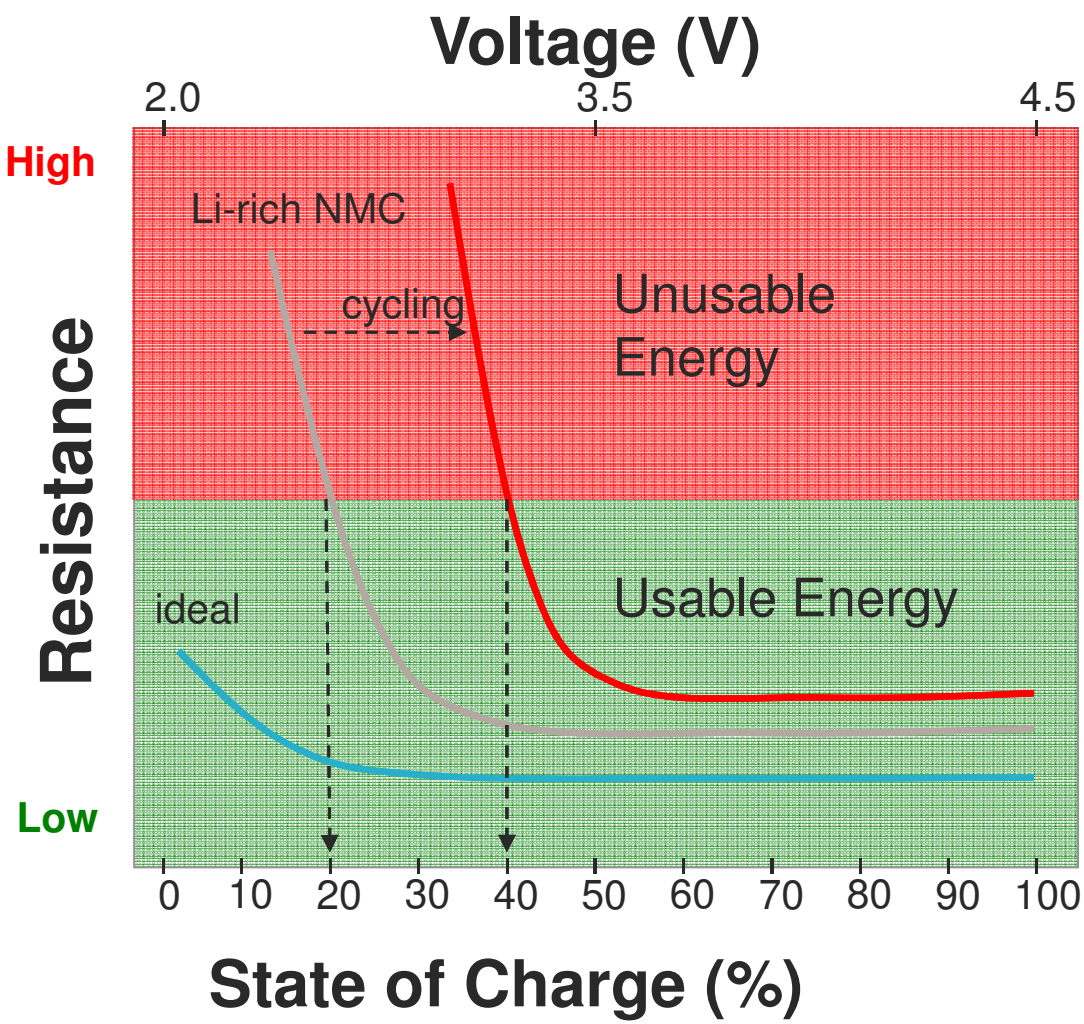
HCMR Cathode: 260 mAh/g

SiO-C Anode: 1450 mAh/g

Specific energy of 45 Ah Pouch Cell in voltage window of 4.6V-1.5V

- 430Wh/kg at C/20
- 410Wh/Kg at C/10
- 390Wh/Kg at C/3

# Productization issues for 400 Wh/Kg Cell




Encountered several challenging issues in meeting product specs:

**Voltage profile:**

Consumer devices do not accept any energy below 3.0 V. Most automotive application have 2.5V as lower cut off.

**High DC Resistance:**

Very high DC-R below 40% SOC was observed leading to poor power characteristics & low useable energy

**Voltage fade:**

Voltage fade upon repeated cycling

**Poor Cycle life:**

Severe capacity fade and DC-R growth at 100 % DOD cycling.

# Product development strategy

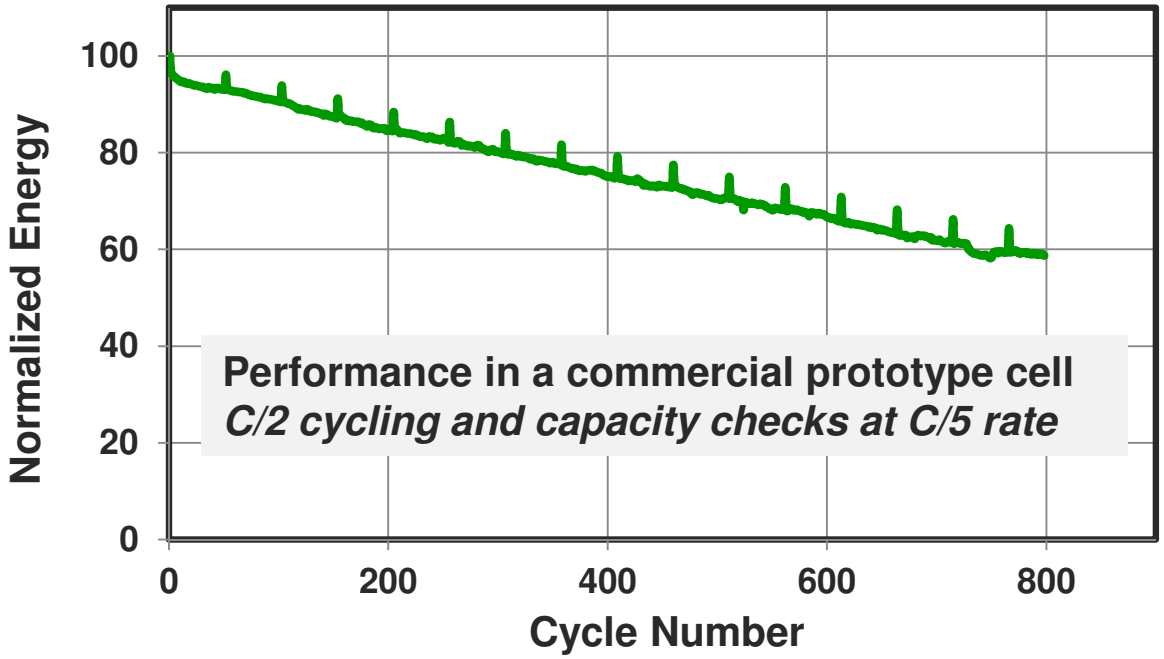
- Commercialization of Envia's proprietary Silicon Anode paired with a commercial cathode
  - Remove complications from introducing two new chemistry at the same time
  - Avoid operations at high voltages
  - First Product: Paired with 4.35V LCO cathode for a consumer battery
- Development of Cobalt Rich Composite or CRC cathode:
  - High voltage operation at 4.45V with no voltage fade upon cycling
  - High active content and high electrode density
  - High conductivity & low DC-Resistance
- Improvement of HCMR cathode
  - Blend approach to lower DC-R & improve electrode density
  - Limit voltage window to avoid voltage fade and DC-R growth
  - Capacity ~200 mAh/g

# Commercialization of Silicon Anode

# Silicon based Anode

- Developed Silicon based anode achieving reversible capacity of 1450 mAh/gm and 400 cycles at 80 % capacity retention.
- Current Industry standard is graphite based anode having reversible capacity of 350 mAh/gm. Silicon anodes are not used today due to poor cycling and swelling.

- Envia uses commercial silicon based anode raw material and several proprietary electrode processing techniques to improve cycle life and swelling.

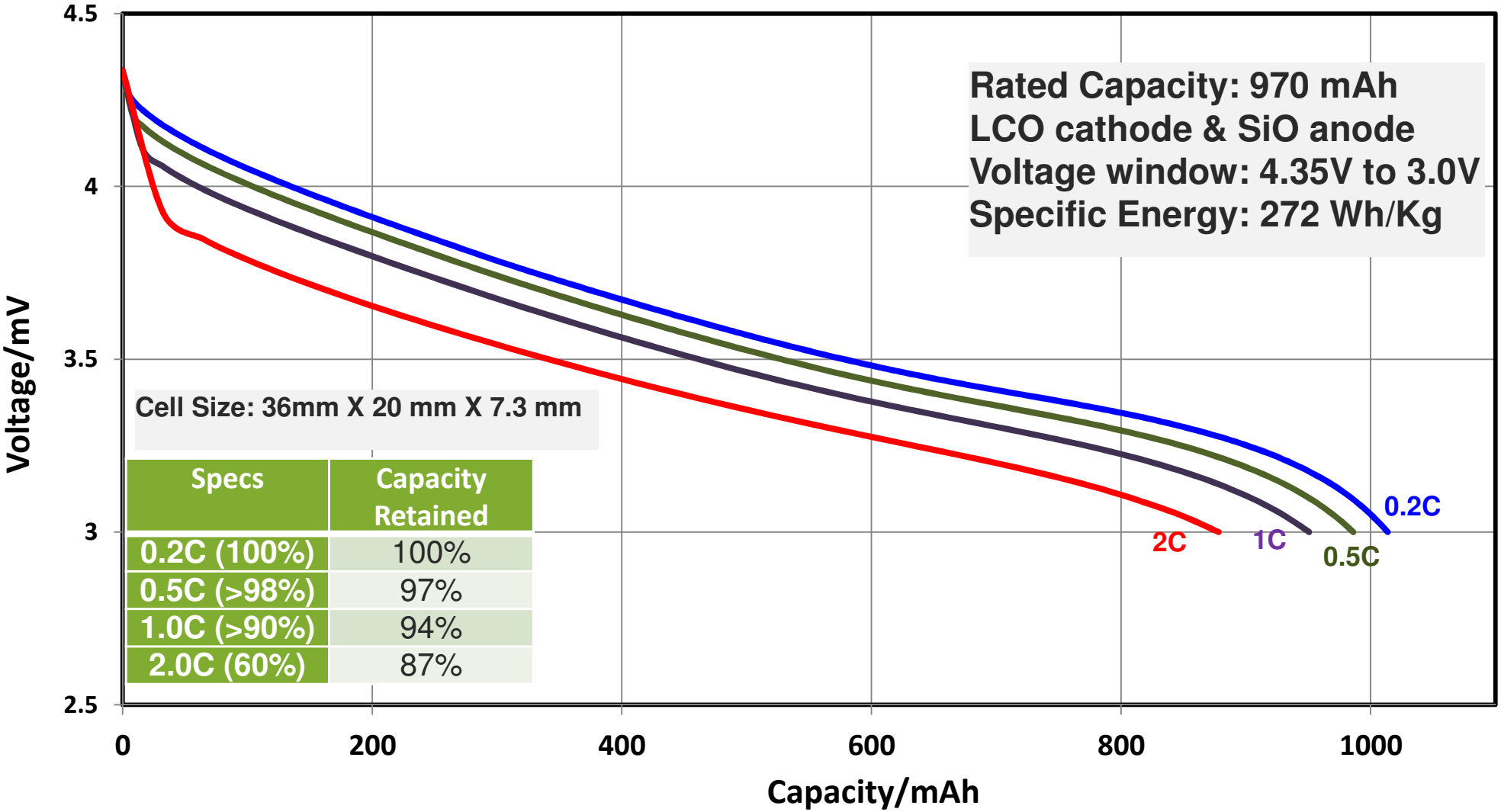


# 970 mAh cell with Silicon Anode for Wearables

- Developed a 970 mAh cell for wearable device in a customer funded program.
- 24% improvement in capacity by replacing Graphite with proprietary SiO anode while keeping other components same.
  - State of Art: 780 mAh using 4.35 LCO cathode & Graphite anode.
  - Envia: 970 mAh using 4.35V LCO & SiO anode (SiO content >80 %)
- Status: Completed pre-production trials. Applying technology to a 3Ah smartphone battery for market introduction in 2017

**Cell Size: 36mm X 20 mm X 7.3 mm**

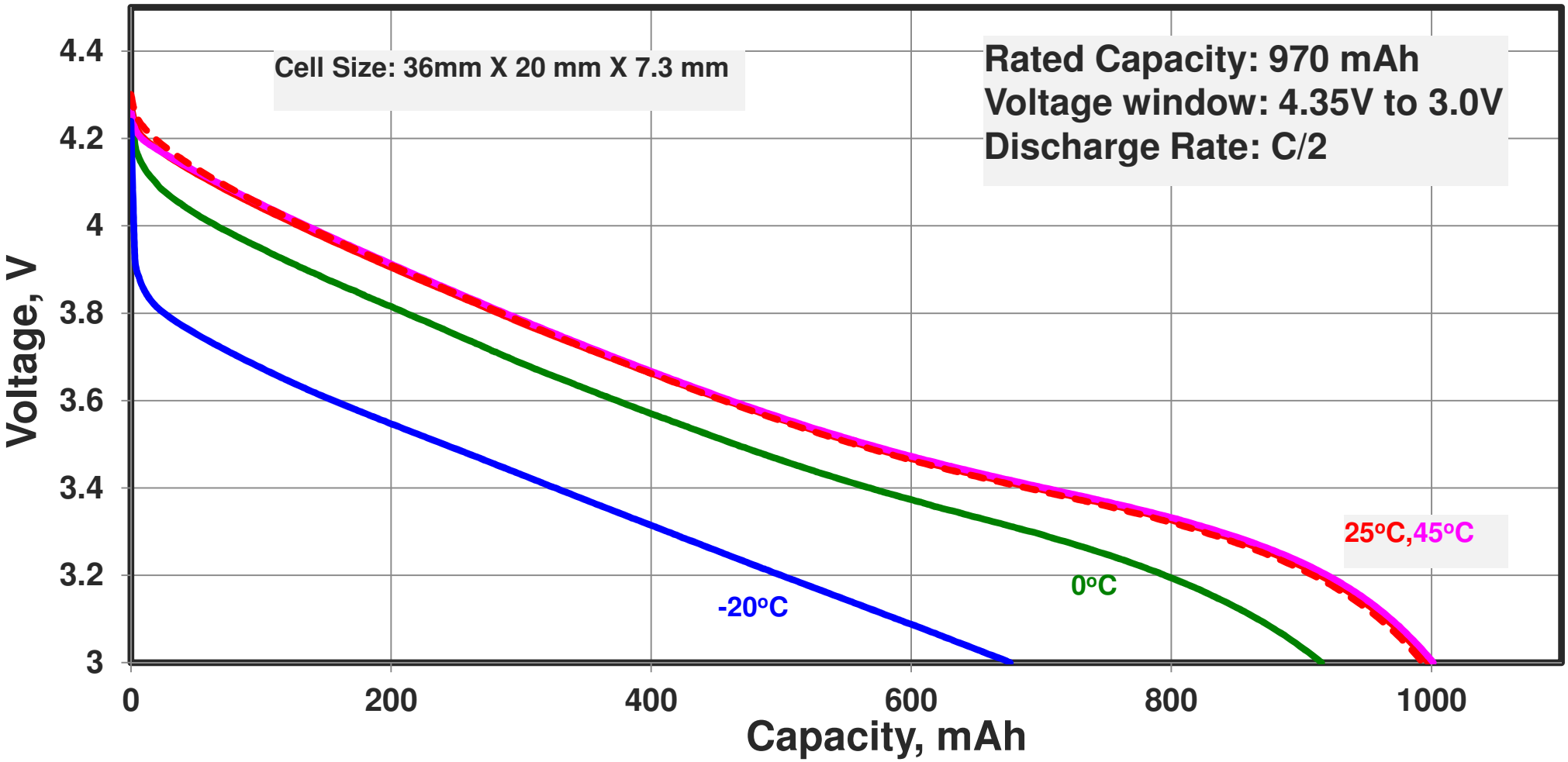
# 970 mAh cell: Discharge rate capability



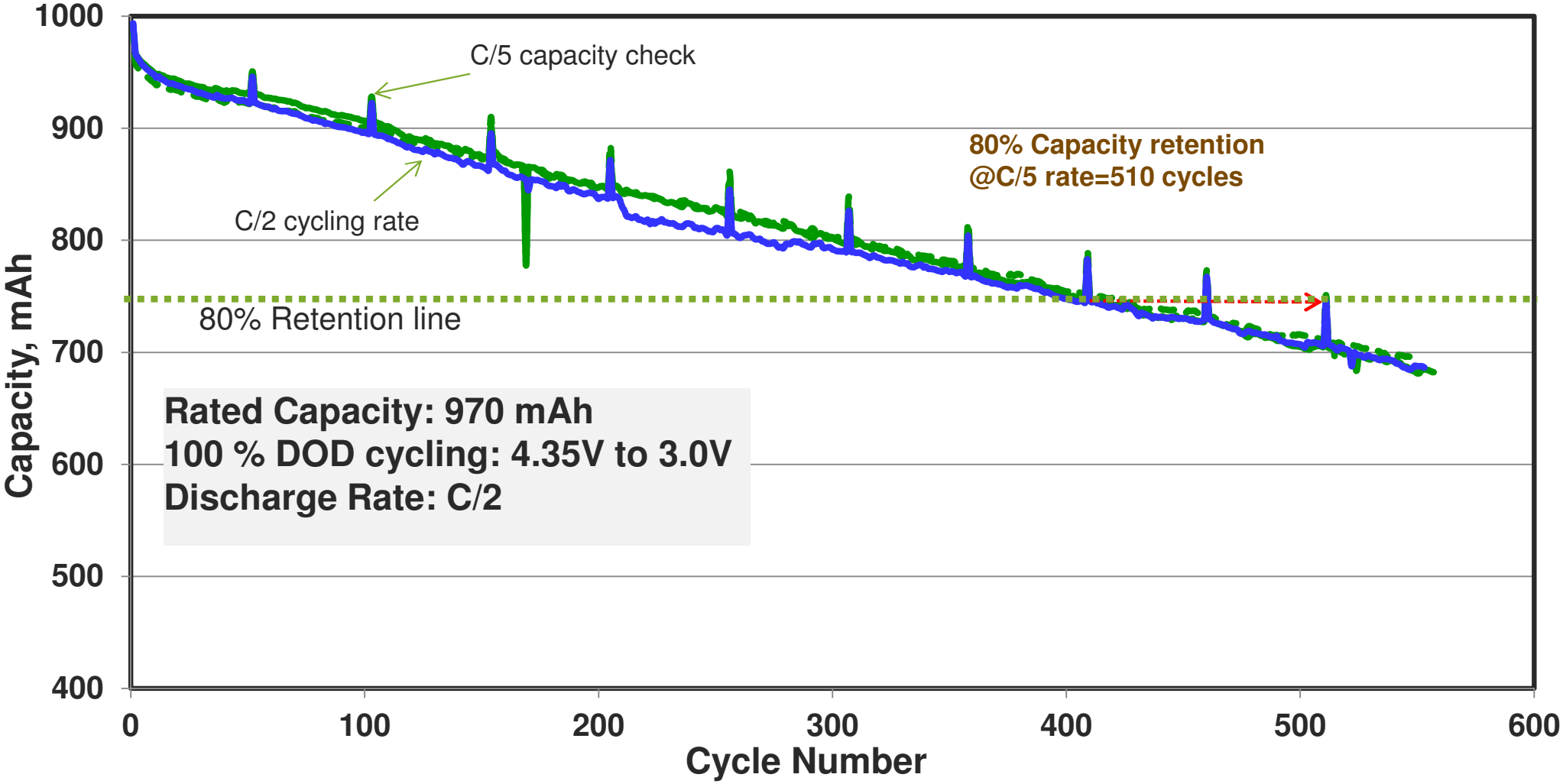

| Specs | Capacity Retained |
|---|---|
| 0.2C (100%) | 100% |
| 0.5C (>98%) | 97% |
| 1.0C (>90%) | 94% |
| 2.0C (60%) | 87% |

- Over 85% capacity retention at high discharge rate of 2C current

# Discharge Curve at various Temperatures

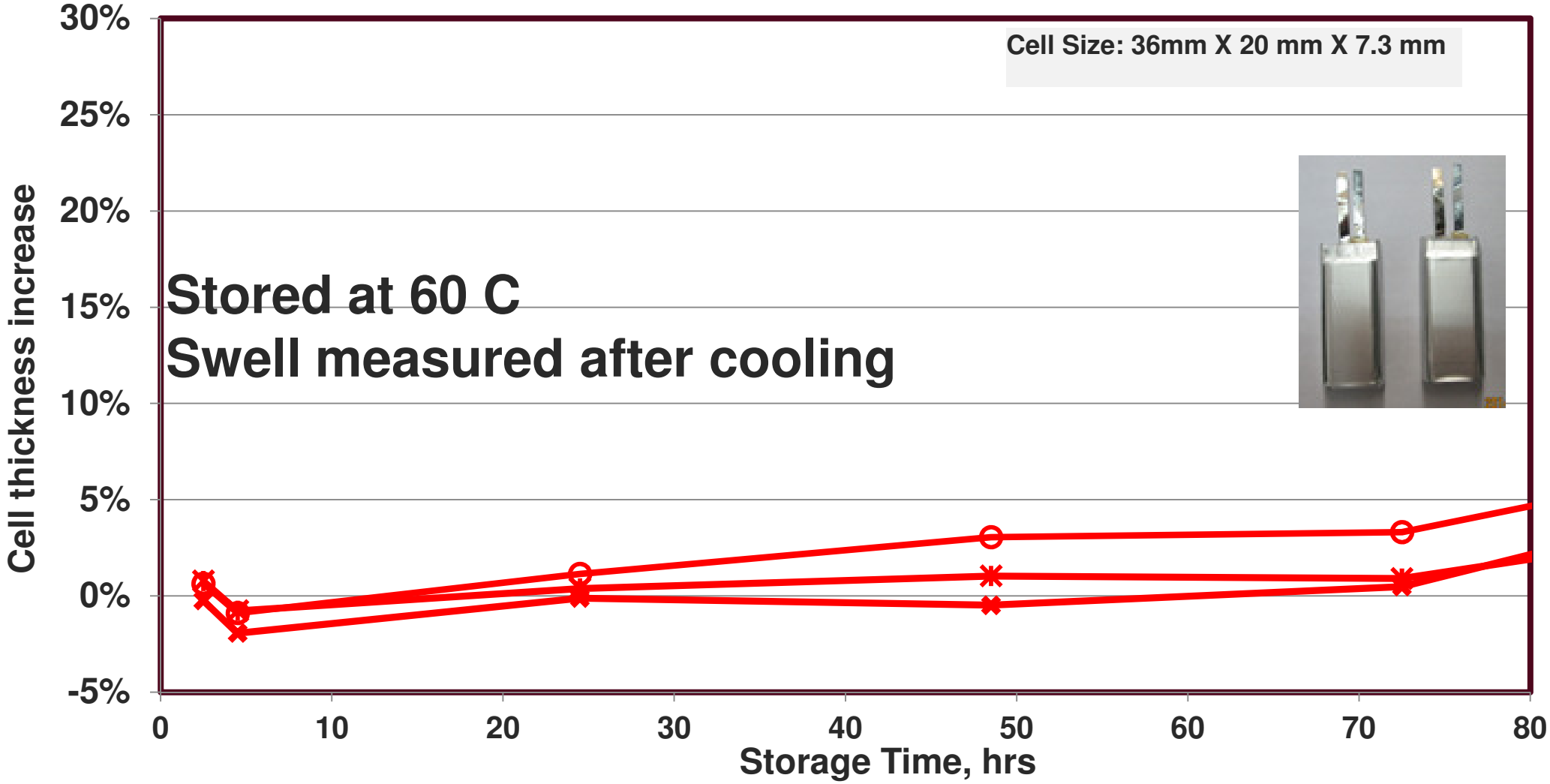


# 970 mAh Cell: Cycle Life



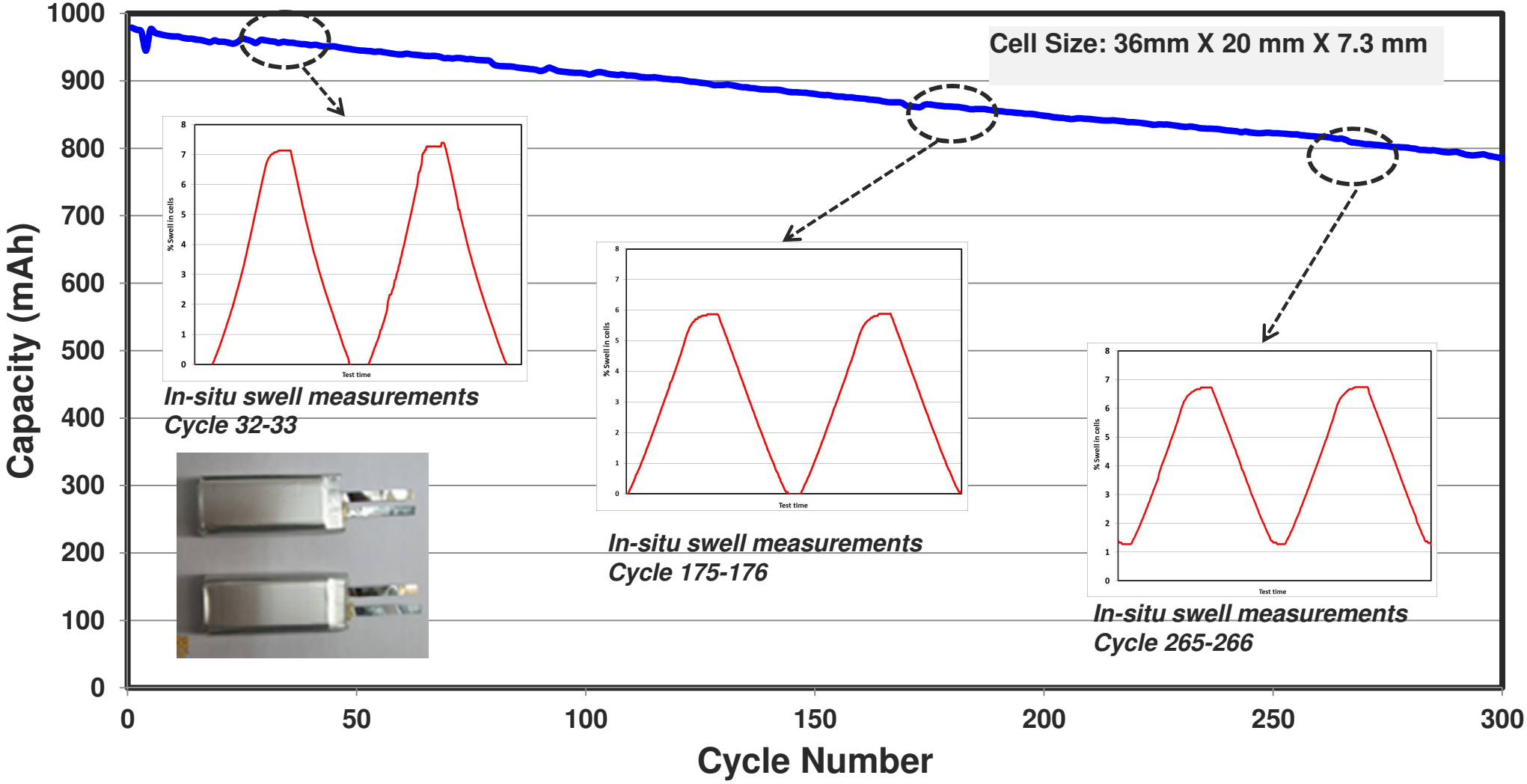

Cells are cycled at C/2 rate. Capacity check at C/5 rate.
Cycle life is projected to be 500 at C/5 rate retaining 80 % capacity

# High Temperature Swell Test




Swell characteristics of the cell have been reduced to <8%

# 970 mAh Cells: Cycling Swell Test




**Swelling of the cells is being continuously monitored as a function of cycling. Cell thickness is less than <8% meeting specs.**

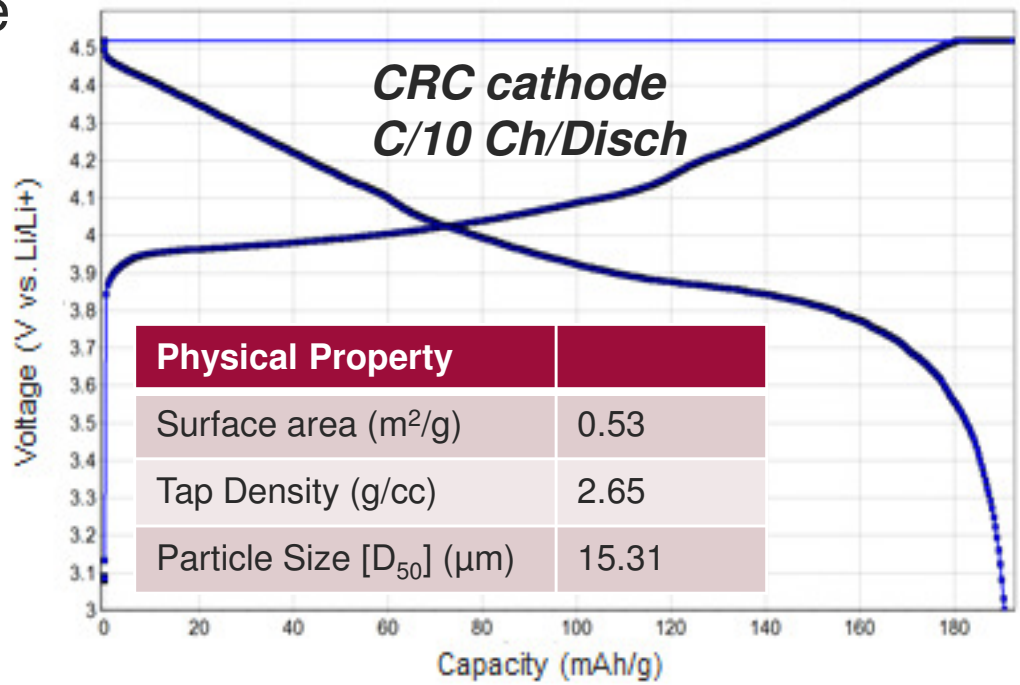
# Development of Cathode

# CRC Cathode for Consumer Batteries

CRC cathode is Cobalt rich composite with significant amounts of Ni & Mn.

**Key benefits:**

- Higher voltages of 4.45V for higher capacity
- No Voltage fade upon cycling
- High active content >97%
- High electrode density > 4.0 g/cc




| Physical Property | |
|---|---|
| Surface area ($m^2/g$) | 0.53 |
| Tap Density (g/cc) | 2.65 |
| Particle Size [$D_{50}$] (µm) | 15.31 |

***Half Cell Data:***

| Chemistry vs. *Li metal anode* | *Voltage Window (V)* | Capacity @ C/5 (mAh/g) | Active (%) | Electrode Density (g/cc) | Average Voltage (V) | Energy Density (Wh/l) |
|---|---|---|---|---|---|---|
| **NCA** | **2.75 ~ 4.3** | 187 | 96.0 | 3.46 | 3.82 | 2372 |
| **CRC** | **3.0~4.52** | 196 | 97.7 | 4.10 | 4.02 | 3156 |

Energy Density (Wh/l)= Capacity X Active % X Electrode density X Avg V



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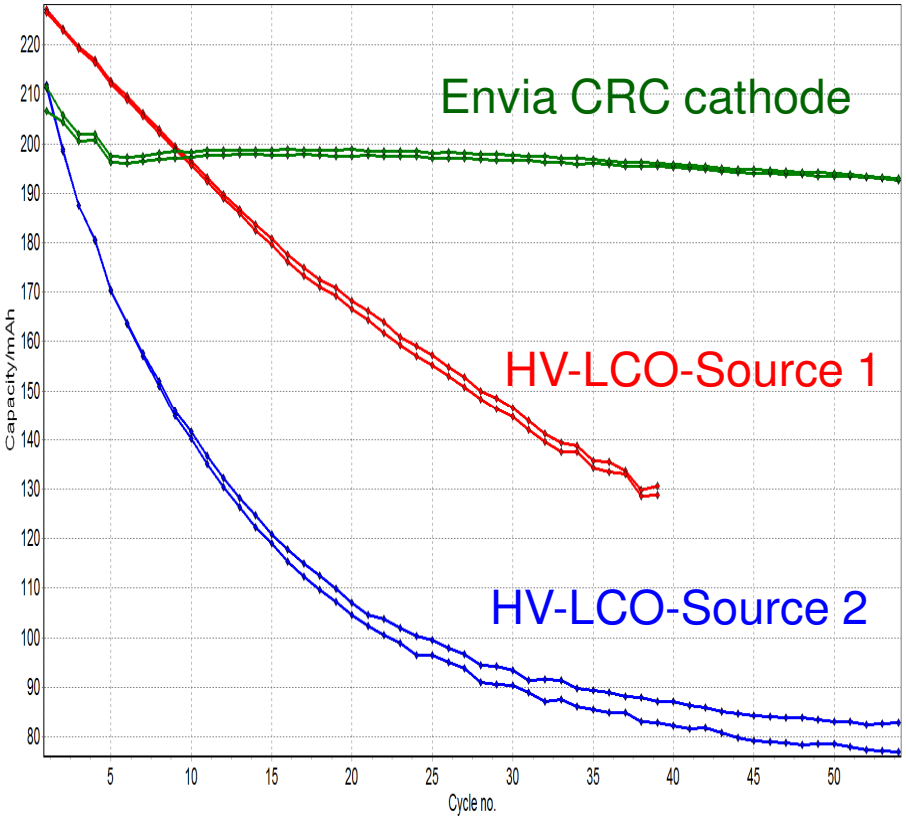
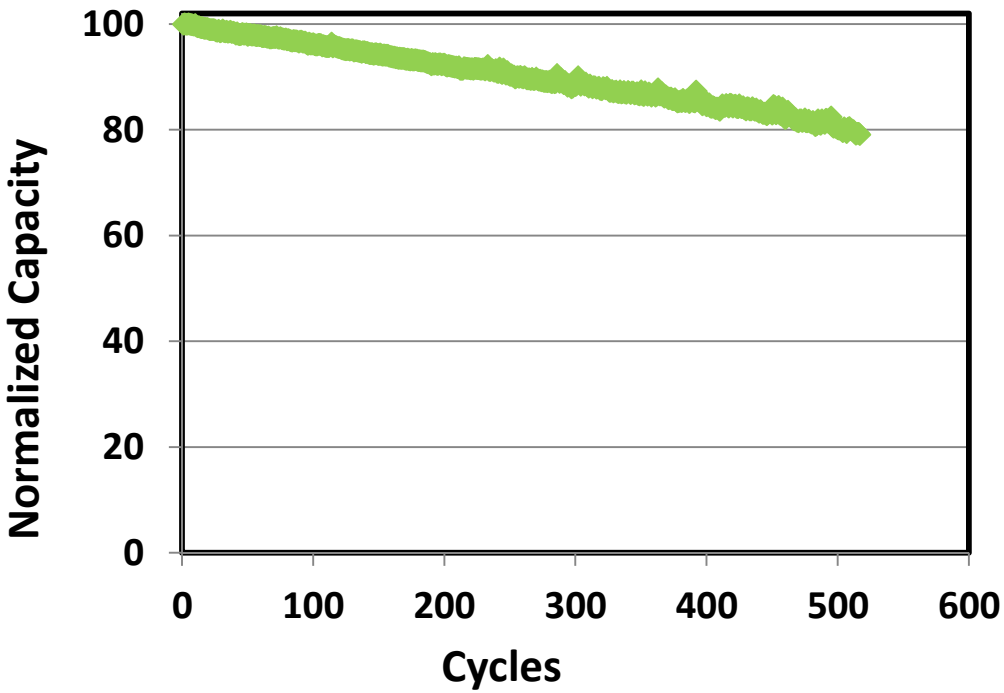
# CRC Cathode: Cycling Performance

***Half Cell*** **80% Active Vs Li**
**Test Voltage : 3- 4.6 V, C/5- C/3 cycling**

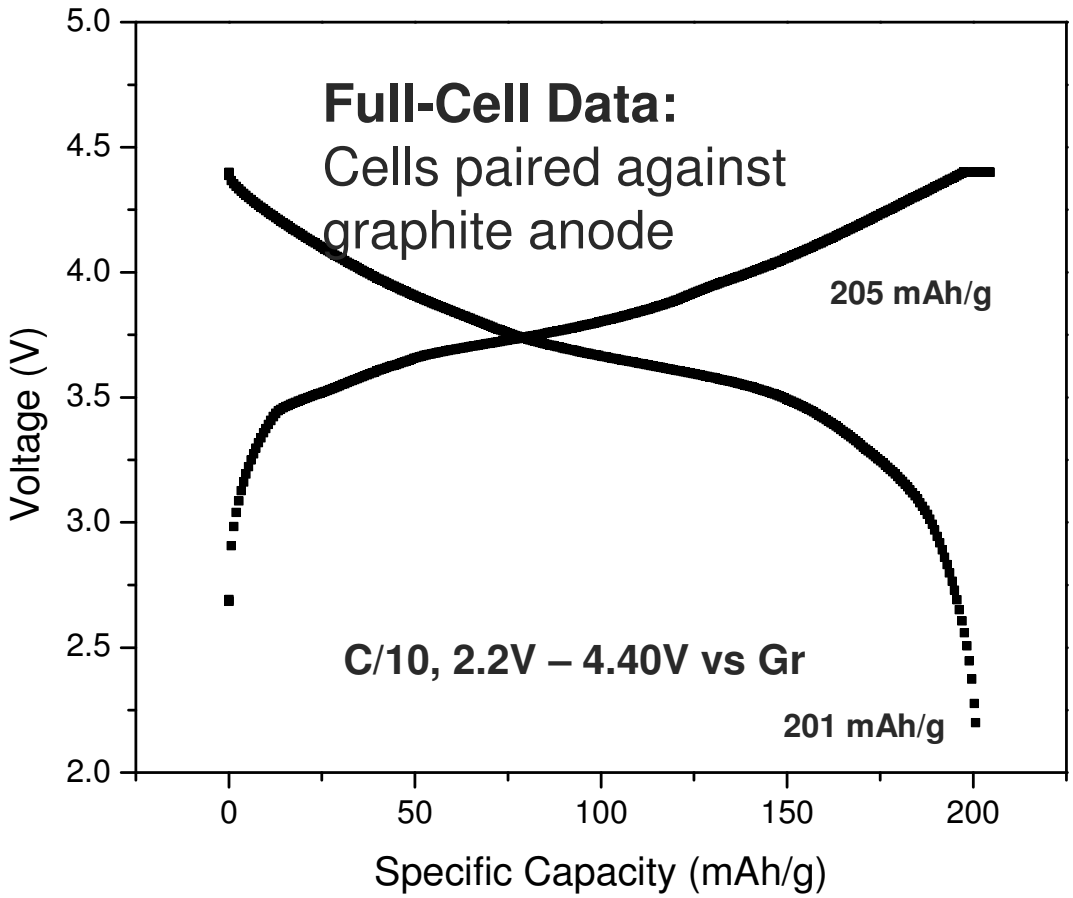


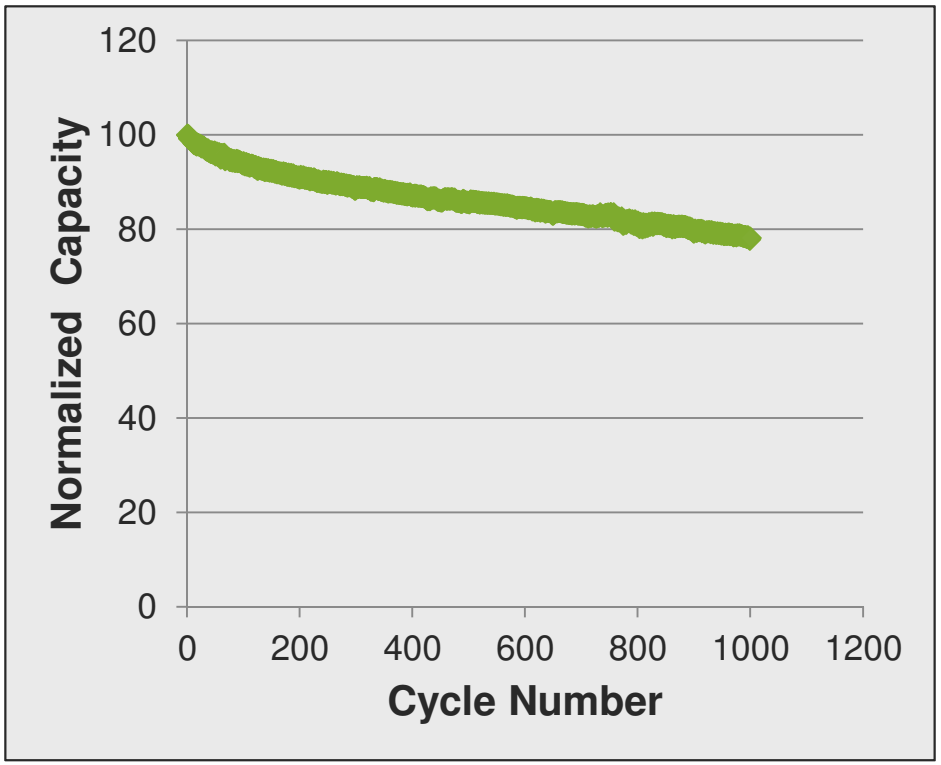

***Full Cell*** **92% active Vs Graphite**
**Test Voltage : 3- 4.47 V, C/3- C/3 cycling**




- In Full cells, CRC cathodes show ~ 500 cycles to 80% cycling efficiency when cycled between 4.47V-3.0 V.

# HCMR™-XE : Discharge capacity in Full cell




| Voltage Window | C/10 (mAh/g) | C/5 (mAh/g) | C/3 (mAh/g) | C/2 (mAh/g) | C/2 Avg. V (V) |
|---|---|---|---|---|---|
| **2.2-4.4VV** | 201 | 197 | 194 | 191 | 3.584 |
| **2.2-4.35V** | 196 | 192 | 189 | 185 | 3.576 |

# Blended Cathode for Automotive

| HCMR Cathode | CRC Cathode |
|---|---|
| High Capacity | High Capacity |
| Better safety | Poor safety |
| Low Cost | High Cost |
| High DC-R | Low DC-R |
| Poor Electrode density | High Electrode density |
| Voltage Fade | No Voltage Fade |

Blended Cathode with combined benefits

- Co-rich composite (CRC) cathode can enable 350 Wh/Kg with good voltage profile when paired with Si anode. Blending with HCMR™ can reduce cost and improve safety
- Blended cathodes can enable high specific energy and higher capacity cells >40 Ah while meeting safety requirements



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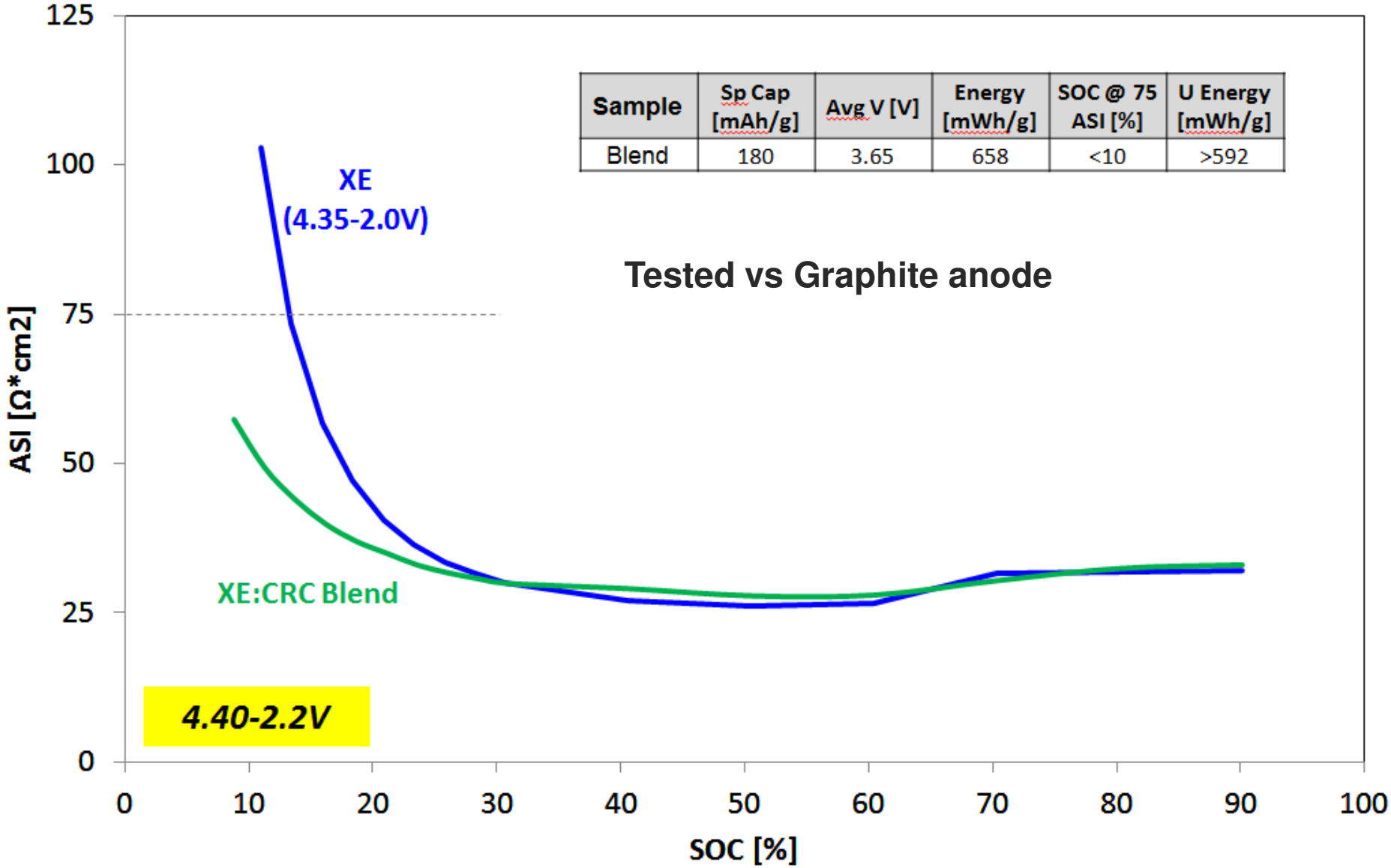
# HCMR™ XE & CRC Cathode Blend: DC-R

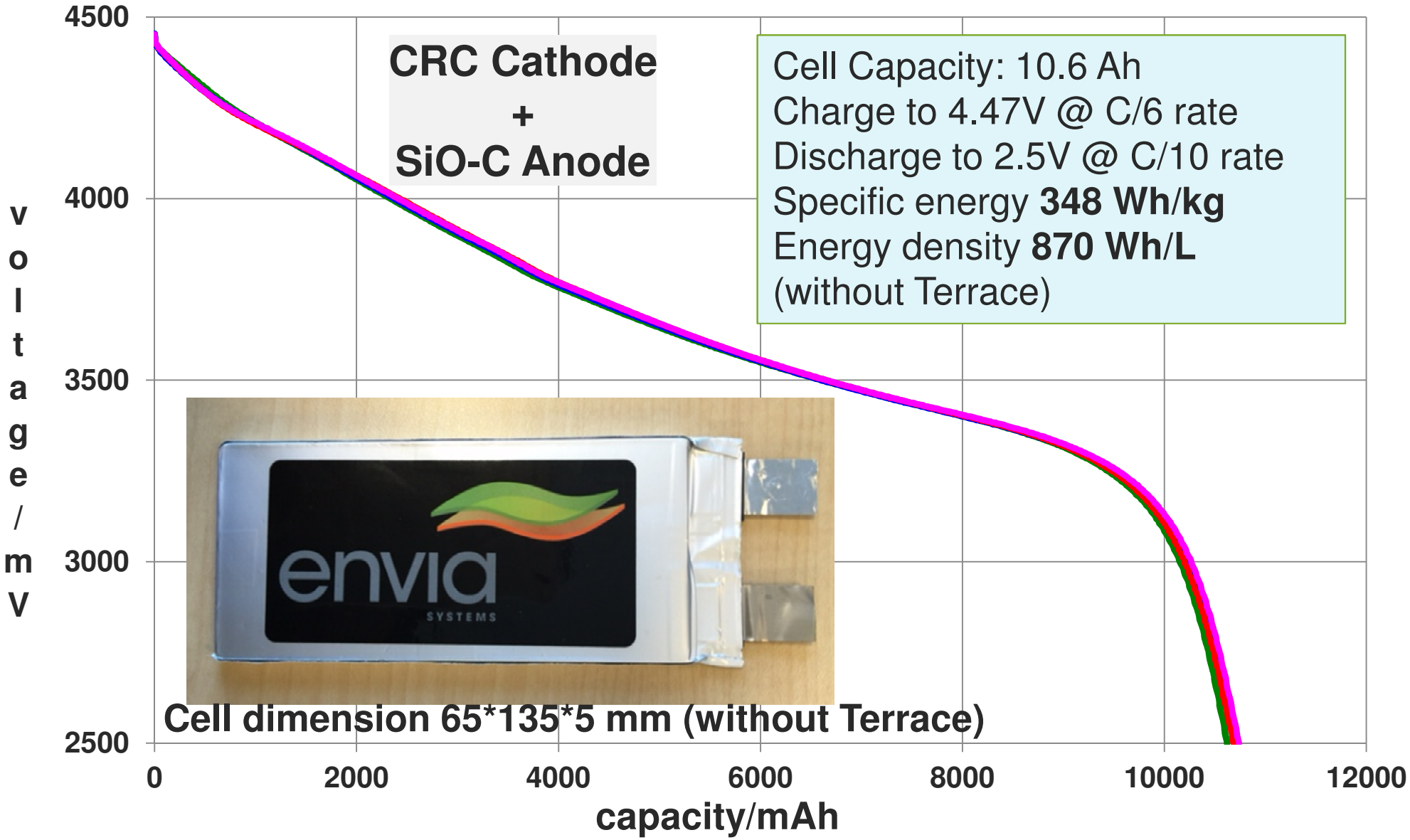



| Sample | Sp Cap [mAh/g] | Avg V [V] | Energy [mWh/g] | SOC @ 75 ASI [%] | U Energy [mWh/g] |
|---|---|---|---|---|---|
| Blend | 180 | 3.65 | 658 | <10 | >592 |

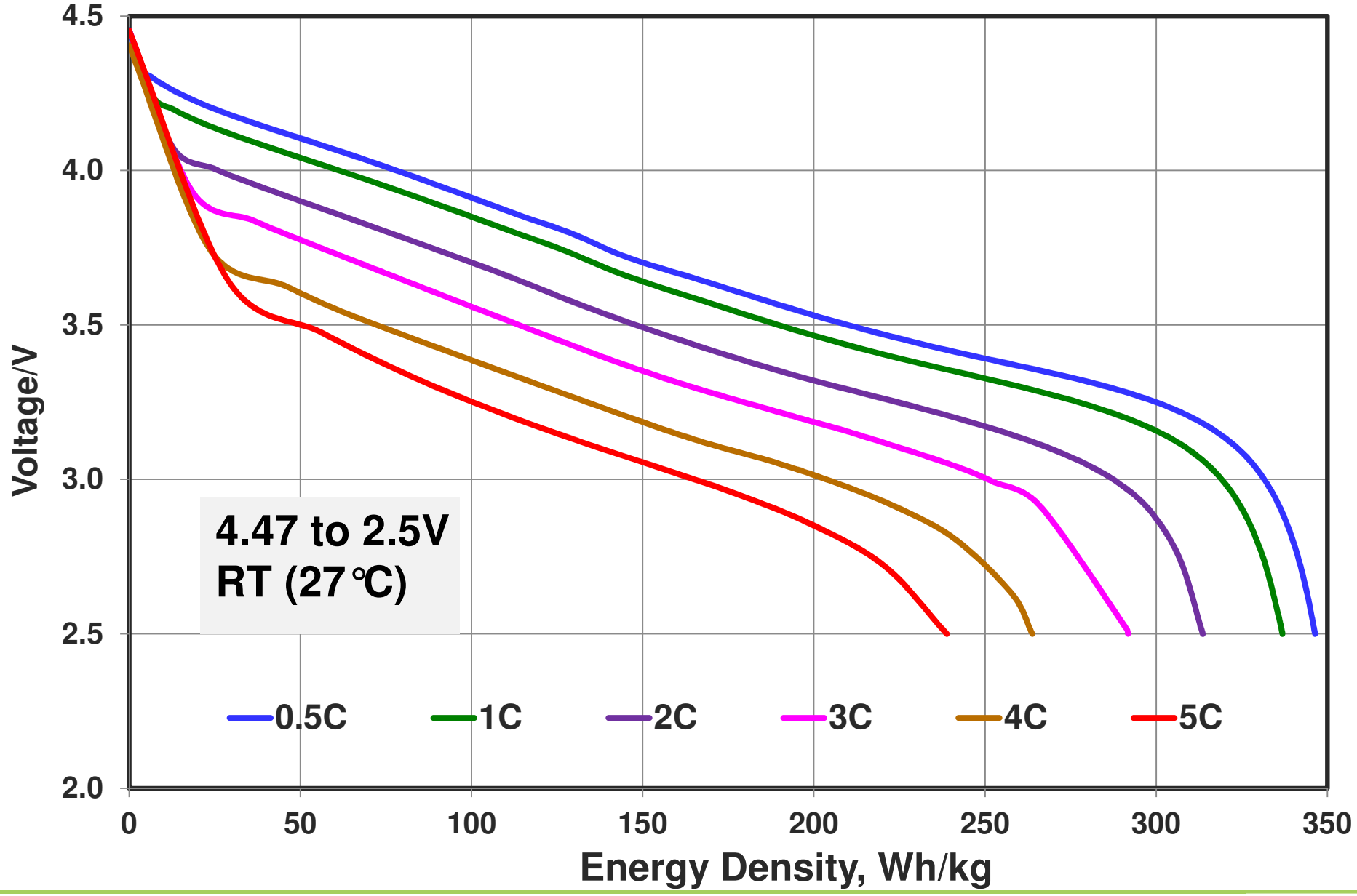
**Tested vs Graphite anode**

# Development of 350 Wh/Kg Cell

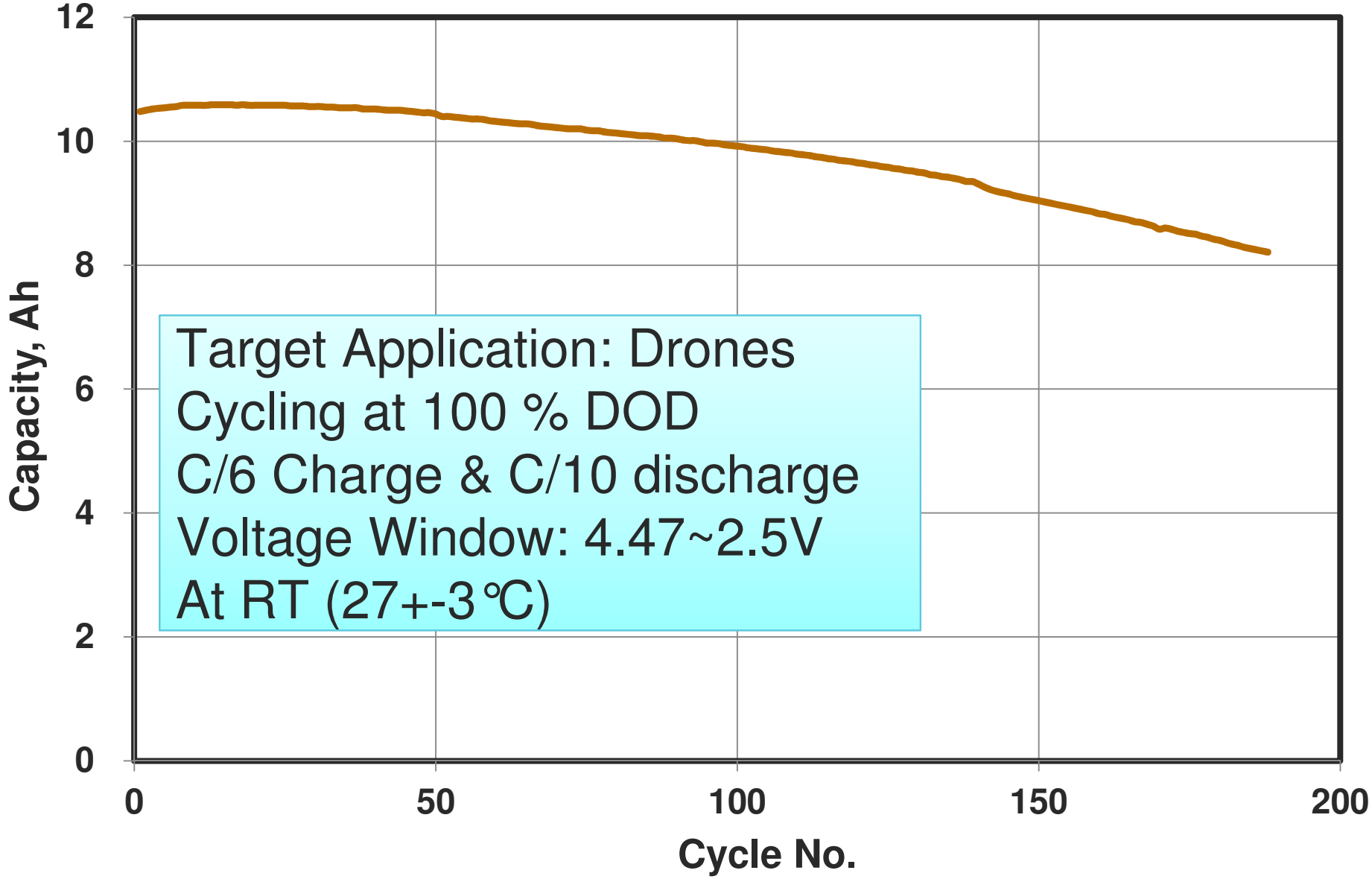
# 10.6 Ah Cell: Discharge Curve



# 10.6 Ah Cell : Rate Test



# 10.6 Ah Cell: Cycle Life



# EV Battery Technology

Lowering cost ($/KWh) and increasing driving range.

- $7.7 M award from USABC
- Enables a 300 mile car for *masses* with battery cost <$10,000
- 3 year program starting July 2014

| Gen 2 EV Cell | Metrics |
|---|---|
| Capacity | 40 Ah |
| Specific Energy @ C/3 | 350 Wh/Kg |
| Energy Density @ C/3 | 750 Wh/l |
| Specific Discharge Power-30 s pulse | 700 W/Kg |
| DST Cycle Life | >1000 |
| Cell Cost | $100/KWh |

USABC
UNITED STATES ADVANCED BATTERY CONSORTIUM LLC

U.S. DEPARTMENT OF ENERGY



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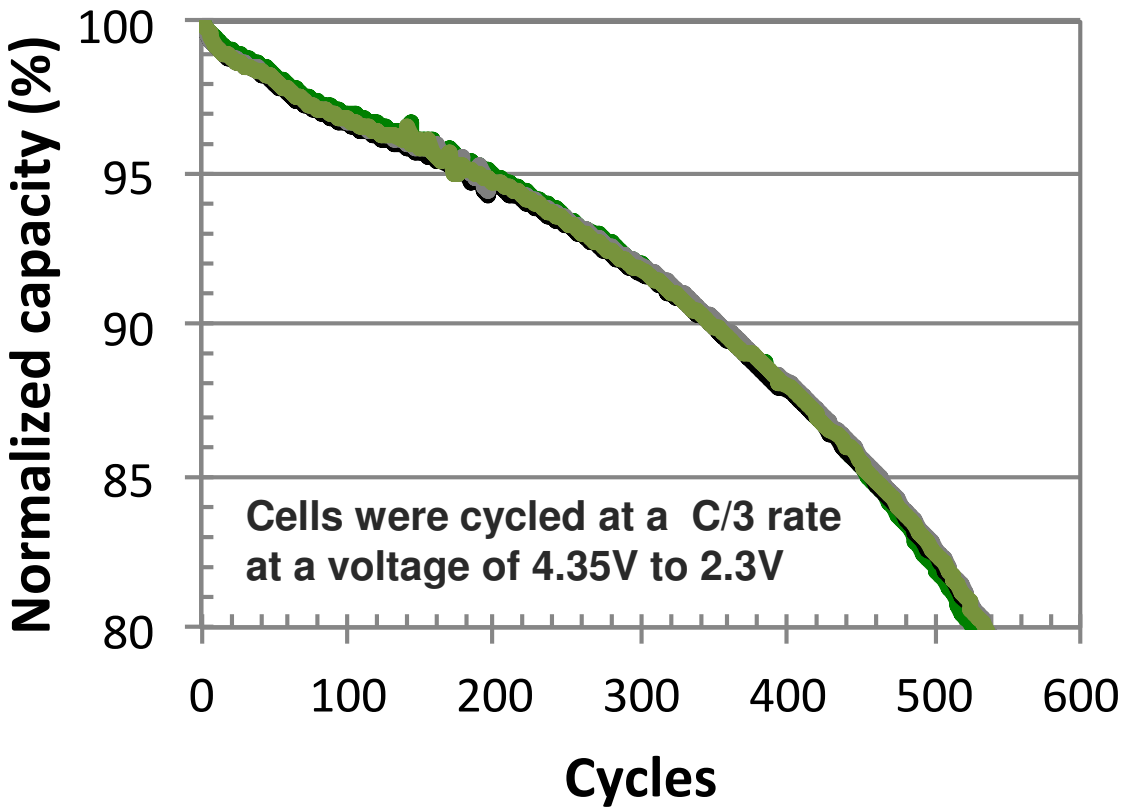
# Large Format EV cell

**21 Ah capacity (~260Wh/kg) pouch cells or 45 Ah 275 wh/kg 600 Wh/l cell**



- **Cycle life >500 cycles** is observed from 21Ah pouch cells
- HCMR Blend cathode. Silicon content >50 % Capacity ~1100 mAh/g

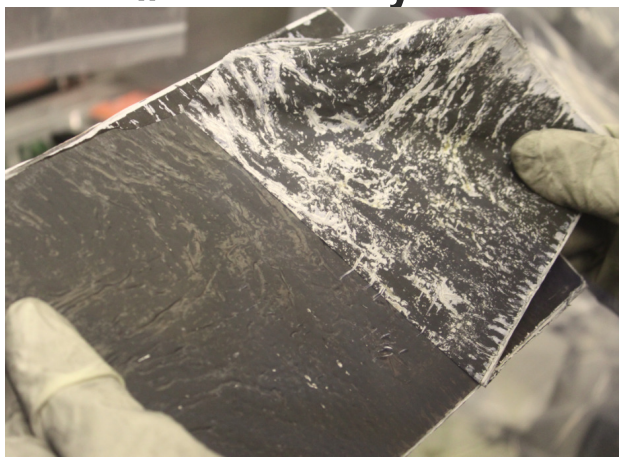
# Failure Analysis – Cell Tear-Down

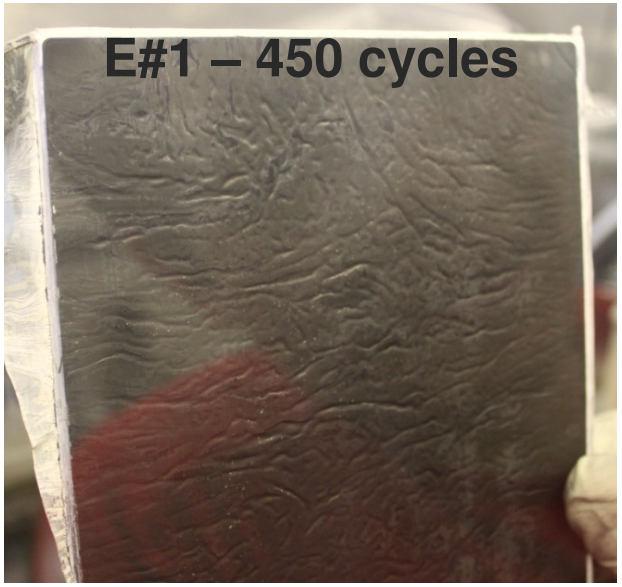
E#0 – 480 cycles

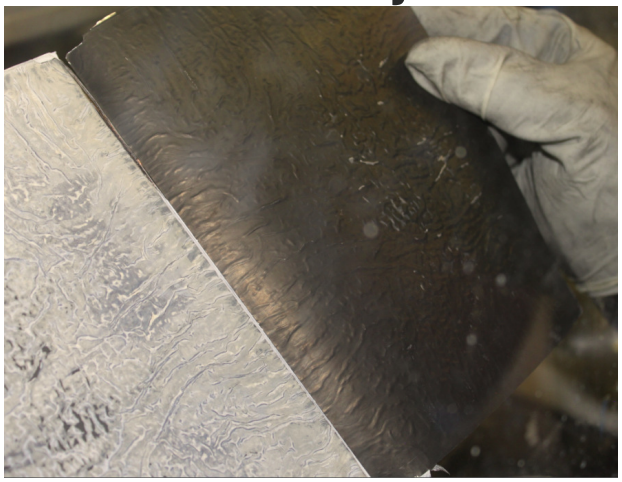
E#1 – 450 cycles

E#3 – 520 cycles

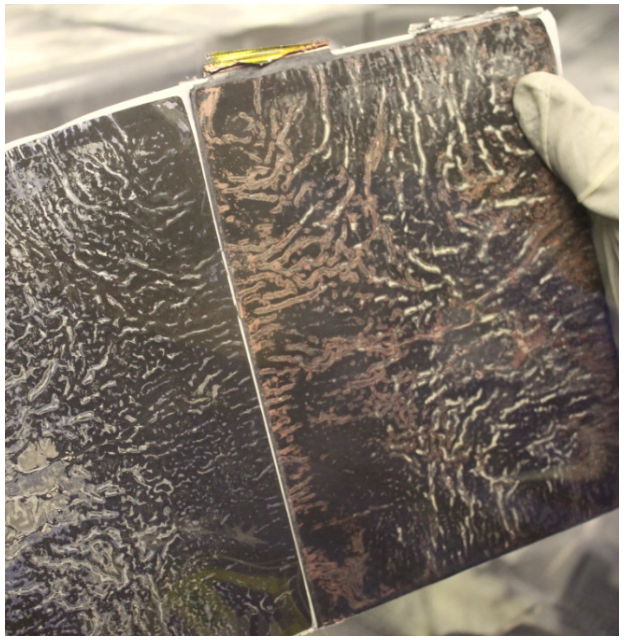
*Cathode*

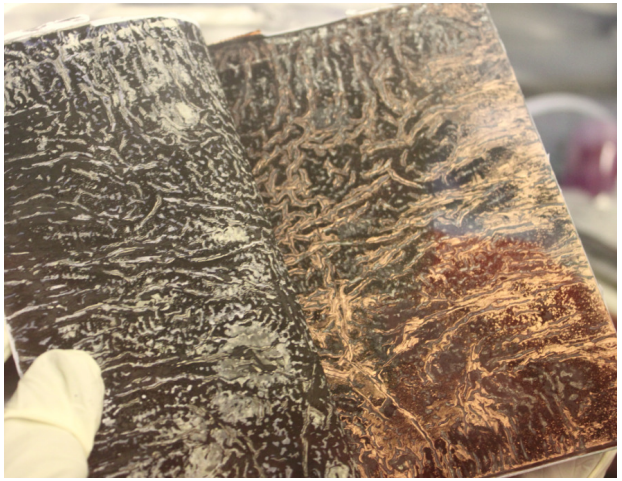


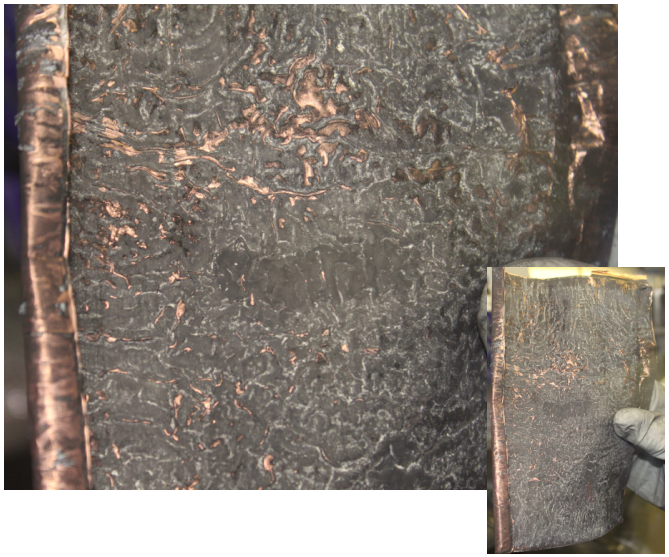




*Anode*







# Summary

- Although 400 Wh/Kg cell of specific energy can be achieved but hard to meet product specs.
  - 350 Wh/Kg & 870 Wh/l is practical limit for lithium ion batteries
- Envia's proprietary silicon anode market introduction in 2017 for a smartphone battery
  - Specific capacity 1450 mAh/g, 400 cycles at 100 % DOD and swelling less than 8 %
- CRC cathode ideal to pair with a silicon anode
  - Enables a 350 Wh/Kg cell 4.47V-2.5V. Developed for drone application. Further market penetration with improvement in cycle life.

# Energy density limit of Lithium ion Batteries

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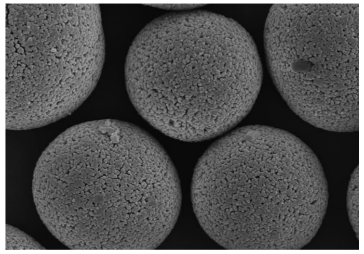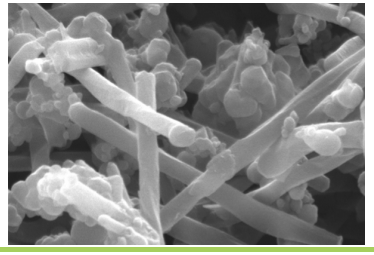
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