EaglePicher™
Technologies, LLC

Achieving Ultra High Power in Lithium-ion Technologies

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Space Power Workshop, April 2018

Who We Are…

EaglePicher™ Technologies, LLC

EaglePicher Technologies is a global leader in the development and manufacture of integrated power solutions and technologies for the defense, aerospace, and medical device markets. We are the partner of choice for leading OEMs worldwide.

EaglePicher™ Technologies, LLC

Materials research and electrochemistry expertise leading to specialized Cell, Battery, integrated Power System solutions, and Energetic Device applications

TRUSTED POWER. RELIABLE POWER. INNOVATIVE POWER.

Where We Innovate and Operate

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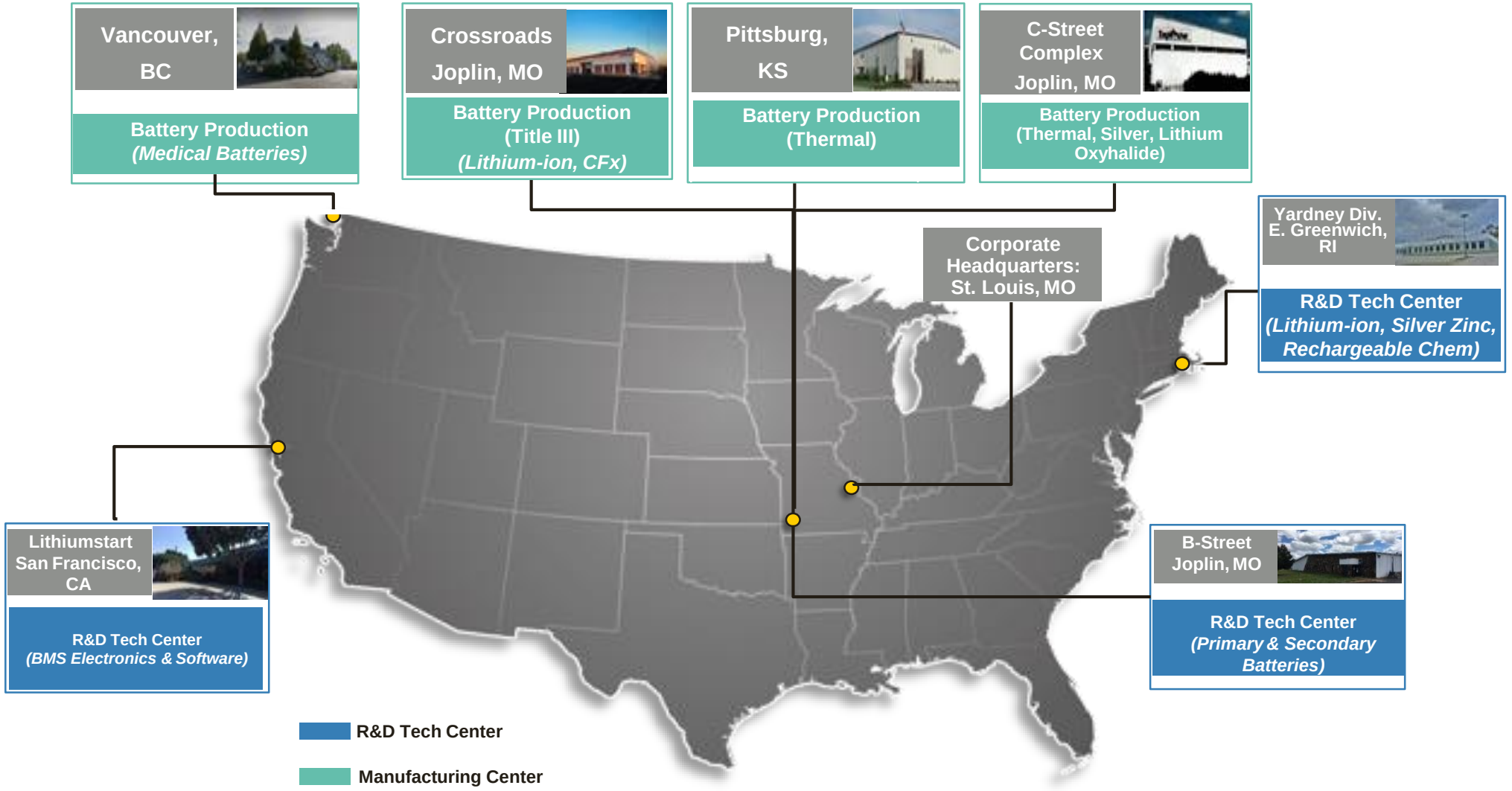


Dual certification to ISO 9001:2008 & AS9100C; and ISO 13485 (medical devices)

Where We Play

EaglePicher™ Technologies, LLC

EPT's products are uniquely suited to meet the highly-specialized demands of current and developing technologies across defense, aerospace and medical applications

UAV: Lithium-ion / CFx Batteries

Directed Energy Weapons: Lithium-ion Battery Systems

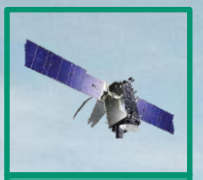
Anti-Tank Missiles: Thermal Batteries

Implantable Medical Devices: Lithium-ion / CFx Batteries

Ballistic Missile Defense: Thermal Batteries

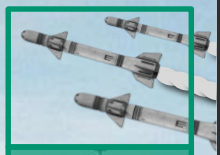
Portable Soldier Power: Lithium-ion / CFx Batteries

Military Radios: Lithium-ion / CFx Batteries



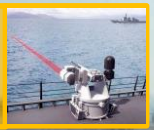
Satellite: Lithium-ion Batteries

Aircraft Battery: Lithium-ion Batteries



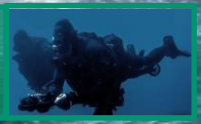
Precision Guided Munitions: Thermal Batteries

Shipboard Directed Energy Weapons: Lithium-ion Power Systems



Torpedoes: Silver Zinc Batteries

Diver Propulsion: Lithium-ion Batteries



Currently Deployed

In Development

Directed Energy

Summary of Directed Energy Programs

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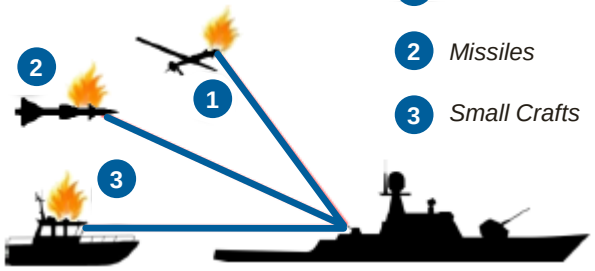
Ship-Based

A ship-based laser weapon Engineered to quickly Incinerate enemy drones, Missiles and small crafts

Targets

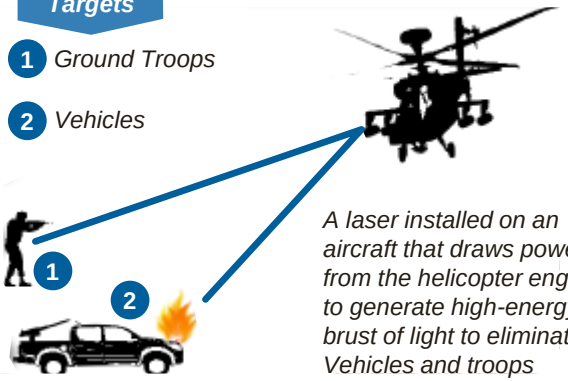
1. *UAVs*
2. *Missiles*
3. *Small Crafts*



Air-Based

Targets

1. *Ground Troops*
2. *Vehicles*



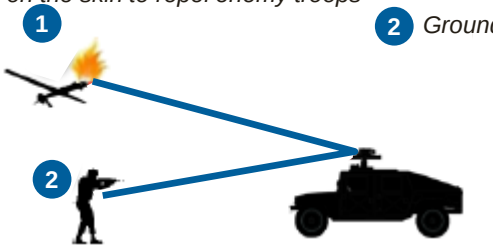
A laser installed on an aircraft that draws power from the helicopter engine to generate high-energy brust of light to eliminate Vehicles and troops

Ground-Based

A laser mounted on a combat vehicle that can destroy enemy drones and produce an overwhelming burning sensation on the skin to repel enemy troops

Targets

1. *UAVs*
2. *Ground Troops*



		Overview	EPT Positioning
HEL APACHE		▪ High energy laser mounted on Apache helicopter for an attack on designated targets	▪ **Awarded prototype development contract**
HEL TVD		▪ "High Energy Laser Tactical Vehicle Demonstrator" ▪ $3.1bn program officially launched in March 2017	▪ **Awarded D3I** (Design, Develop, Demonstrate and Integrate) IDIQ (Indefinite Delivery / Indefinite Quantity) **contracts to 8 prime contractors**
Defensive Lasers: SNLWS / HELIOS		▪ Energy magazine for shipboard support power, with sufficient energy for ~360 shots of 150kW laser	▪ EPT is a principal subcontractor
U.S. Air Force | Defensive Lasers		▪ Self-Protect High Energy Laser Demonstrator (SHiELD) Program Defensive Laser Pod for aircraft	▪ EPT baselined as battery solution for LPRD
U.S. Air Force | Offensive Laser (Special Operations)		▪ High Energy Liquid Laser Area Defense System (HELLADS) ▪ Offensive laser for Special Operations AC-130 gunship	▪ Low weight / high power cell chemistry

Focus Areas for High Power Li-ion

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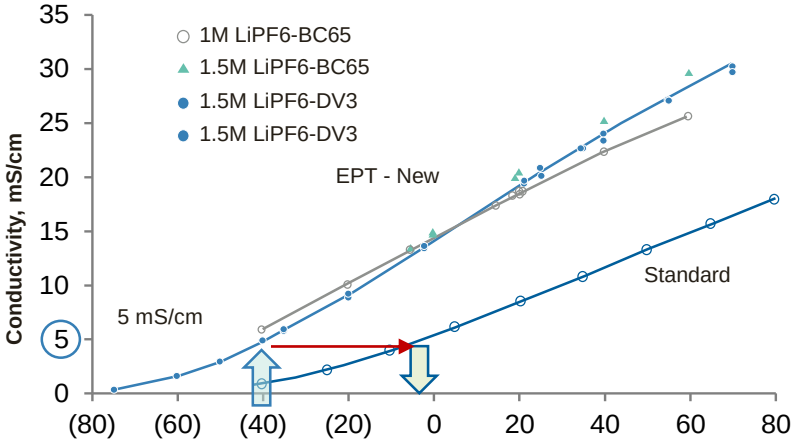
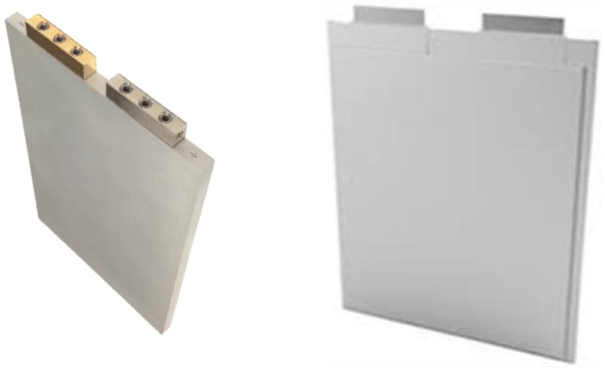
Development focus on High Power and Low Temperature operation for Military Applications, without sacrificing Safety

Materials & Electrolytes



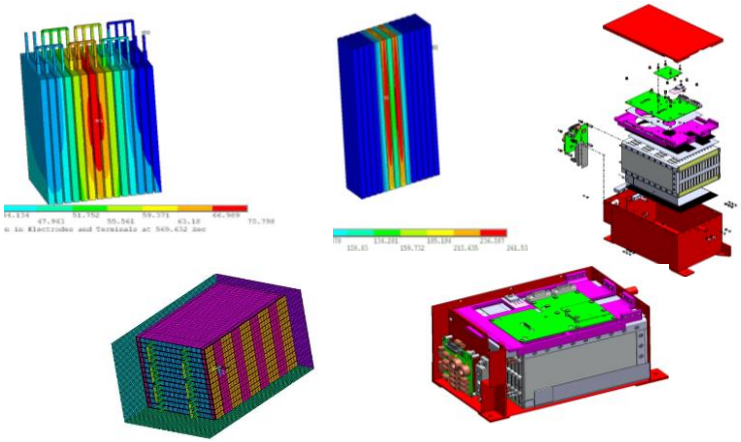
EPT has developed unique electrolyte formulations to provide tremendous low temperature capability

Cell Designs



EPT's incredible high power and low temperature performance enables a new solution for DEW and the next generation of More Electric Aircraft such as JSF

System Designs



EPT's proprietary, individual cell and battery thermal design can keep a cell cool during high power operation and abuse

Electrolyte

Effect of Individual Solvent

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- Effect of its dielectric constant
  - High dielectric constant promotes electrolyte dissociation increasing the number of charge carriers
- Effect of its viscosity
  - High fluidity mechanically enhances ion's mobility
- Effect of its melting point
  - Low melting point solvent components can decrease freezing or separation temperature of the blend
- Other possible effects

Low Temperature Electrolyte Developments at EP

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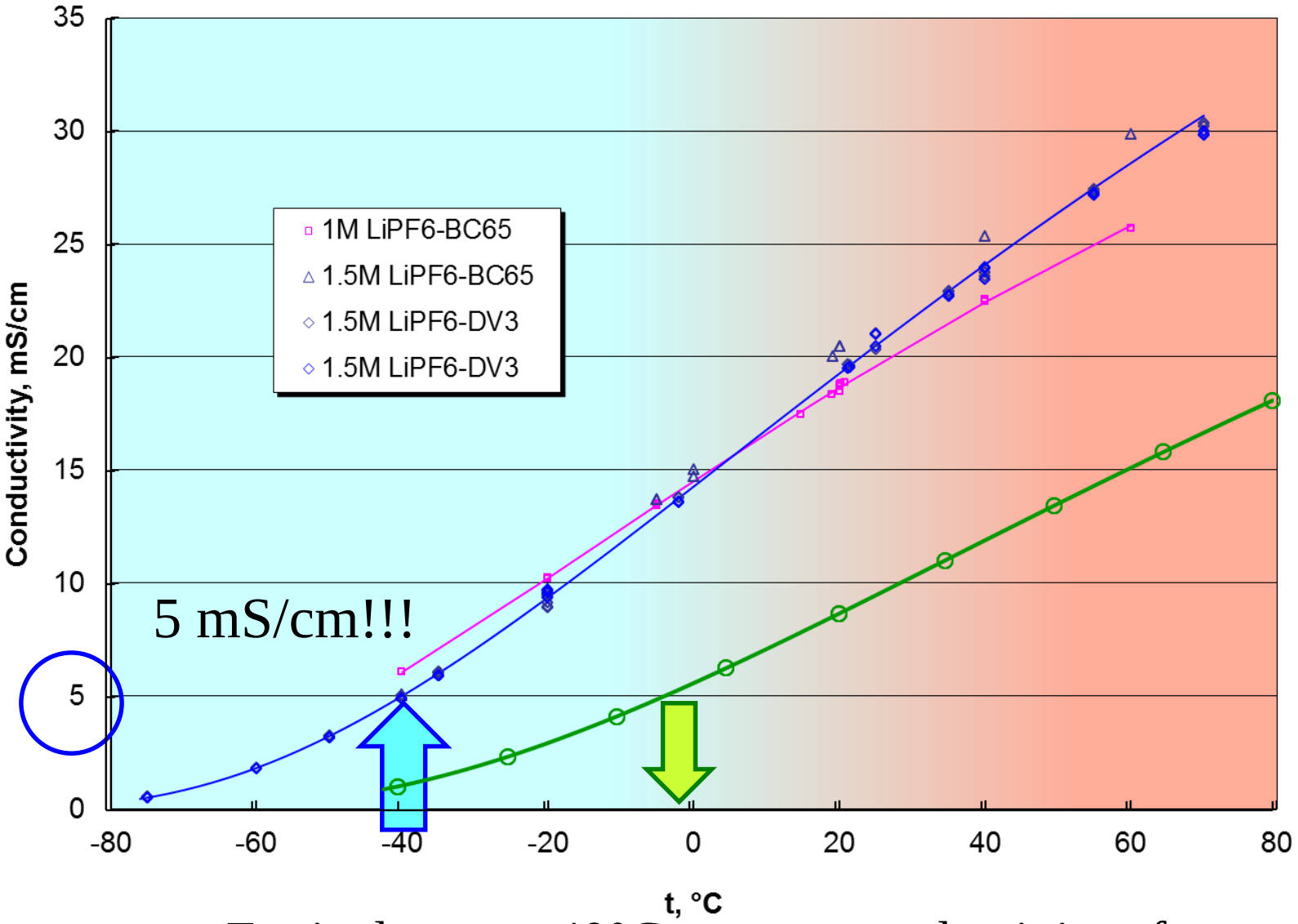

Equivalent to a 40°C warmer conductivity of
1M $LiPF_6$ in EC/DMC/EMC (-40°C ~ 0°C)

Cell Testing at Low Temperatures

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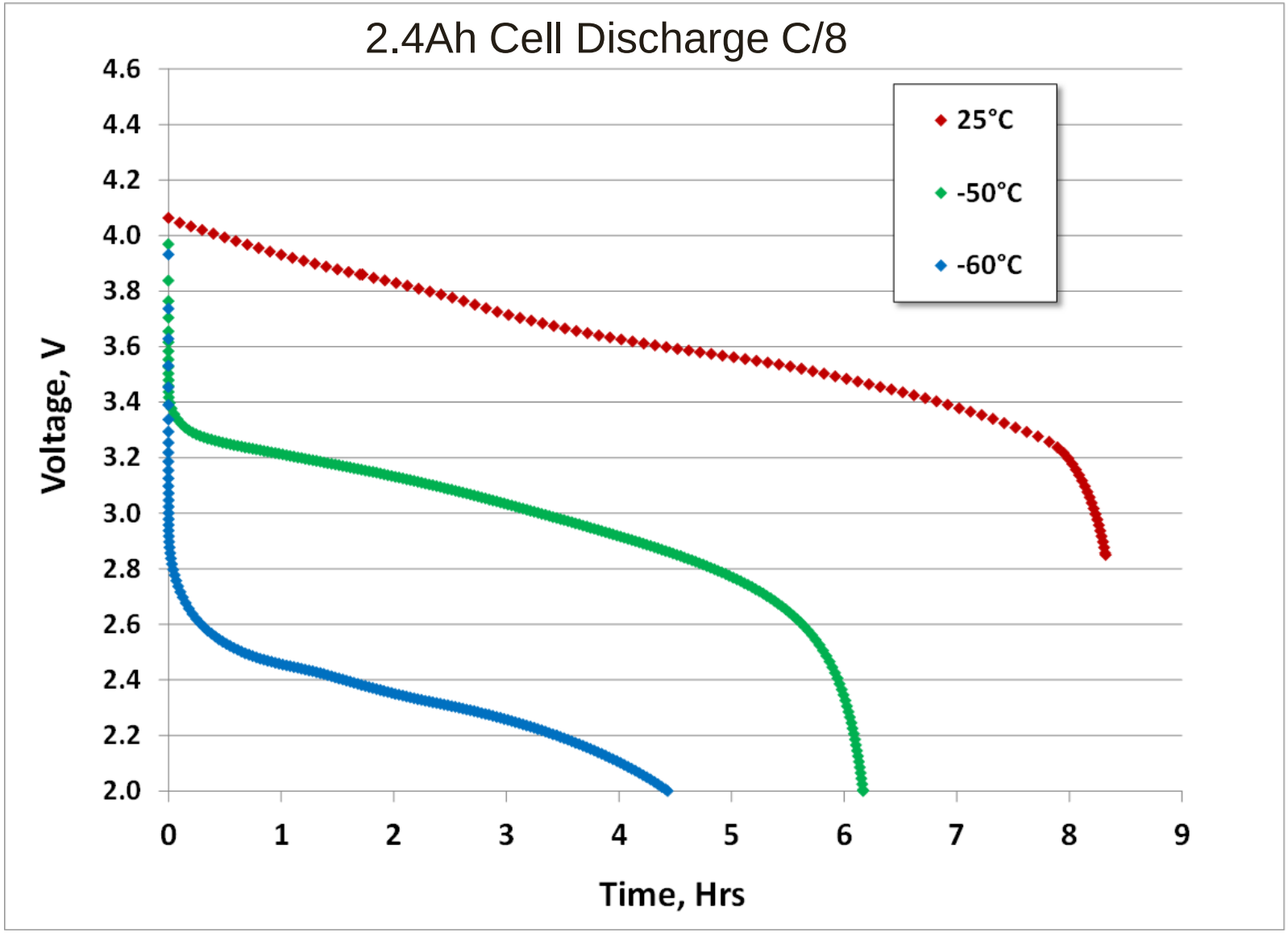
- 2.4Ah Pouch Cell, Discharge at C/8 (charges at 25°C)



Pushing Power at Low Temperatures

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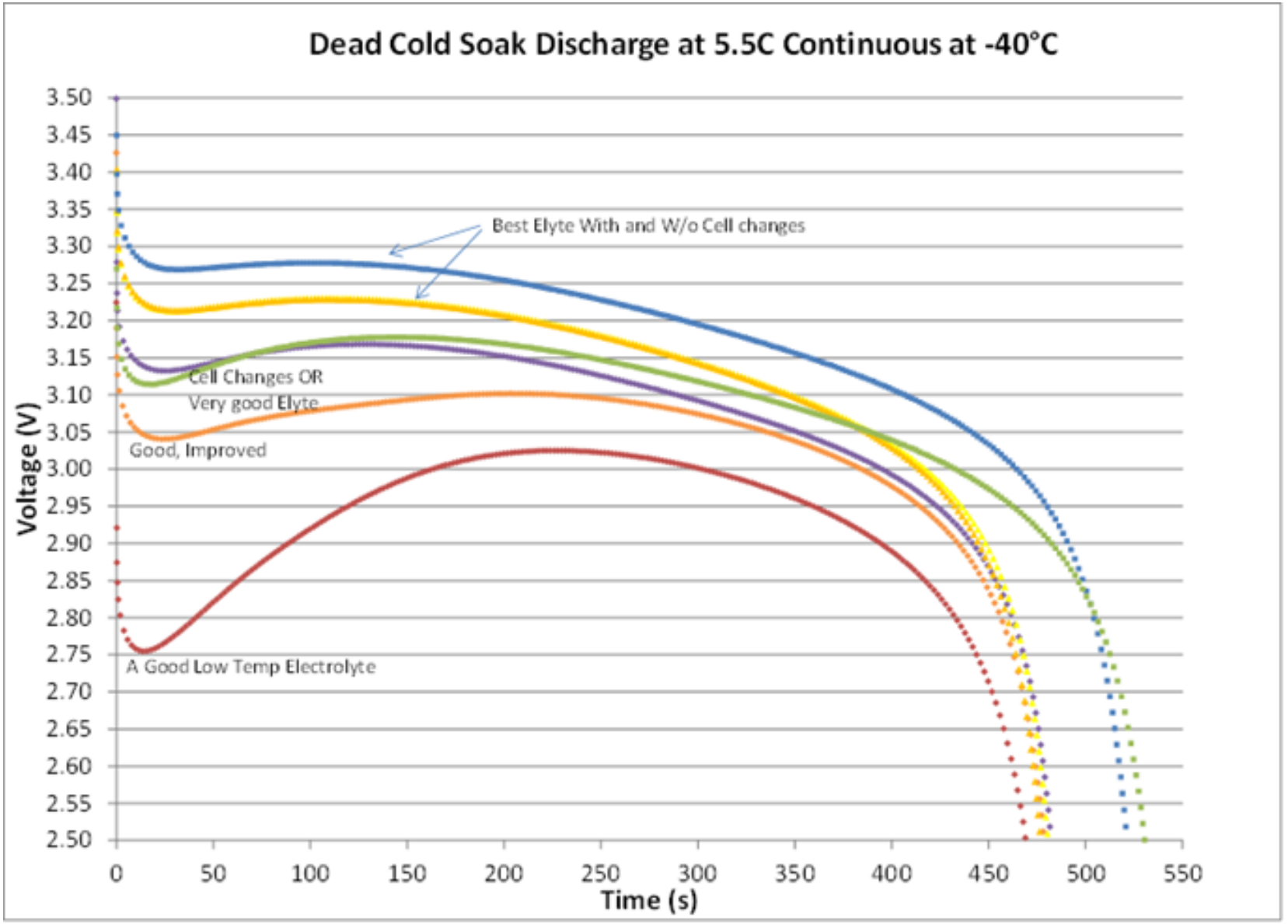
- 5Ah Aircraft cell with new Low Temperature Electrolytes. Charge at room temp.



Cell Designs

Custom High Power Prismatics

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- The 5Ah, Hard Cased Cell

- The 6Ah Hybrid Pouch Cell

(and a 10-12Ah sibling in 2018)

- The 14Ah Aircraft Cell

- The 18Ah DEW Cell

18Ah Cell at 20°C: ~114C Cont.

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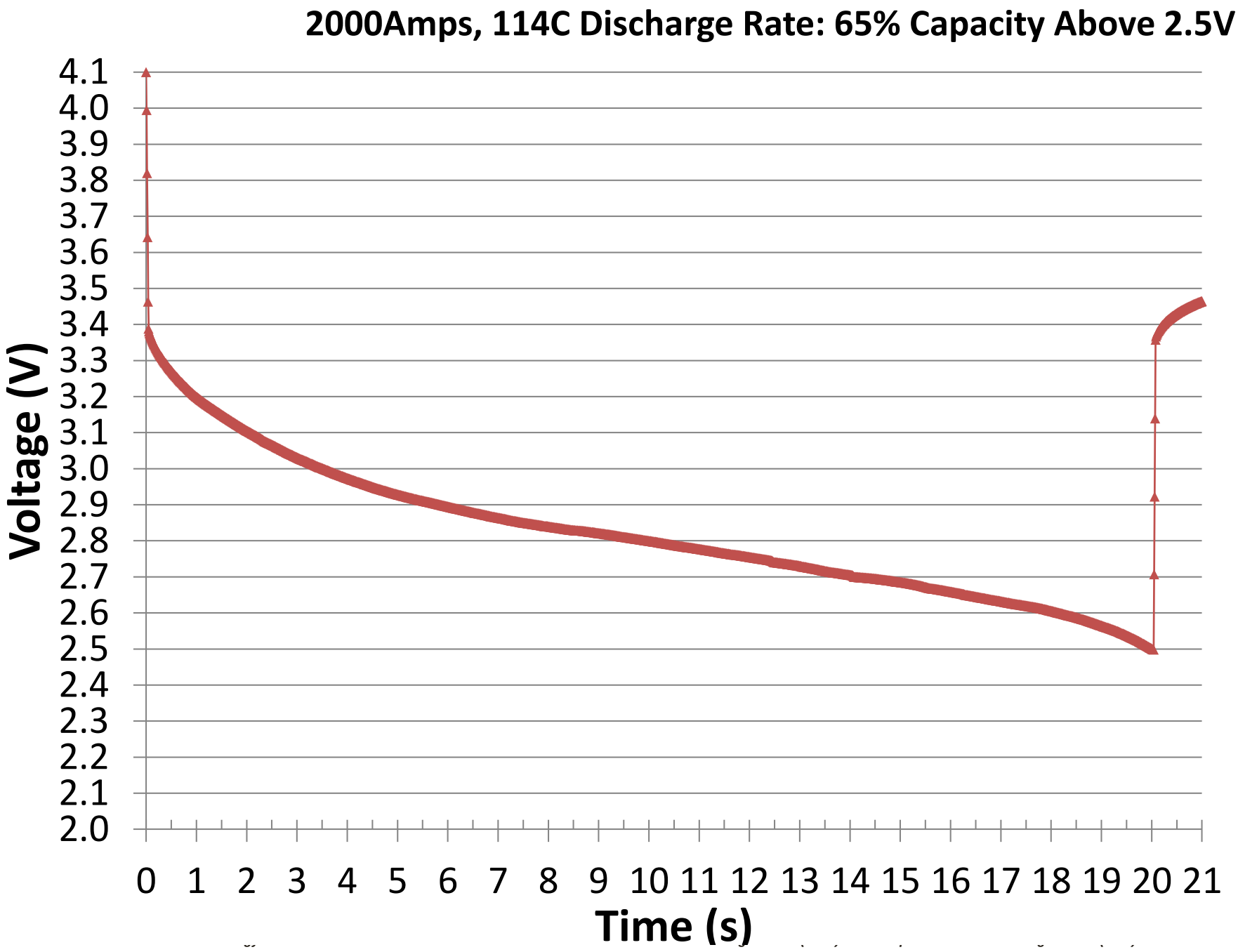

2018 Chemistry Improvements

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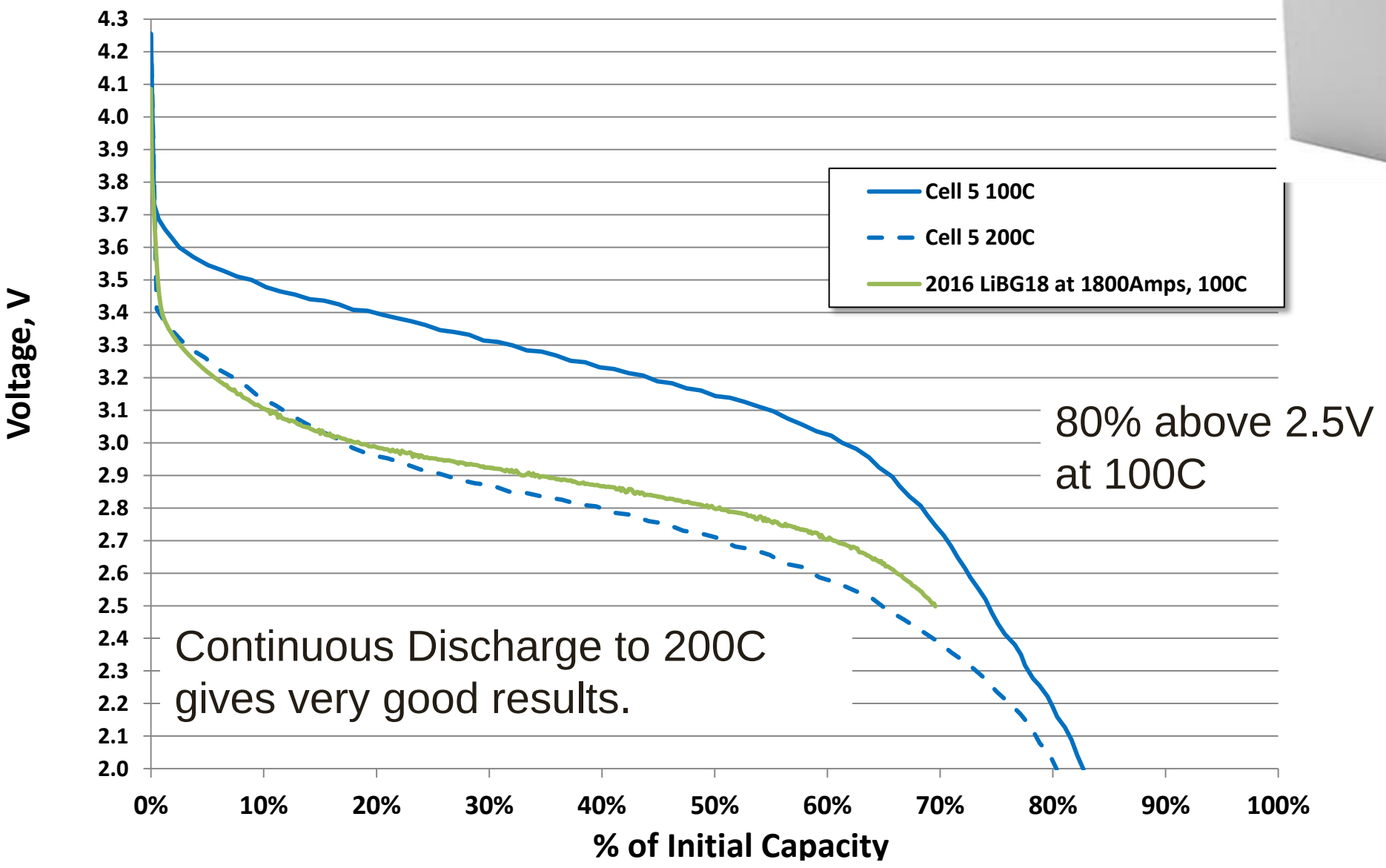

So what is the PEAK Power?

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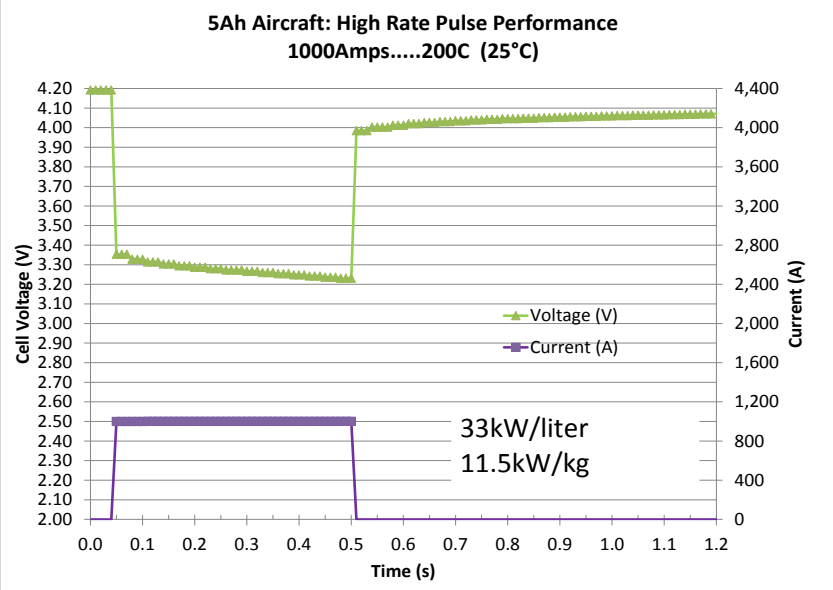
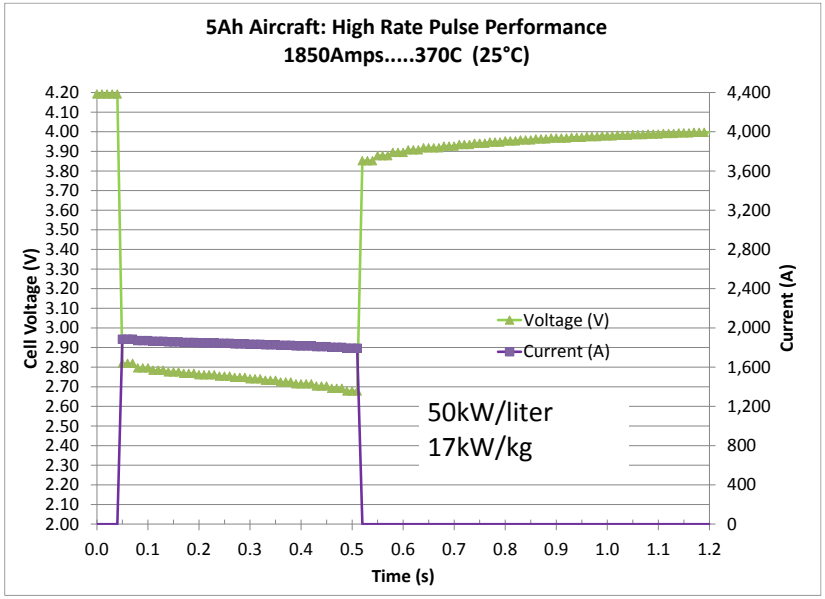
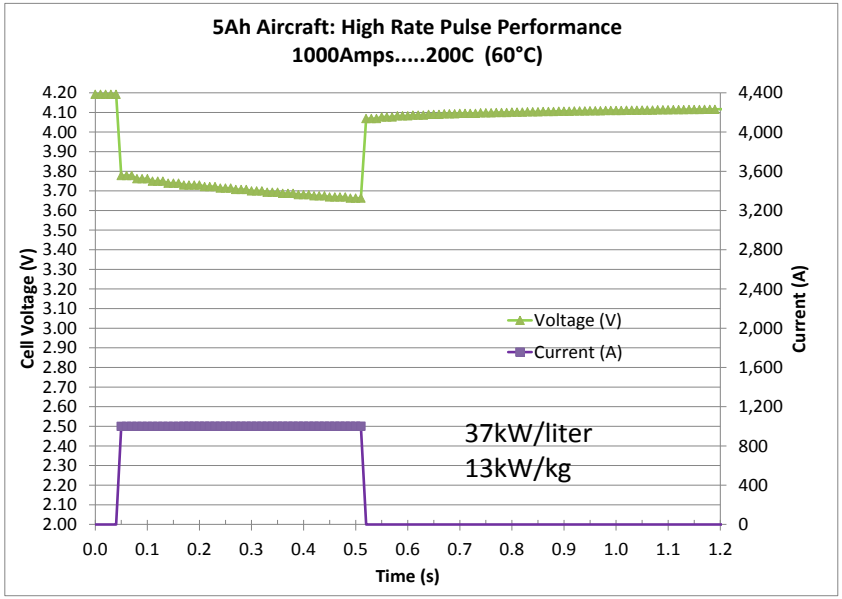
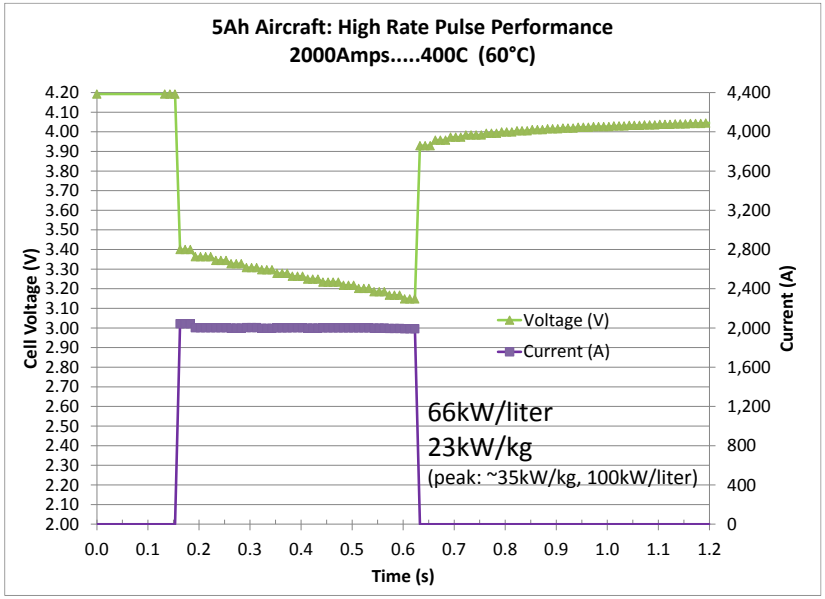
The cells are capable of very high power – 35kW/kg, 100kW/l









Magazine Depth & Very High Duty Cycle

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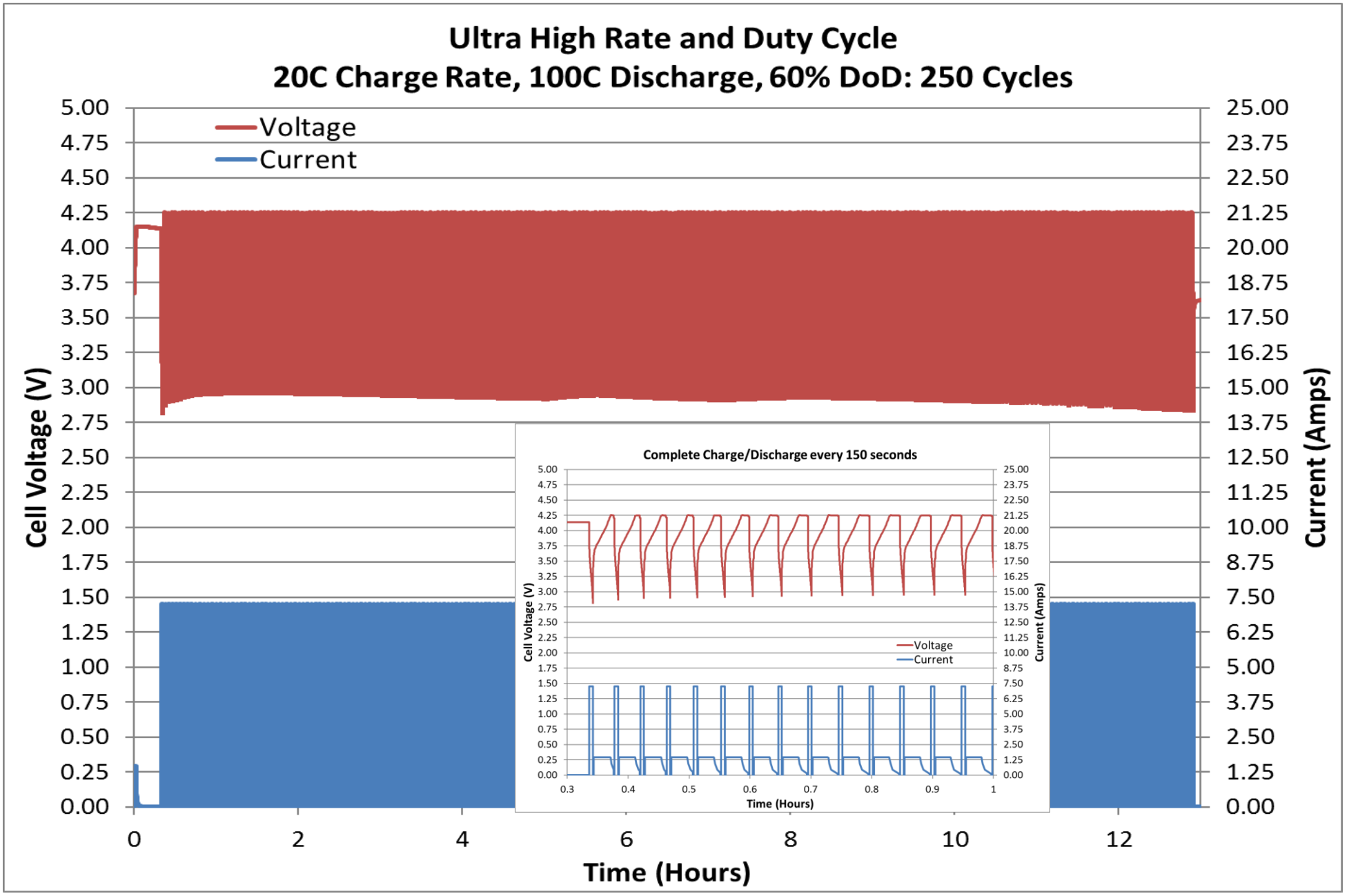

More Magazine Depth (60C Recharge, 40+% Duty)

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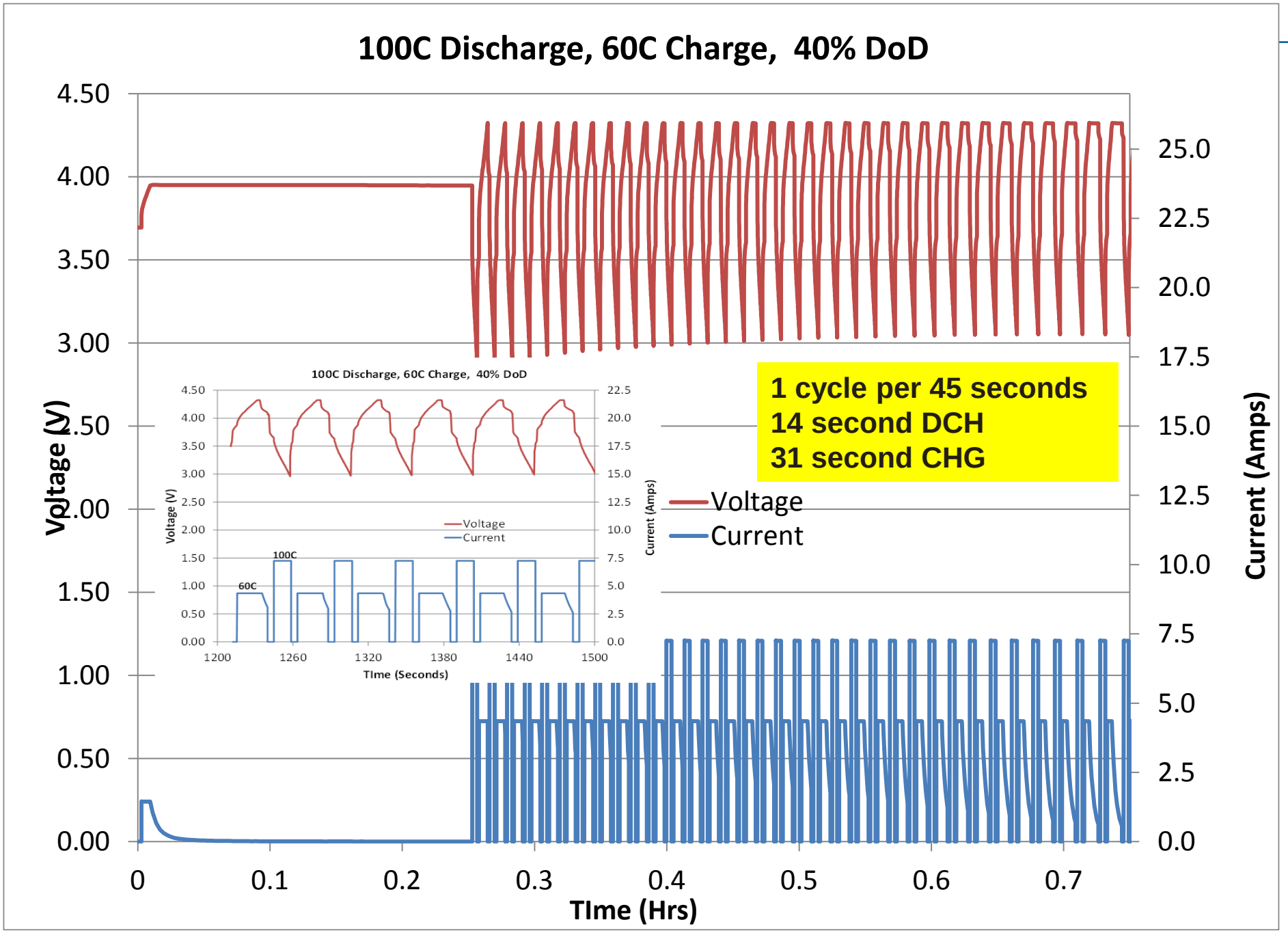

What does this mean from a Con-Ops Perspective?

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A hypothetical battle:

- **Step 1:** Monitor Mode, Battery at 90% SOC, Small alternator providing 555 Watts
- **Step 2:** Detect and Fire 10kW for 5 seconds=33kW: 98.3% battery, 1.7% alternator
  - (87C Discharge), assumes 30% conversion efficiency
- **Step 3:** Re-acquire for 2.5 seconds, Recharge battery during those 2.5 seconds at 555 Watts
- **Step 4:** Detect and Fire 10kW for 5 seconds. 98.3% battery, 1.7% alternator
- **Step 5:** Re-acquire for 2.5 seconds, Recharge battery during those 2.5 seconds at 555 Watts
  - Main GenSet is now on, stabilized and available for constant power at 11kW (1/3 of load)
- **Step 6:** Detect and Fire 10kW for 5 seconds. 67% battery, 33% GenSet (59C Discharge)
- **Step 7:** Re-acquire for 2.5 second, Recharge battery for the same 2.5 seconds at 11kW
  - (30C recharge)
- **Step 8:** Repeat Steps 6 and 7 for 8 more kill shots (10 total shots, can be adjusted to 15+)
- **Step 9:** Recharge for 90 seconds at main GEN SET POWER (30 C Recharge)
  - Additional shots are available after just a few seconds, Full profile at 90 seconds
- **Step 10: Laser, Rinse, Repeat forever….**

Scaled Battery Testing Results

(Scaled from 10kW at Laser to 33kW at battery and to test cell level)

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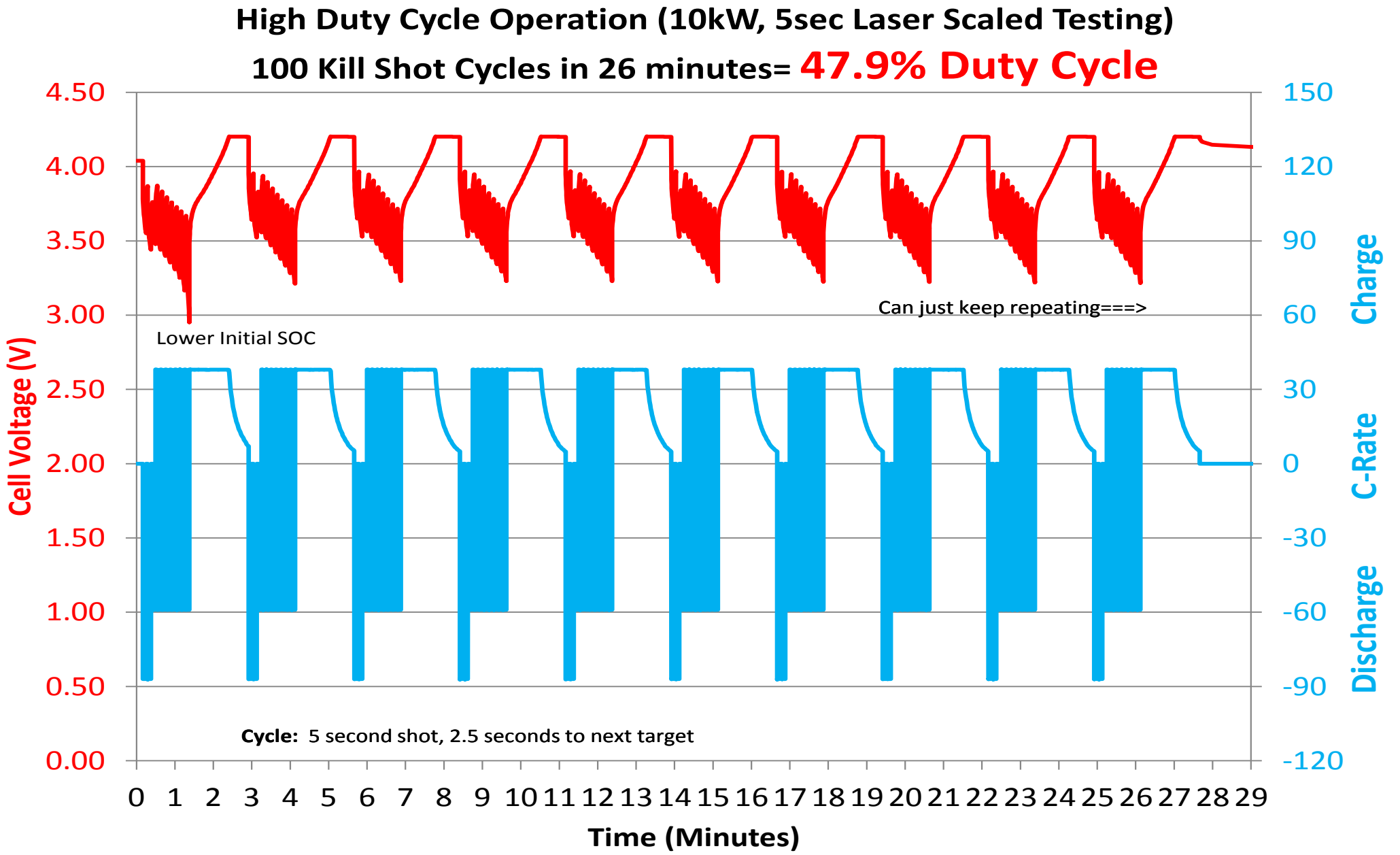

Thermal Design and Safety

Thermal Design

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- There is no more important factor in Li-ion system design than the Thermal Design
- We have shown that the chemistry can support 30^{+}C charge rates followed by 100C discharges, or 200C continuous discharges, or 600C pulses
- All of this is only possible because of the advanced thermal design at the cell and battery level.
- Commercial cells not designed for power often overheat with a single, high rate discharge. If they don't overheat they reach higher temperature for longer periods and that degrades life

Heat Transfer and Duty Cycle

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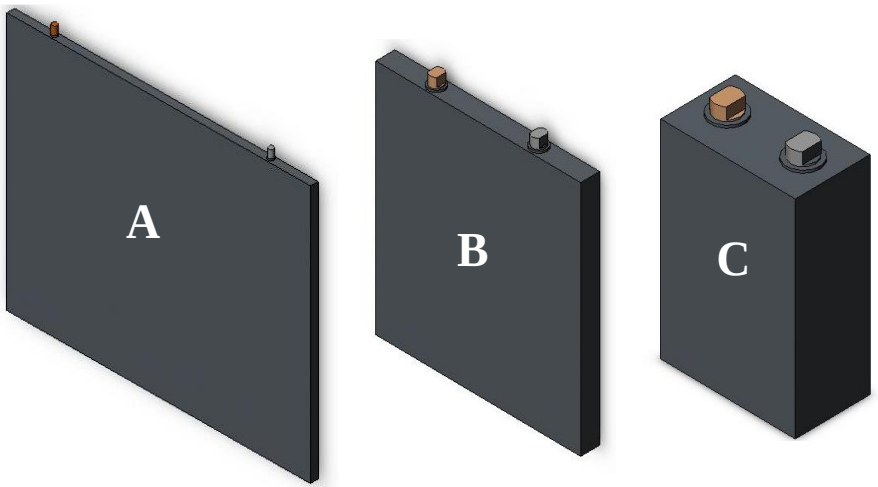
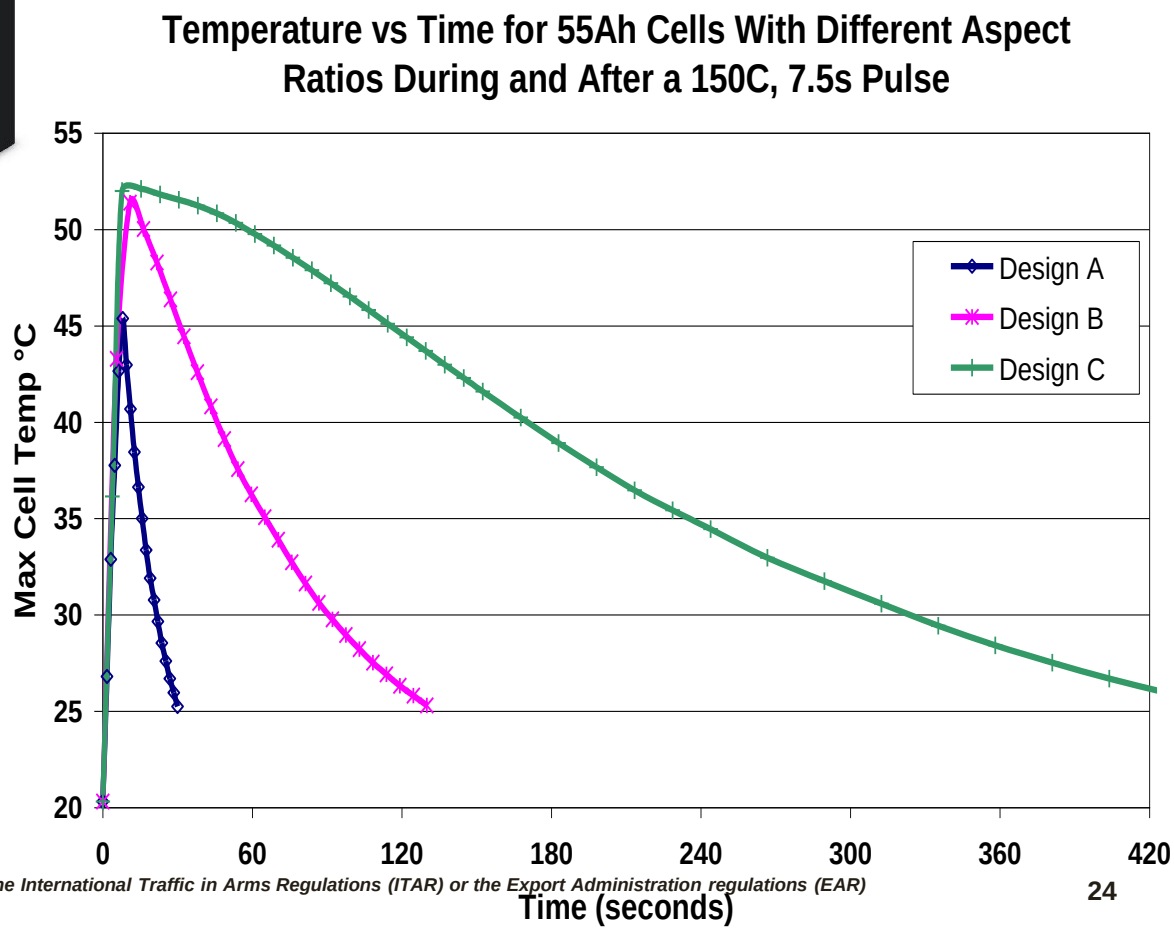
- The ability to pull heat out of cell is critical for a DEW cell to have a duty cycle/magazine depth.



Thick and wound cells are struggling with thermal accumulation that leads to poor life and low duty cycles.



Safety Advantage

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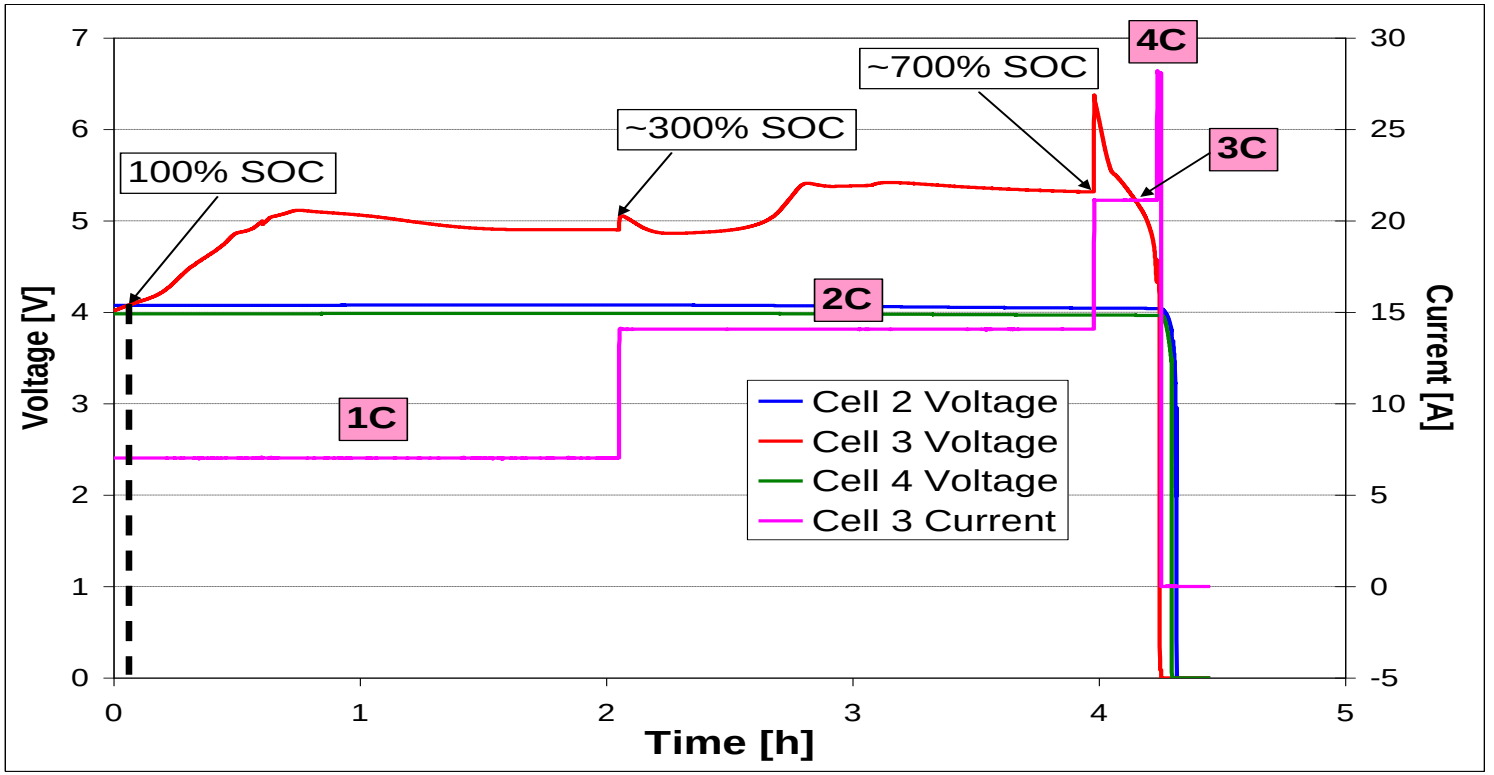
- An advanced thermal design is also critical in changing the safety performance of the cells.
- “Normal” cells will vent violently at 170% SOC
- Thermal design has the ability to change the failure point and failure exuberance.



5 Cell Pack, Single Cell Overcharge Test

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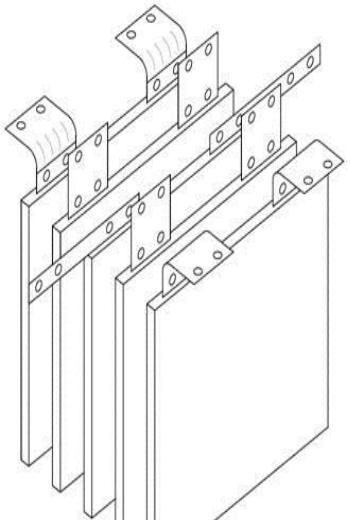
Heat flow control systems required between cells



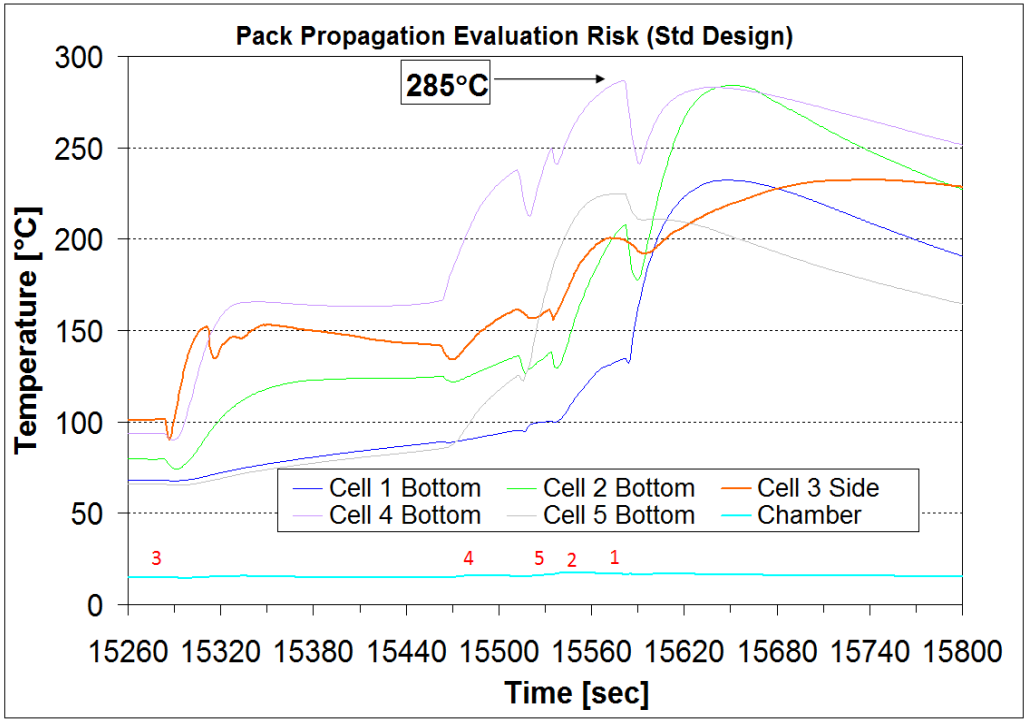
Demonstrated Non Propagation:

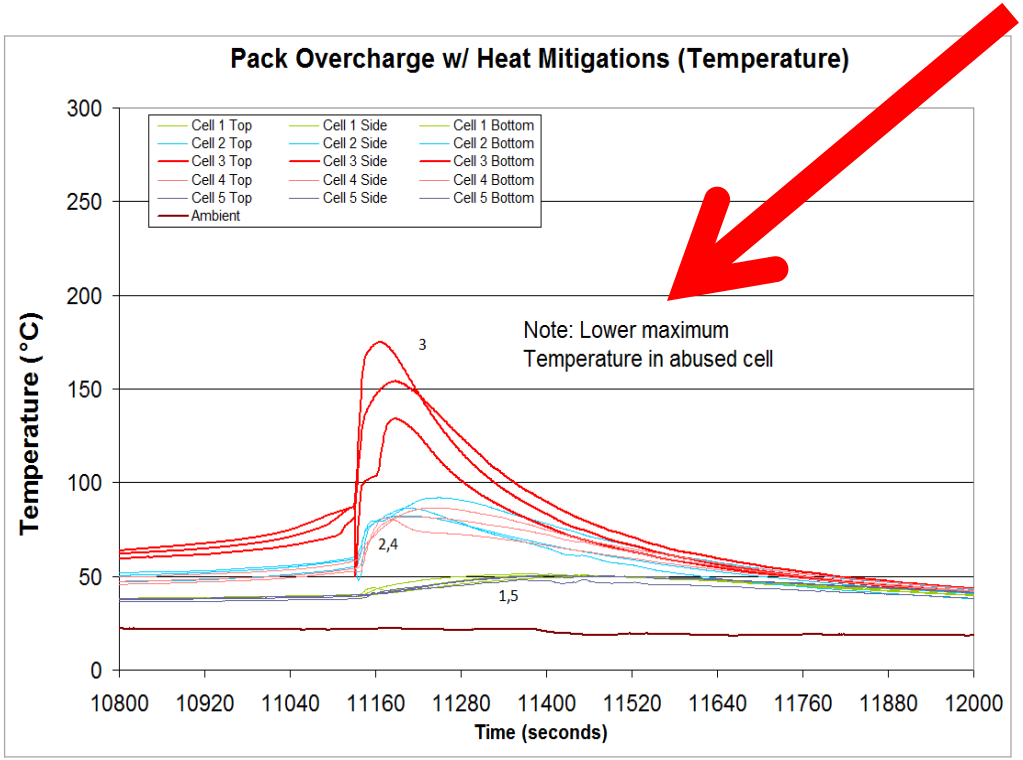
5Ah

14Ah

18Ah

Prismatics





Note larger rise in secondary events: The most violent reactions are not from the initial cell failure but are from cells that in a pre-heated condition.

HESM Area #3 and EP Internal Cooling Designs

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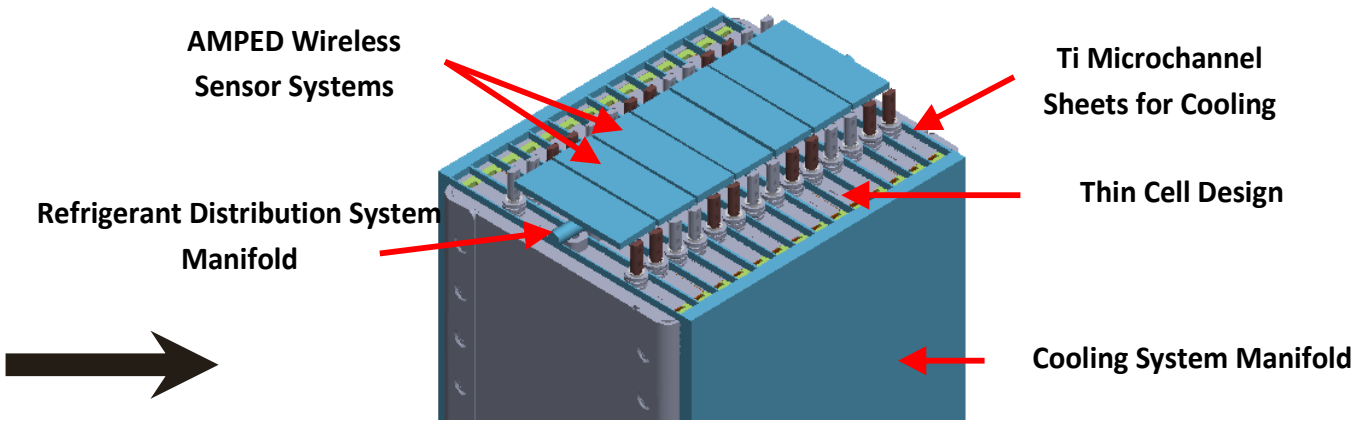
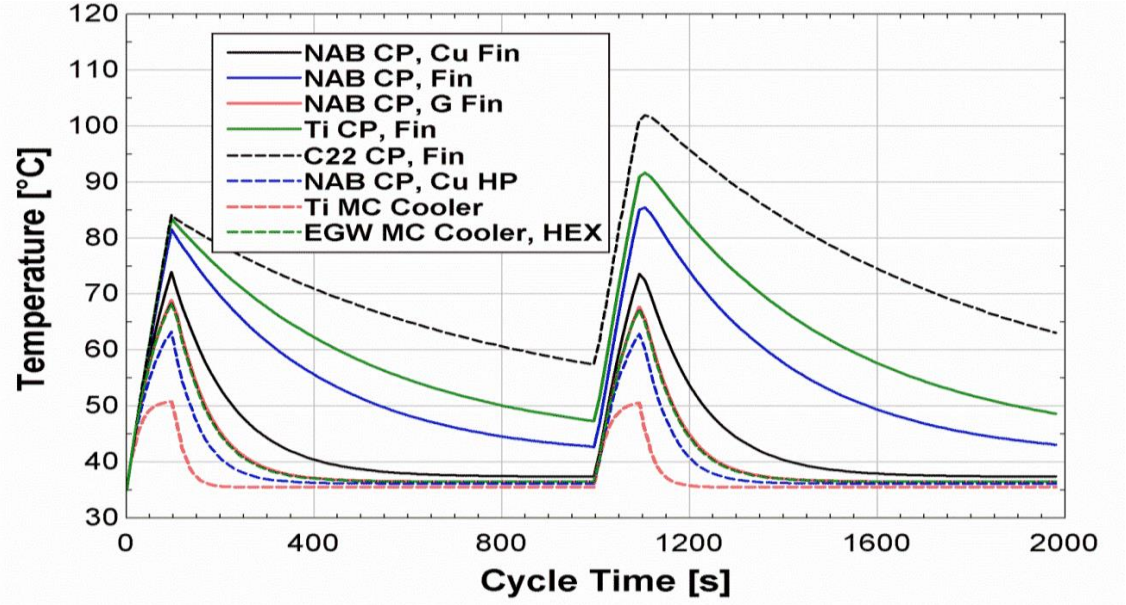
- Optimizing Thermal Management



Modeled Relative Performance of Various Cooling Options Under Failure Modes (500°C)



Summary

EaglePicher™ Technologies, LLC

- EaglePicher's unique High Power designs provide mission-enabling power densities for DEW and MEA applications
- Low Temperature electrolytes support high power discharges (>11C) at very low temperatures (-40°C)
- The cell, and system, Thermal Design is critical for operational capability (shed heat quickly to provide magazine depth) and SAFETY
- Proper design and packaging of NCA-based cells can prevent propagation of Thermal Runaway events, and can even significantly reduce the likelihood of an issue.

Acknowledgements

EaglePicher™ Technologies, LLC

- Thanks to the authors and coworkers at EaglePicher, in East Greenwich, RI and Joplin, MO
- Funding for these developments combination of internally funded R&D and support from US NAVAIR, USAF, Department of Defense

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