Rechargeable Li-metal Cell Development for High Power and Low Temperature Applications

14 November 2023

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What We **Do**

Applied Research & Development

CRG focuses on rapid innovation and delivering new capability to our customers

Core Competencies

Aerospace Systems

- Aircraft Design/Build/Fly
- Quiet Electric Propulsion
- Aircraft Repair and Sustainment
- Electromagnetics

Human Health & AI

- Casualty Care
- Wearable Sensors
- Environmental Sensors
- Autonomous Detection and Deterrence
- Edge Computing

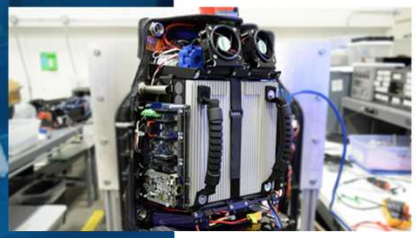
Power & Energy

- Energy Storage
- Power Generation and Conversion
- Power Distribution and Management

Advanced Materials & Manufacturing

- Advanced Polymers
- Additive Manufacturing
- Affordable, Agile Composite Structures
- Manufacturing Process Development

Power & Energy



Energy Storage

Li-ion and Li-metal cell development
Pilot scale cell manufacturing line
Battery pack integration

Power Generation & Conversion

Hybrid-electric power systems and solid-state power converters

Power Distribution & Management

Digital circuit breakers & intelligent electrical load management
Digital twin, predictive maintenance

Battery & Cell Development Labs

Facility

- 174,000 ft^2 (total)
- >5400 ft^2 for cell and battery development, assembly, and test

Battery Cell Manufacturing

- 1000 ft^2 Dry Room
- Li-ion & Li-metal capable (dew point < -40°C)
- Semi-Automated Pilot Line
  - Pouch Cells (approximately 30 x 30 mm to 100 x 100 mm)
  - Li-metal compatible

Need: High Power Energy Storage

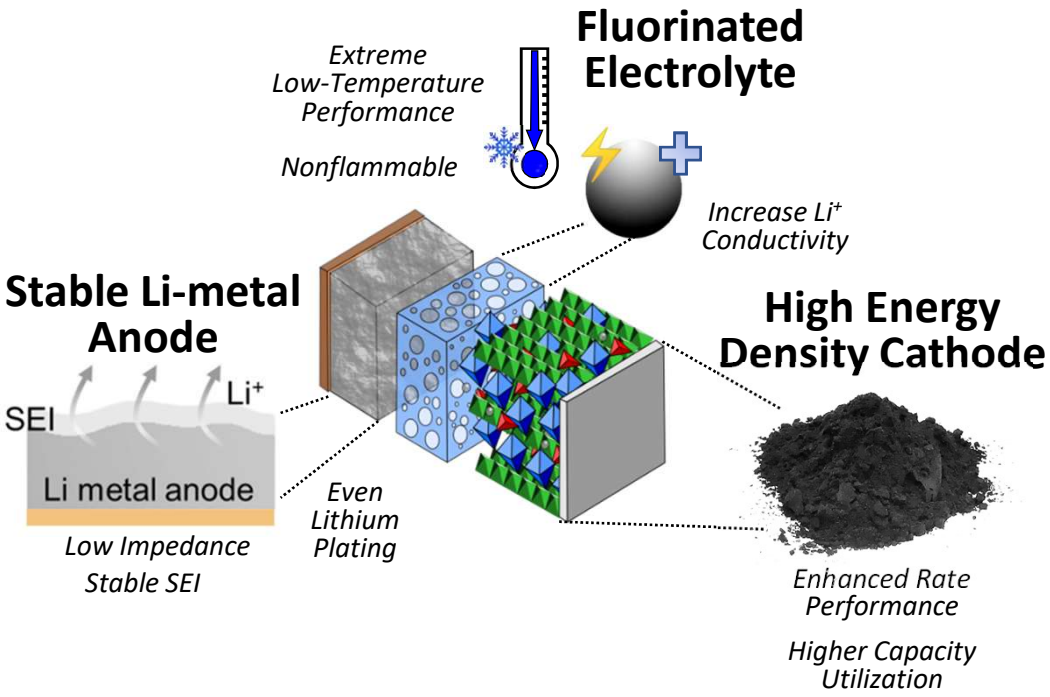
- Hybrid eVTOL needs high power batteries
  - Vertical take-off and transition to level flight
  - Emergency landings
  - Full discharge in 4 – 6 minutes: high power and discharge rate
- Battery charged on board during flight

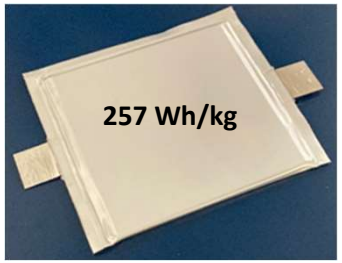
Light weight, safe, powerful batteries enabling hybrid eVTOL/UAM platforms

aEro 2 VTOL Aircraft, Dufour Aerospace

- COTS Li-ion power cells (pouch, 18650, 21700, etc.)
- 145 – 160 Wh/kg typical to enable 10C – 20C discharge rates

Power Cell Design





10.1 x 10.1 x 0.6 cm

Design:

- 6 Ah capacity
- 100 A terminals
- Large surface area format for heat rejection

Trade-offs:

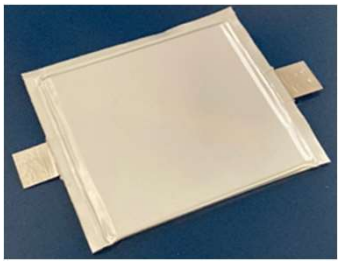
- High discharge current
- Minimized impedance
- Lower specific energy

Data Publicly Released at Power Sources 2023.
"Development of a High Power Rechargeable Li-Metal Cell".

eVTOL Hybrid Aircraft Battery

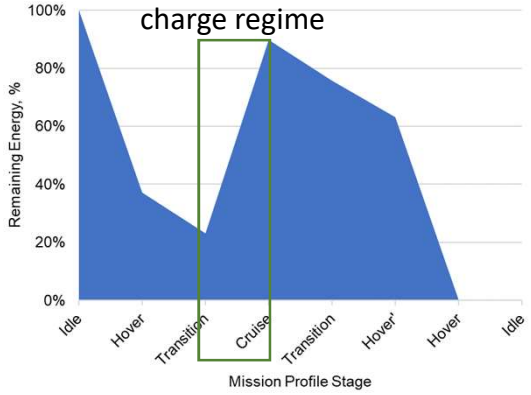
Example of a battery requirements for a hybrid eVTOL urban mobility vehicle

Stage	Stage Definitions	Duration, min	Cell discharge rate
Idle	Aircraft sits on the ground		0
Hover	VTOL climb	5	5-10C
Transition	Transition from VTOL climb to fixed wing cruise	0.5	15-20C
Cruise	Fixed wing cruise, **battery charged by generator**	40	1C
Transition	Transition from fixed wing cruise to VTOL hold	0.5	15-20C
Hover	VTOL hold before descent	1	5-10C
Hover'	VTOL descent	5	5-10C
Idle	Aircraft sits on the ground		



10.1 x 10.1 x 0.6 cm

- First transition is the most demanding
  - High power & partially discharged
- Cell testing
  - Rate stairs
  - Simulated flight profile



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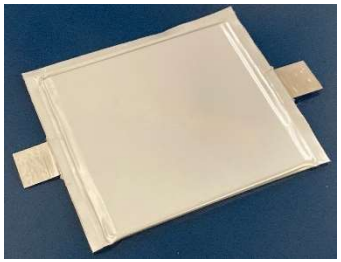
Power Pouch Cells

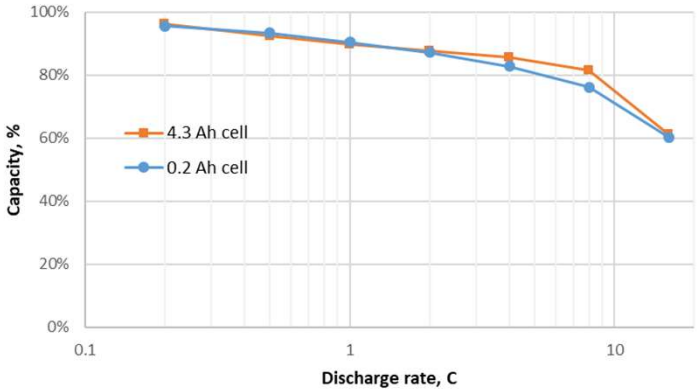
Rate performance

High energy cathode

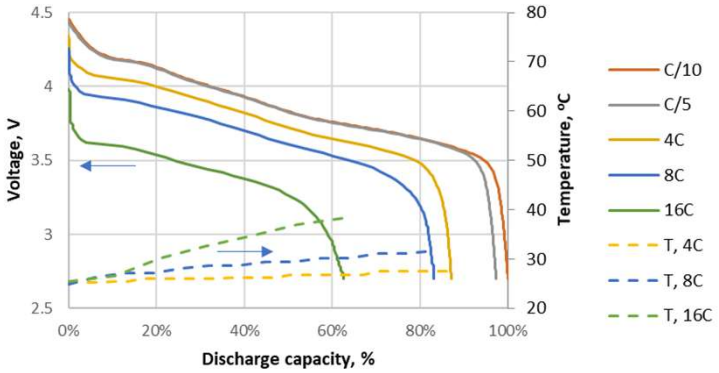
- 4.3 Ah multilayer cells
- CRG proprietary electrolyte
- Compared to subscale 0.2 Ah cells
- C/2 Charge to 4.5 V, discharge to 2.7 V



10.1 x 10.1 x 0.4 cm



<u>Moving from subscale pouches to full size cells:</u>
8 C rate performance improved from 76% to 82%
16C performance improved from 60% to 61%
Temperature increase during 16C = 68.6 A discharge: 25 °C -> 38°C
Comparable Li-ion cells can reach 60-80 °C at these currents



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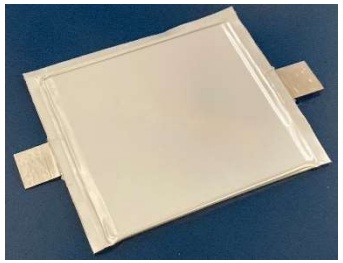
Power Pouch Cells

Simulated take-off flight profile

High energy cathode

- 4.3 Ah multilayer cells
- C/2 charge to 4.5 V, discharge to 2.7 V



10.1 x 10.1 x 0.4 cm

Simulated flight profile at increasing rates

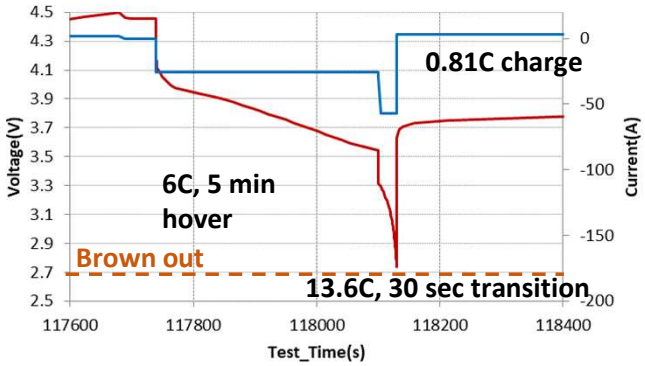
- CC charge at 22 °C to 4.5 V
- Discharge to 2.7 V

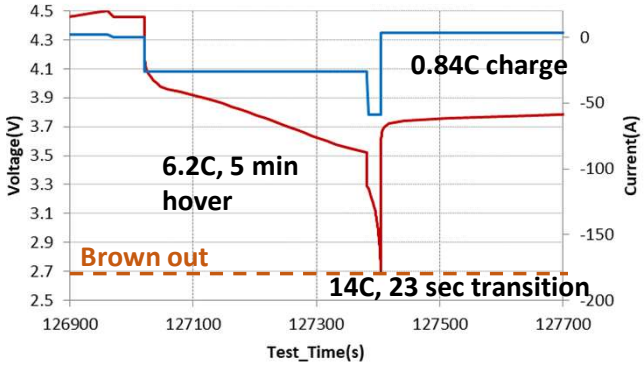
First hover + transition (aircraft take-off)

- Always fails first (brown out at <2.7V)
- High power output from a partially discharged state

6 Ah cells demonstrated further improvement

13.6C maximum discharge rate in first transition.
61% total discharge capacity





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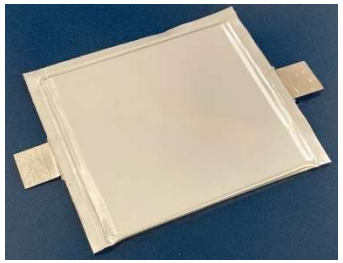
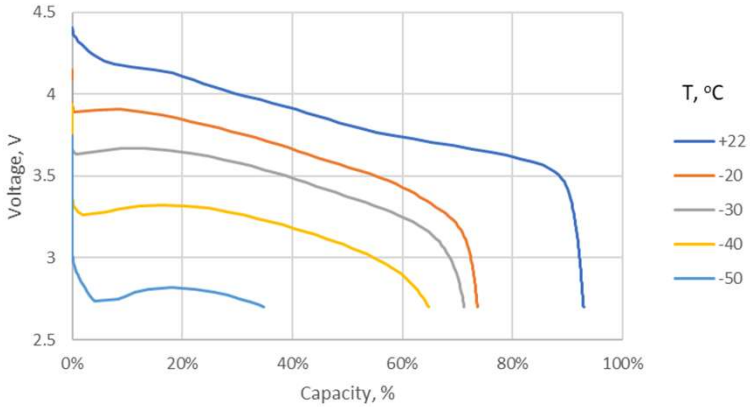
Power Pouch Cells

Low temperature performance



10.1 x 10.1 x 0.4 cm



Low temperature performance
C/2 charge at 22 °C to 4.5 V
4 hour soak
C/2 discharge at low temperature to 2.7 V

71% capacity at -30 °C
>34% at -50 °C

T, °C	Discharge capacity
22	92.9%
-20	73.6%
-30	71.2%
-40	64.8%
-50	34.8%

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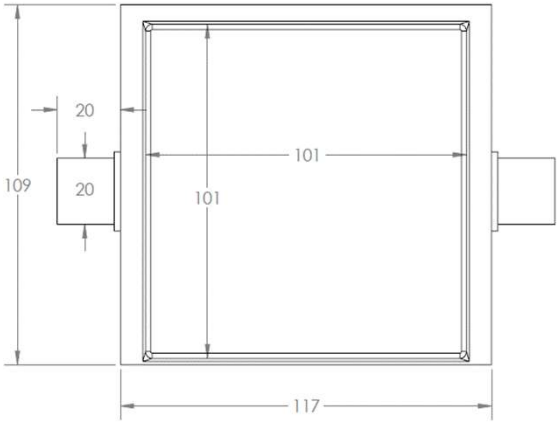
Preliminary Spec Sheets



CRG Li-metal

	CRG Li-metal
Nominal capacity, Ah	6
Nominal specific energy, Wh/kg	230 - 257
Nominal voltage, V	3.86
Voltage range, V	2.7 – 4.5
Cell dimensions, cm	10.1x10.1x0.6
Cell weight, g	90 - 100
Cycle life, C/2 rate	~130 - 145 cycles
Max discharge, sustained	16 C

COTS Li ion comparison

Kokam SLPB11543140H5	Samsung INR18650-20R
5	2
140	160
3.6	3.6
2.5 – 4.2	2.5 – 4.2
14.25x4.3x1.17	6.5x1.83 diam.
132	45
1000	>250
30 C	11 C

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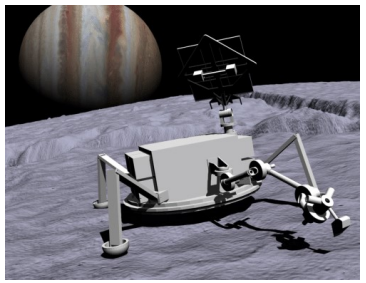
Need: High Energy, Low Temperature Energy Storage

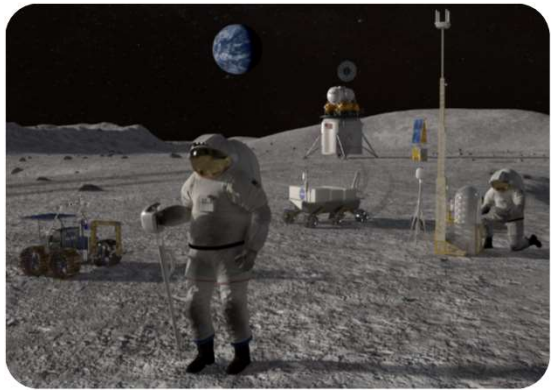
Deep space missions:
Europa, Enceladus, Titan, etc.

- Operation to -200 °C
- 30 to 60 days duration



Lunar surface applications:

- Operation at -230 to +120 °C
- Lunar night survival and operations



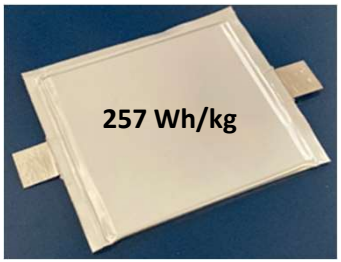
Rechargeable cell-level goals:

- >250 Wh/kg specific energy
- >500 Wh/L energy density
- Eliminate or reduce battery management

COTS Li-ion cells (pouch, 18650, 21700, etc.)

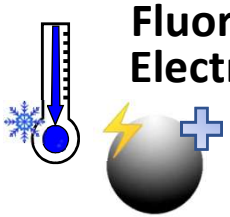
- Typical: no energy at -30°C
- Exceptional: ~1/4 energy at -50°C

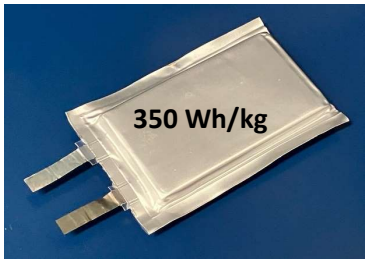
Low Temperature Cell Design



10.1 x 10.1 x 0.6 cm

Low-Temperature Fluorinated Electrolytes





6.2 x 3.5 x 0.7 cm

- 6 Ah capacity
- 100 A terminals
- Large surface area format for heat rejection

Trade-offs:

- High discharge current
- Minimized impedance
- Lower specific energy

- Heavier cathode
- Compact format
- Three new electrolytes

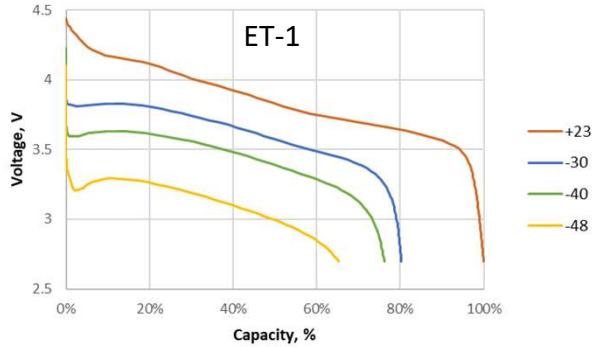
- 3 Ah capacity
- 10 A terminals

Trade-offs:

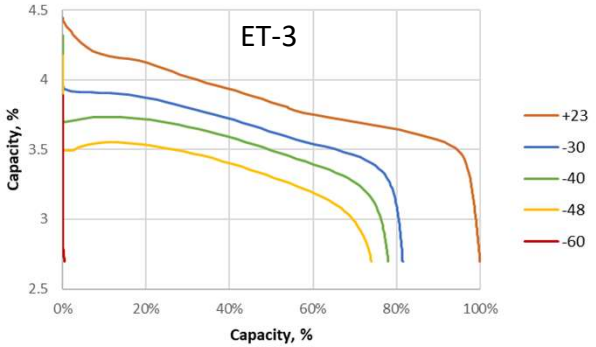
- High specific energy
- Discharge current limited by terminals
- Improved low temperature performance

Low Temperature Pouch Cells

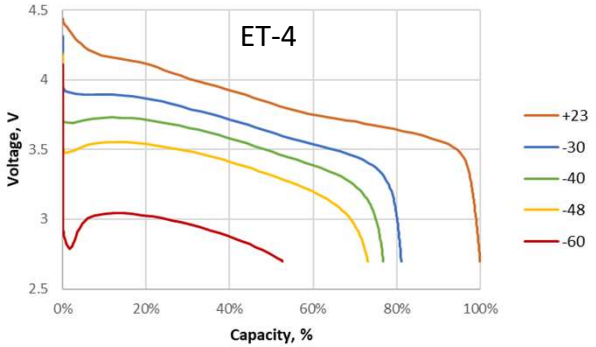
Low temperature performance with three custom electrolytes: ET-1, ET-3 and ET-4



75% capacity at -40 °C
63% capacity at -48 °C
Not tested below -48 °C



77% capacity at -40 °C
73% capacity at -48 °C
No capacity at -60 °C



77% capacity at -40 °C
73% capacity at -48 °C
53% capacity at -60 °C

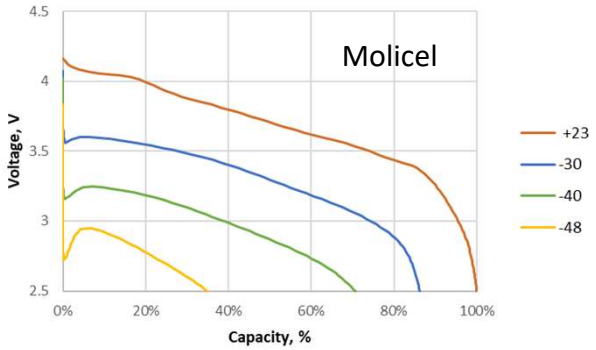
- 0.5 A Charge to 4.5 V (C/6) at 23 °C
- 4 hour soak
- 0.8 A discharge to 2.7 V (0.27C)

Low Temperature Performance, COTS Li-ion Cells

Molicel INR-18650-P28B

- 2.8 Ah nominal, 2.5 – 4.2 V, 45.26 g
- Actual capacity 2.7 Ah at room temperature
- 220 Wh/kg

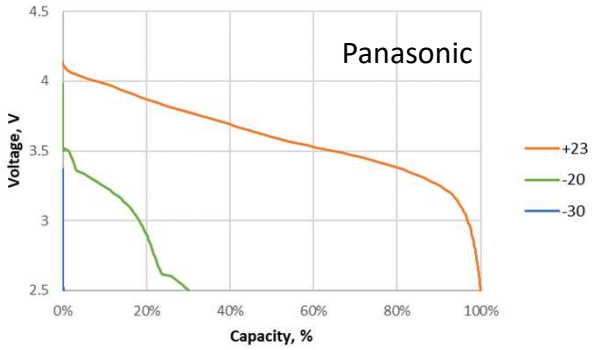
70% capacity at -40 °C
35% capacity at -48 °C
Not tested at -60 °C



Panasonic NCR18650B

- 3.4 Ah nominal, 2.5 – 4.2 V, 45.4 g
- Actual capacity 3.2 Ah at room temperature
- 250 Wh/kg

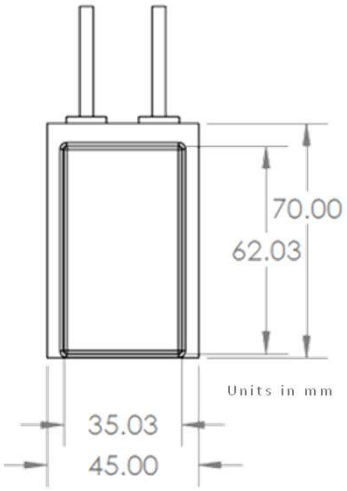
30% capacity at -20 °C
No capacity at -30 °C

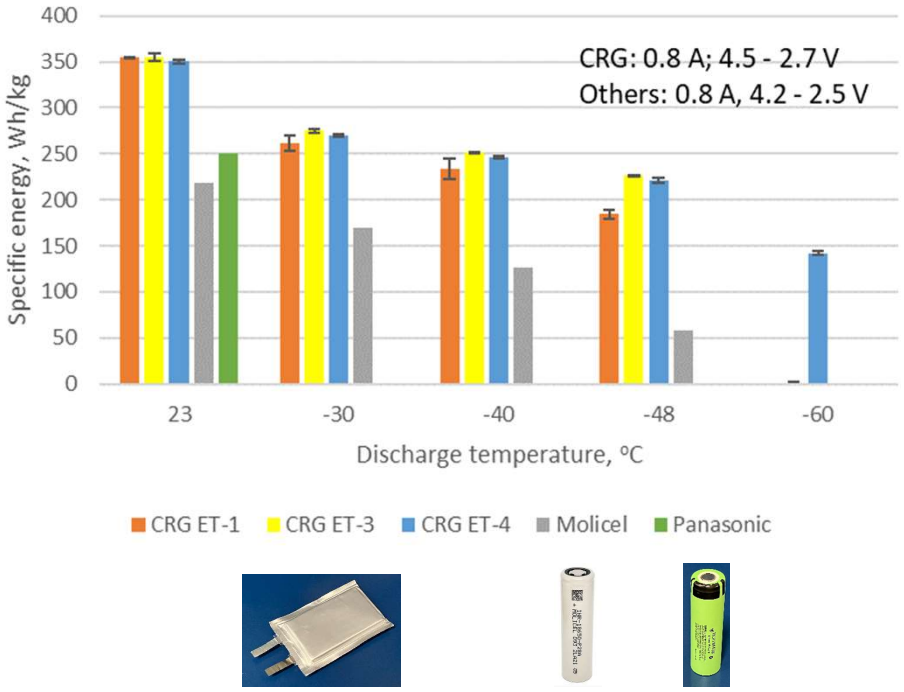


- 0.5 A Charge to 4.2 V at 23 °C
- CCCV, C/20 current cut-off
- 4 hour soak
- 0.8 A discharge to 2.5 V

Specific Energy Vs. Temperature Comparison

	CRG Li-metal
Nominal capacity, Ah	3
Nominal specific energy, Wh/kg, room temperature	350
Nominal voltage, V	3.86
Voltage range, V	2.7 – 4.5
Cell dimensions, cm	6.2x3.5x0.7
Cell weight, g	33
Cycle life, 0.5 A charge / 0.8 A discharge	~60 - 140 cycles
Max discharge, sustained	10 A





CRG ET-1 cells have also been tested with charge voltage reduced to 4.3 V

10% specific energy reduction, same temperature performance

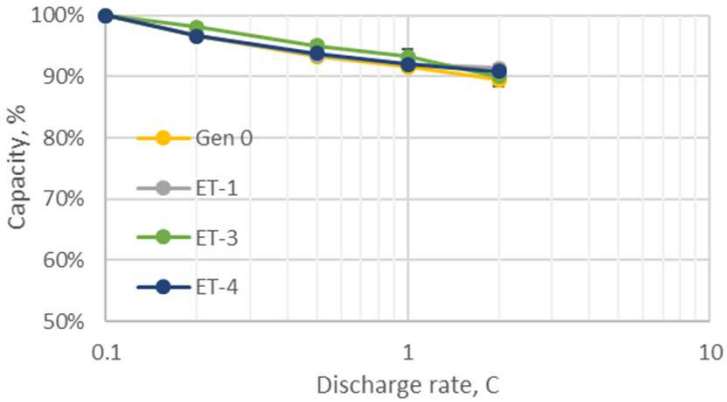
Low Temperature Pouch Cells

Rate performance

6.2 x 3.5 x 0.7 cm

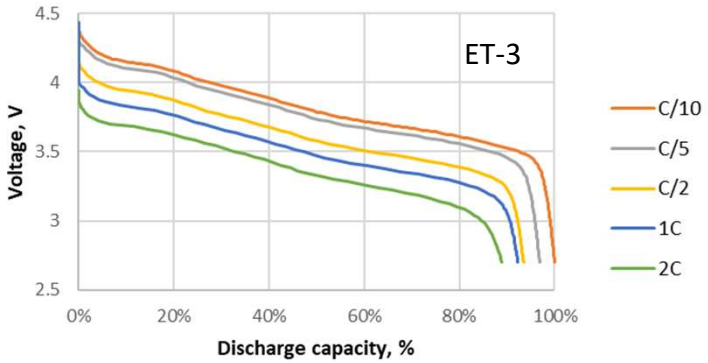
3 Ah multilayer cells

- CRG proprietary electrolytes
- Gen 0 – same as in power cell
- C/5 Charge to 4.5 V, discharge to 2.7 V



<u>Cells limited to 10 A by terminals, tested up to 2C discharge rate</u>

1 C rate performance very similar, 91% to 93%
2 C rate performance very similar, 89% to 91%



Prototype Low Temperature Battery

Nominal capacity, Ah	6
Nominal specific energy, Wh/kg, room temperature	220
Nominal voltage, V	15.4
Configuration	4S:2P
Voltage range, V	10.8 – 18
Dimensions, cm	10 x 7.8 x 4.6
Weight, g	416.4
Cycle life, 1 A charge / 1.6 A discharge	~60 - 140 cycles
Max discharge, sustained	20 A

Nett Warrior connector

6.2 x 3.5 x 0.7 cm

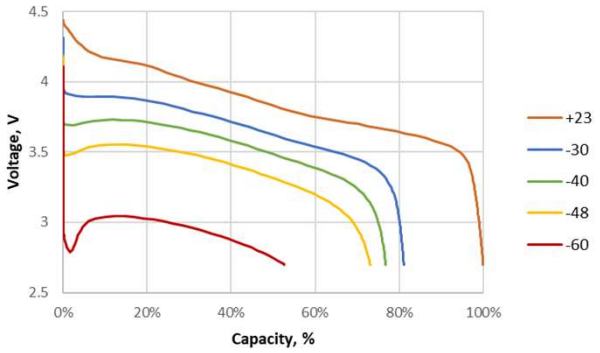
Battery prototype is under testing

Defense Applications: Man Portable Power

- Radio Battery
- Small Tactical Universal Battery (STUB)
- BB2590 Portable Battery
- Ballistic Conformal Battery
- Smart Rail Battery
- Helmet Communication Battery

Conclusions

- Li-metal anodes improve energy density
  - 60-70% increases in Wh/kg
  - Battery weight reduction or capacity increase
- High energy cathode AM is beneficial for rate and temperature performance
  - Thinner cathode, less overpotential
- 4.5 V is beneficial for rate and temperature performance
  - Wider voltage window
- Electrolyte for -60^{o}C is an exciting development



Thank **You**

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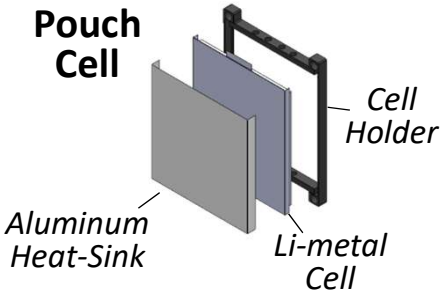
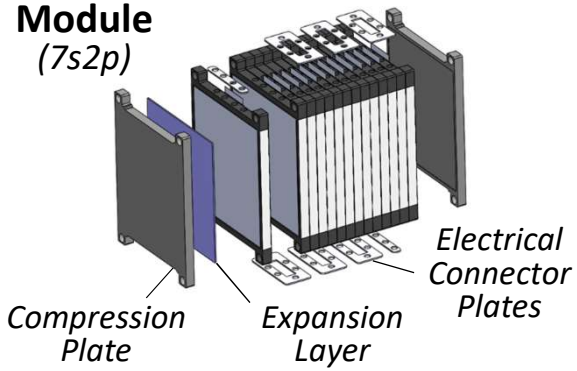
Defense Applications

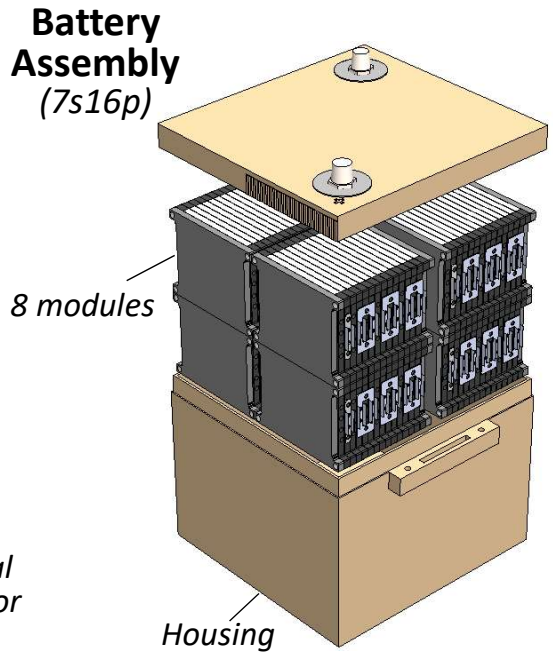
- Man portable power
- Unmanned air systems
- Hybrid/electric ground vehicle power
  - Fault tolerant high energy batteries
  - Directed energy weapons
  - 6T or custom format packs
- Maritime propulsion



Vehicle Battery (6T)







Battery Assembly Level		
Config (S x P)	7x16	(S x P)
Total Cells	112	Cells
Nom. Voltage	25.9	V
Cell Fill	54%	%
Cell Mass	16.0	kg
Total Battery Mass	23.5	kg
Capacity	163	Ah
Specific Energy	179	Wh/kg