CAM-7®/LTO Lithium-Ion Cells for Logistically Robust, Damage-Tolerant Batteries

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2017 Joint Services Power Expo
Virginia Beach, VA
May 3rd, 2017

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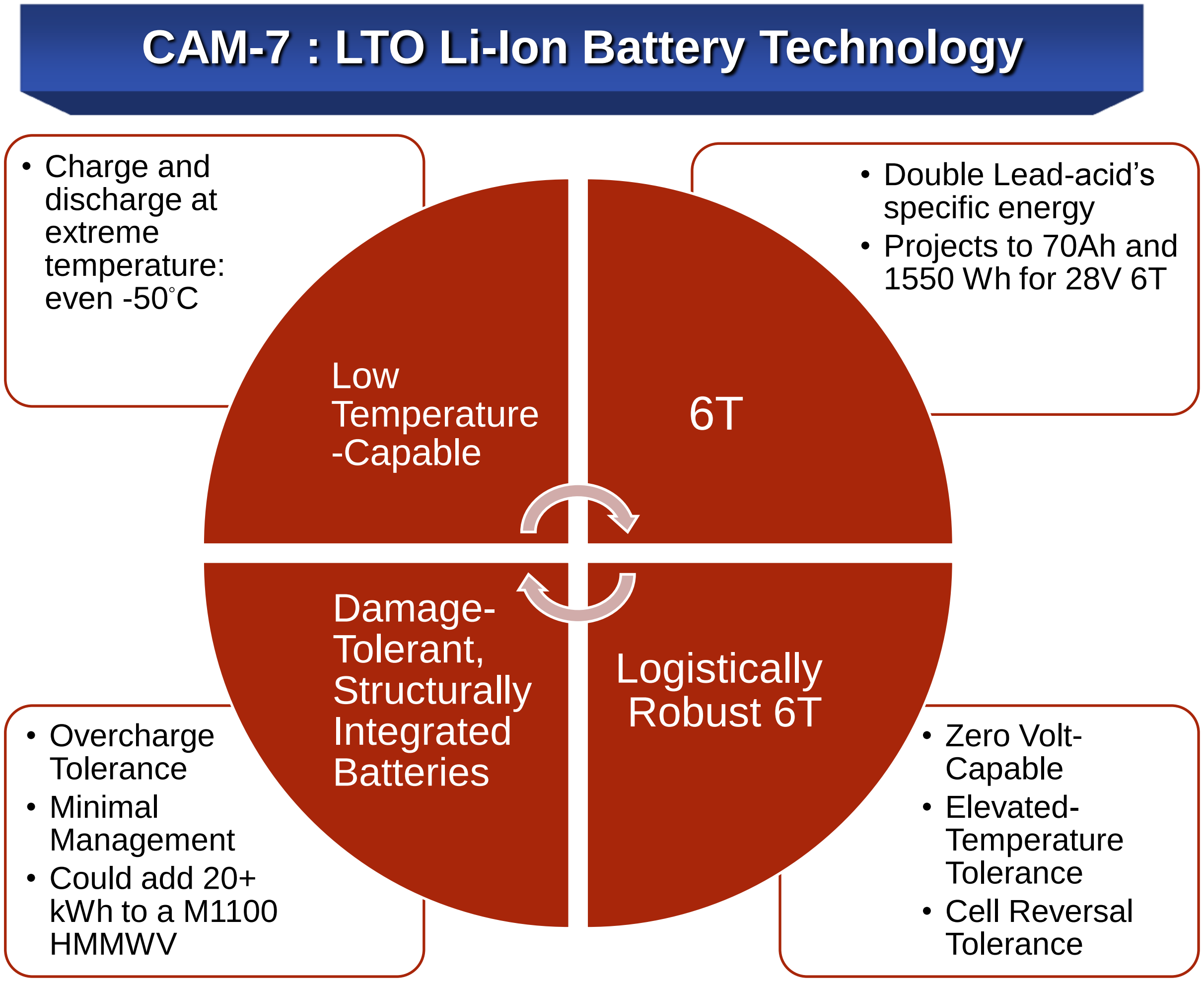
CAMX Power is developing a high-performance CAM-7:LTO based Li-ion battery technology with attractive properties for DoD applications.

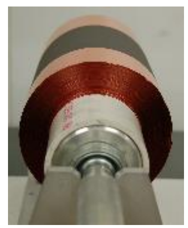


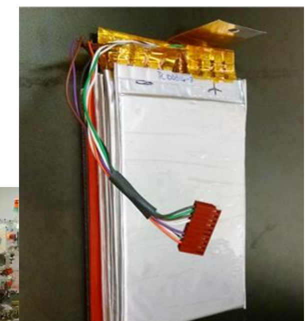
This presentation will review CAMX Power's development of CAM-7 cathode, LTO anode pouch cell technology for military vehicle batteries.

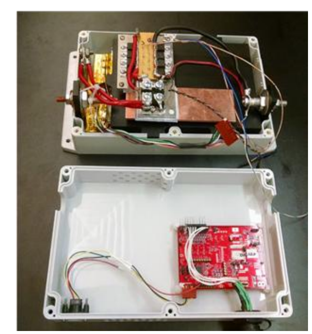
- Introduction and Background on CAM-7, LTO, and 24V 6T Li-ion batteries
- Low-temperature-capable CAM-7/LTO cells for 6T batteries
- CAM-7/LTO 6T-based demonstration module
- CAM-7/LTO cells for logistically robust 6T batteries
- CAM-7/LTO cells for damage-tolerant, structurally integrated batteries.

CAMX Power has the capability and facilities for prototyping of custom battery packs for DoD applications employing novel, high performance materials.

Materials Development → Materials Scale-Up → Electrode & Cell Development → Cell Prototyping → Prototyping of Packs







We recently licensed our CAM-7 high performance cathode material platform to two leading battery materials producers.

BASF We create chemistry

CAMX Power

Joint News Release

BASF obtains battery material license from CAMX Power LLC

License brings together global strength of BASF with product platform capable of increasing energy density of lithium-ion batteries

Iselin, N.J, and Lexington, MA – April 12, 2016 – BASF and CAMX Power LLC today announced that BASF has been granted a license under the intellectual property of CAMX Power LLC (CAMX) relating to the CAMX suite of CAM-7™ cathode materials for lithium-ion batteries. CAM-7 is a patented cathode material that harnesses the unique properties of high-nickel compounds to deliver high energy density with high-power capability.

"In BASF testing, the CAM-7 product platform has shown strong performance and is believed to have the potential to further increase energy density of lithium-Ion batteries," said Kenneth Lane, President of BASF's Catalysts division. "CAMX has established a strong global IP position and we will be collaborating with CAMX's experienced technical staff to develop advanced processing techniques to bring these products to the marketplace."

JM Johnson Matthey

CAMX Power

For release at 9am on Tuesday 14 June 2016

Johnson Matthey obtains high energy battery materials licence from CAMX Power LLC

Johnson Matthey and CAMX Power LLC (CAMX) announce that Johnson Matthey has been granted a licence under the intellectual property of CAMX relating to the CAM-7 platform of nickel based cathode materials for use in lithium-ion batteries.

The CAM-7 platform covers a range of patented, nickel rich cathode materials which offer excellent performance across a range of features including energy density, cycle life, gassing and power handling. This makes products based on this technology particularly suited to demanding applications, such as battery electric vehicles and plug-in hybrid electric vehicles, delivering high energy density with high power capability. With its experience in the scale-up and manufacture of battery materials, in-depth knowledge of nickel chemistry allied to its customer focused technical organisation, Johnson Matthey is well placed to bring CAMX Power's innovative technology to market to meet the rising demand for high energy cathode materials.

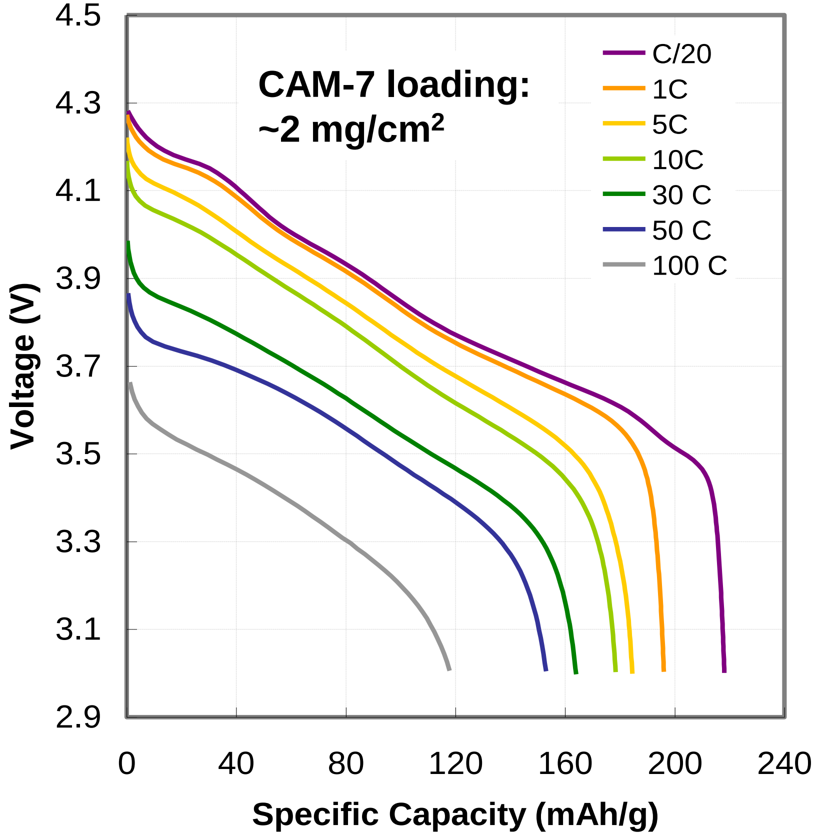
"This licence is another important step in our Battery Technologies strategy where we are building a broad portfolio of battery materials aimed at satisfying the most demanding performance requirements," said Martin Green, Director of Johnson Matthey's Battery

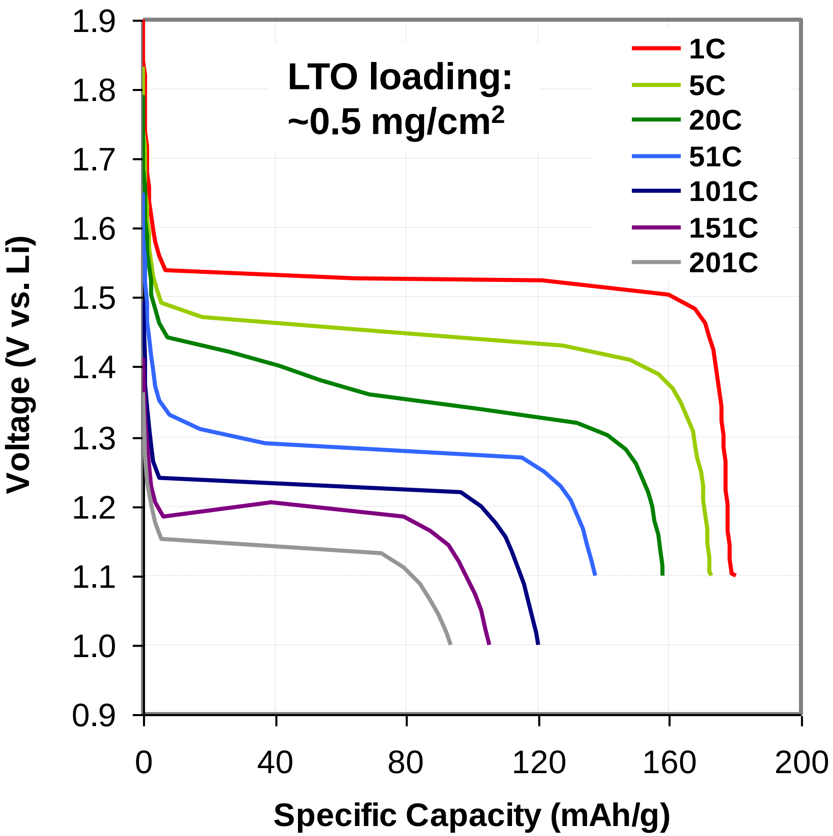
CAMX Power is implementing our CAM-7 cathode material opposite high rate capability commercial LTO anode in high performance Li-ion pouch cells.

- CAMX Power's proprietary CAM-7 cathode material is being paired with high rate-capable LTO and custom-designed electrolytes in pouch cell designs.
- We consistently find that the CAM-7/LTO pouch cells have:
  - Excellent power capability to extreme low temperatures.
  - Excellent cycle life.
  - Excellent tolerance of high temperature storage/cycling with little or no gas generation.
  - Excellent abuse tolerance.
  - Tolerance of overcharge and over discharge.

Both CAM-7* and nanostructured LTO (~10 m^2/g) have outstanding rate capability for charge and discharge

RT discharge of low-loading half cells

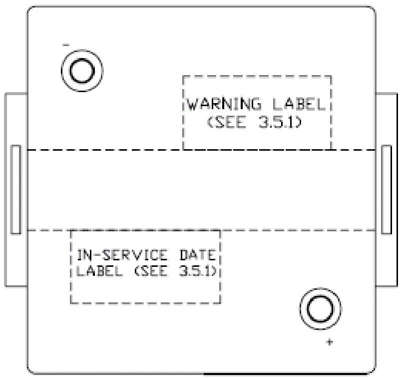


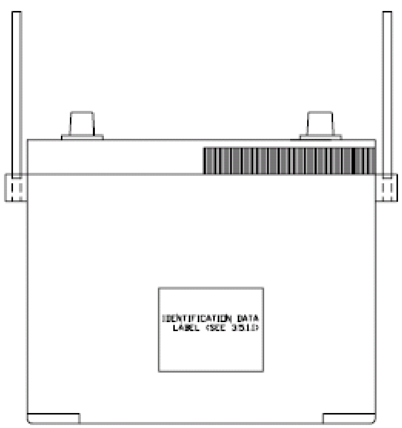


***CAM-7 is a $LiNiO_2$-based material that has been licensed to BASF and Johnson Matthey for commercialization**

Draft Li-ion 6T battery specification suggests cold cranking challenge.

- **6T form factor:**
- **~27cm x 29cm x 23cm**

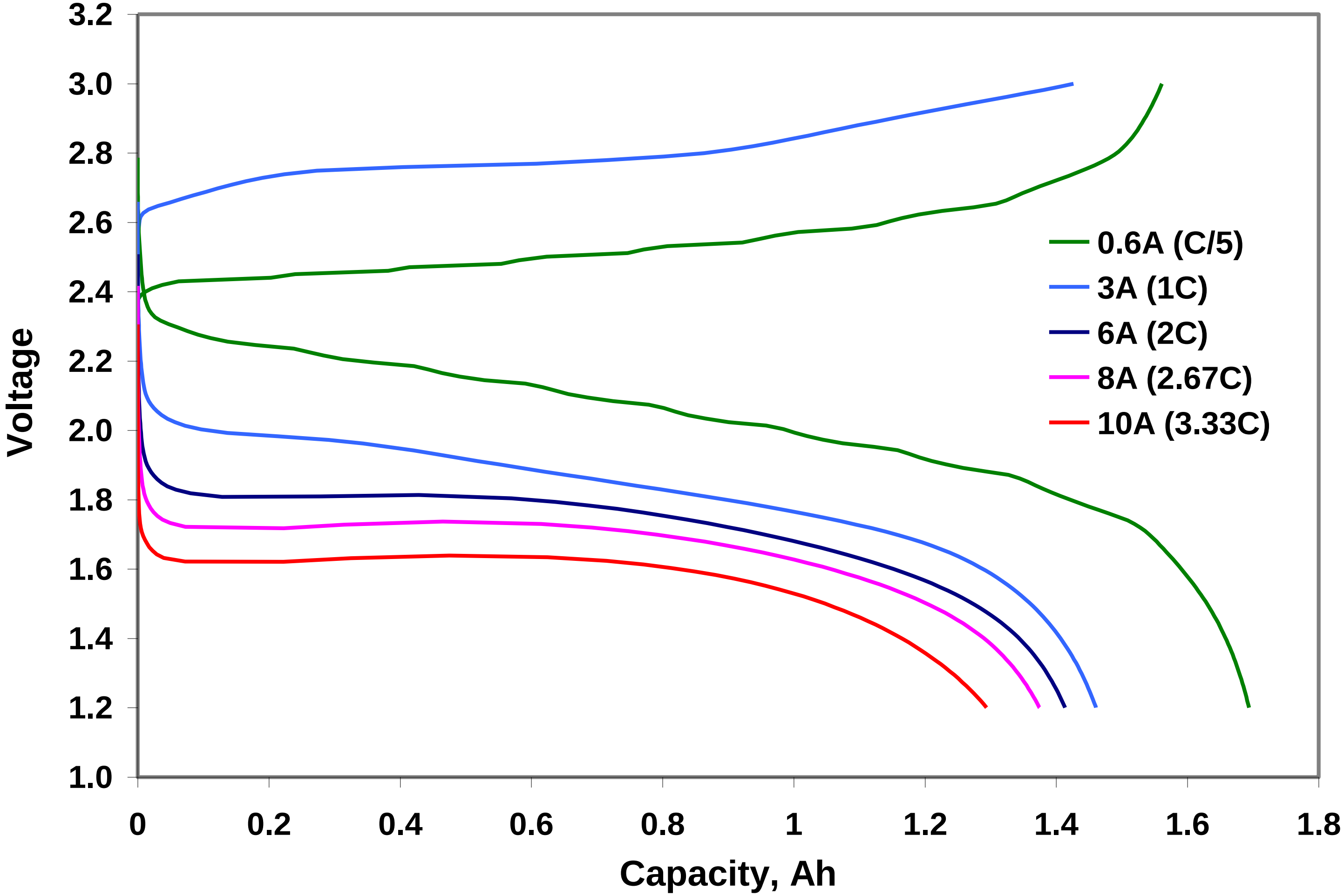




From MIL-PRF-LIBATT/1(CR), 11/18/2015

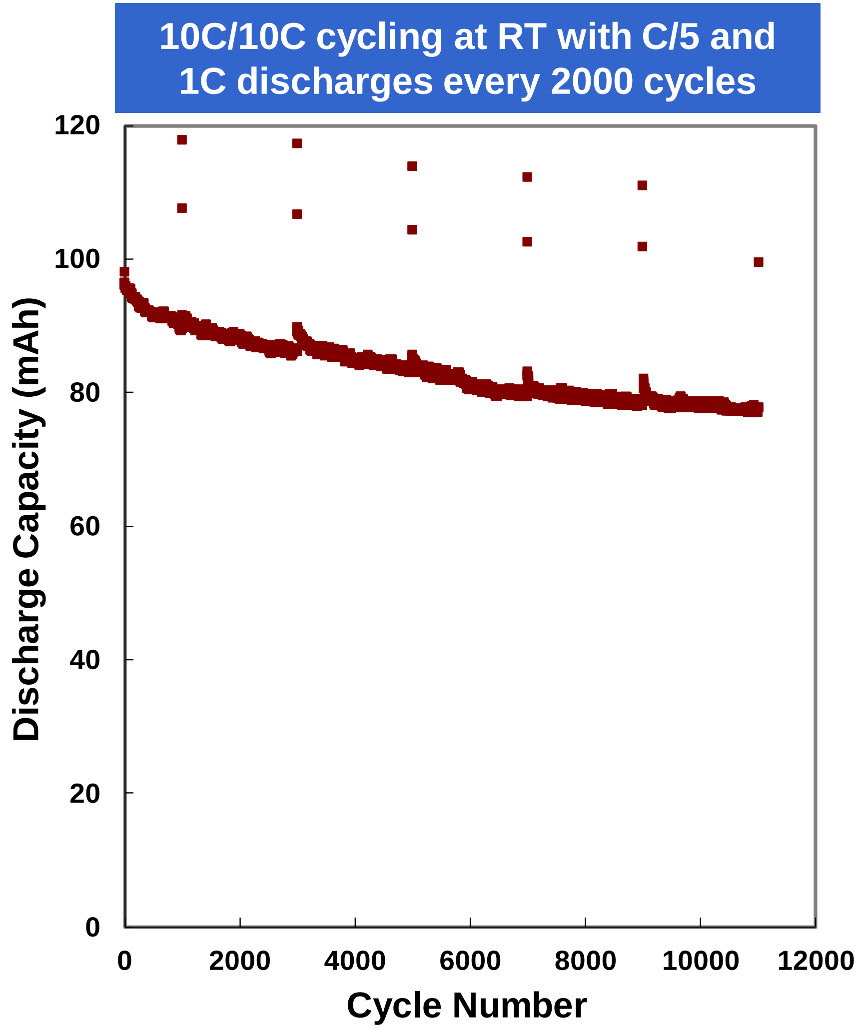
Classification	6TLi-Type1	6TLi-Type2	6TLi-Type2
Charge voltage	28.5 V	28.5 V	28.5 V
C/20 capacity	60 Ah	60 Ah	105 Ah
Cold Cranking (no pre-heating):	600 A for 30 sec at -18ºC 200 A for 30 sec at -40ºC	600 A for 30 sec at -18ºC 200 A for 30 sec at -40ºC	1100 A for 30 sec at -18ºC 400 A for 30 sec at-40ºC
Cold Cranking (5 minutes pre-heating):	1100 A for 30 sec at -18ºC 400 A for 30 sec at -40ºC	1100 A for 30 sec at -18ºC 400 A for 30 sec at -40ºC	1100 A for 30 sec at -18ºC 400 A for 30 sec at-40ºC
Minimum V	14.4 V	14.4 V	Per MILSTD-1275
Pulse load rating	1100A, 30 sec.	1100A, 30 sec.	1100A, 30 sec.
Deep Cycle Life:	≥ 1000 at 38 ºC	≥ 1000 at 38 ºC	≥ 1000 at 38 ºC
Operating temp.	-46° to 71 °C	-46° to 71 °C	-46° to 71 °C
Storage temp.	-54° to 84 °C	-54° to 84 °C	-54° to 84 °C
SAE Hazard level	≤4	≤6	≤6

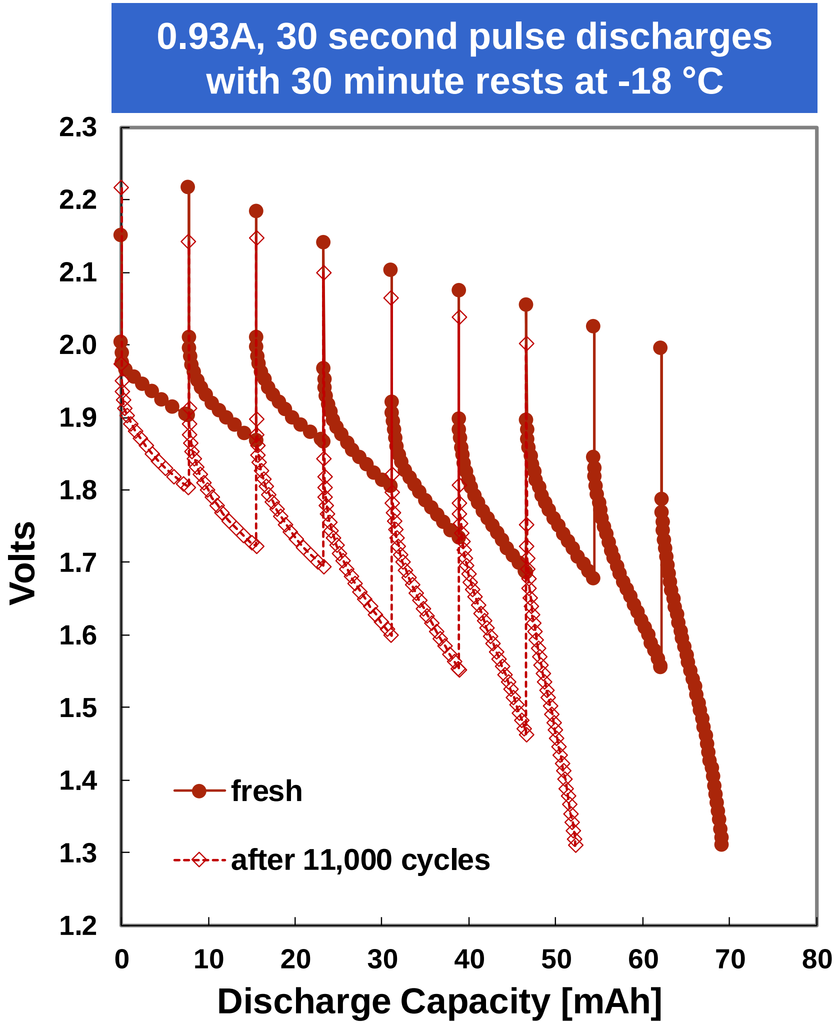
CAM-7/LTO cells with electrolyte formulated for low-temperature performance can be charged and discharged at -50 °C (-58 °F).



3 Ah cell: 1.7 mAh/cm² charged and discharged at -50 °C

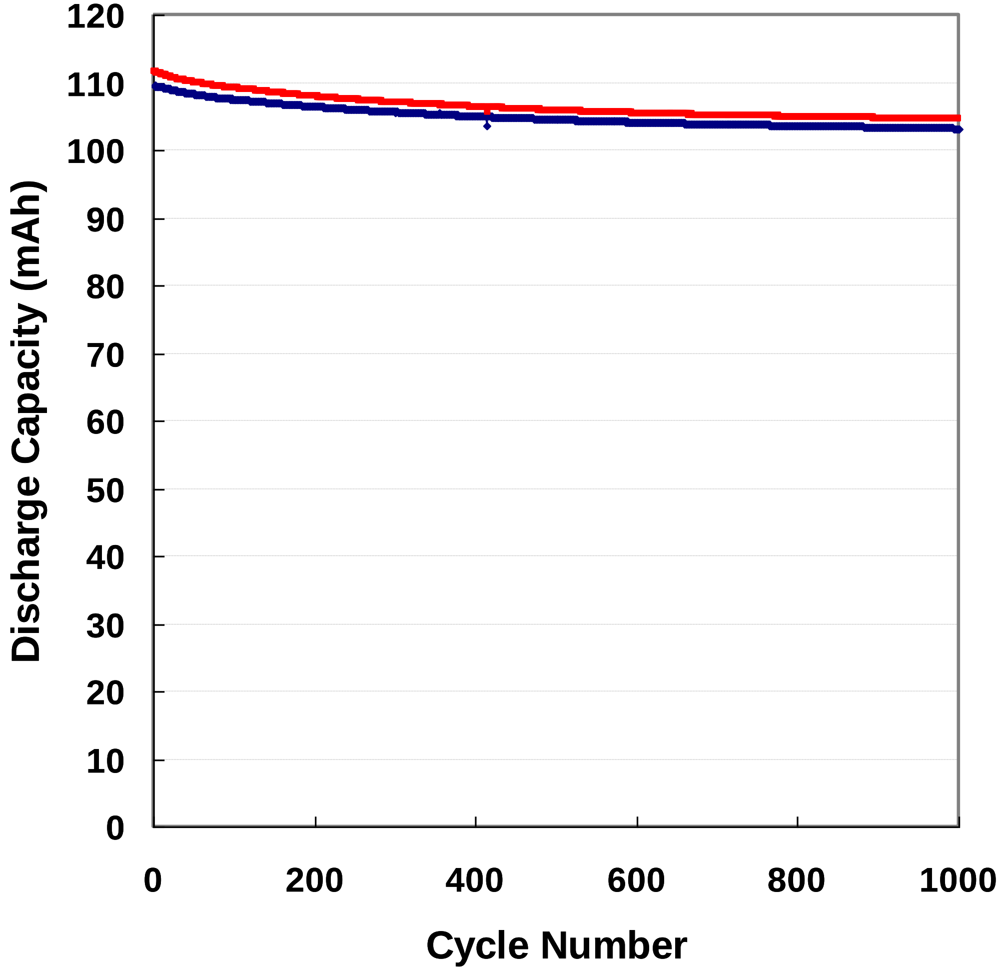
Cells retain cold-cranking capability for over 11,000 cycles (at 10C/10C).

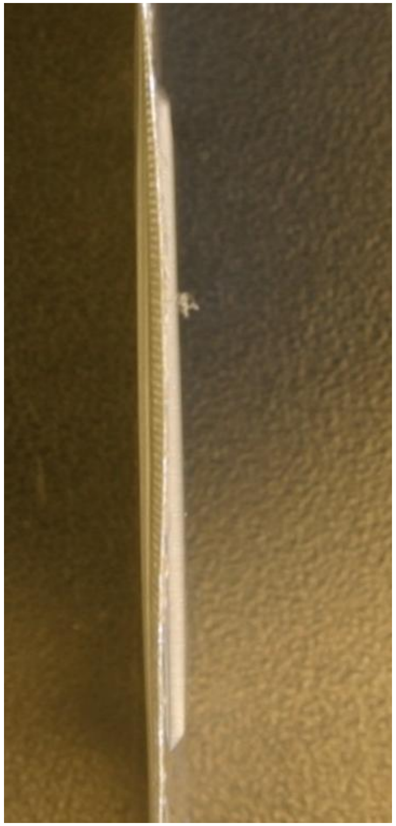




Unfixtured 120 mAh cell: 2.59V – 1.31V. Cold-cranking current scaled to 600 A in 6T

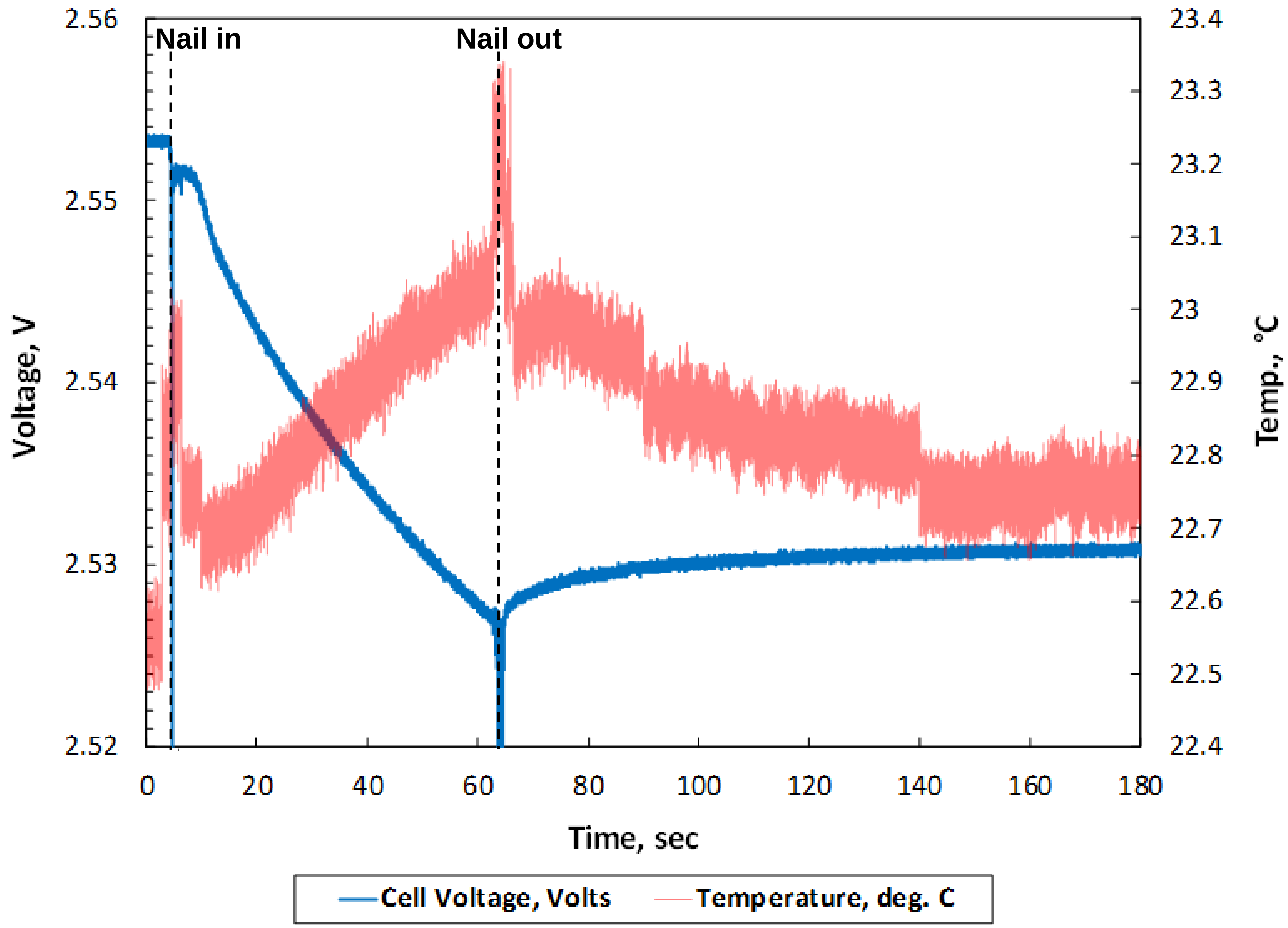
Cycle life at 45 °C (113 °F). is excellent: no evidence of gassing





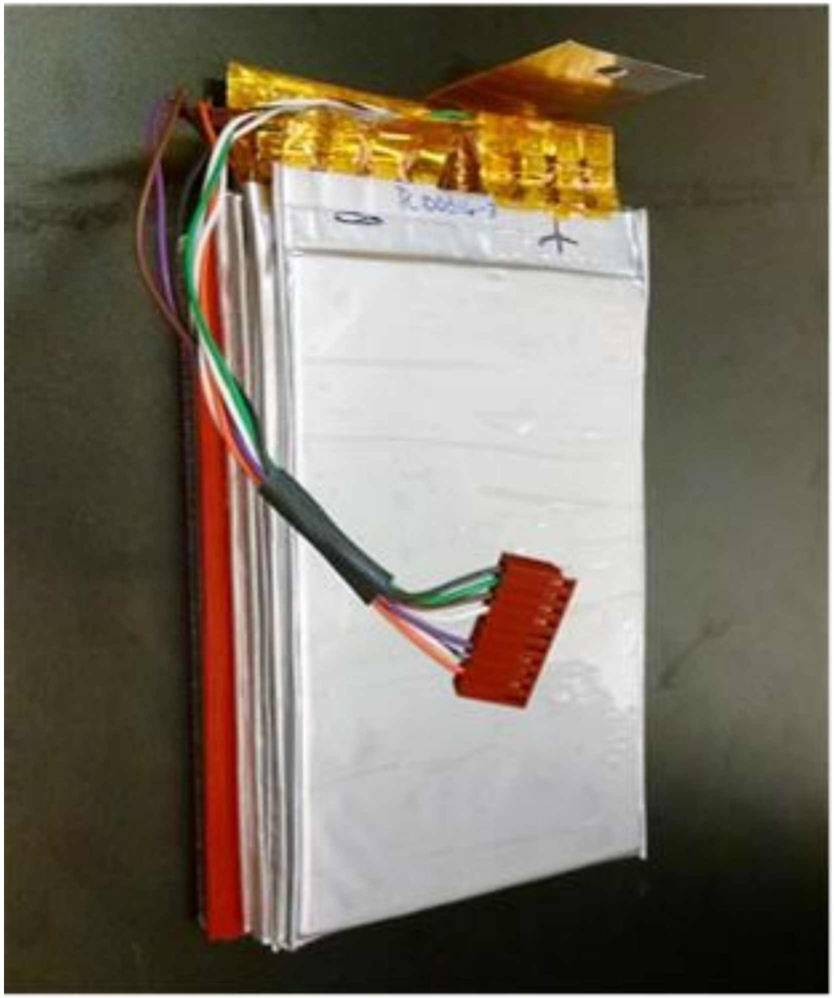
120 mAh cells: ~1.3 mAh/cm^2, 10C/10C cycling 2.43V-1.2V unclamped

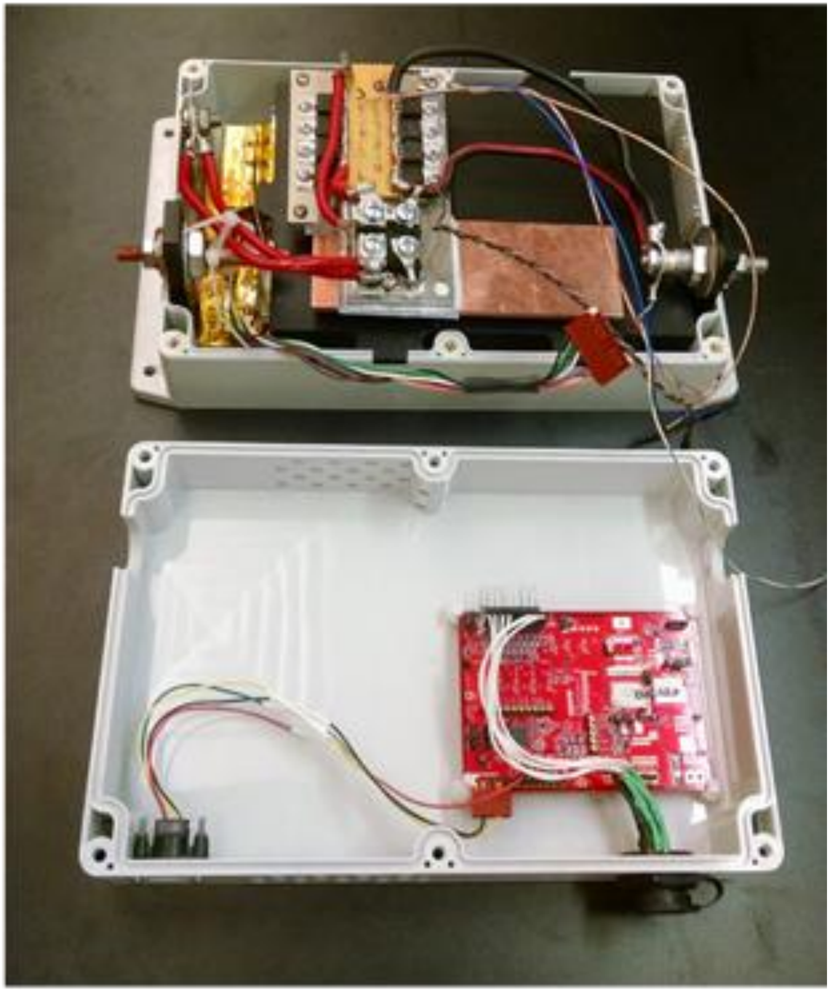
CAM-7/LTO cells have excellent abuse tolerance (e.g., to nail penetration).



2.7 Ah cell charged to 2.65V undergoing blunt 2mm diam. nail penetration at 1 cm/sec

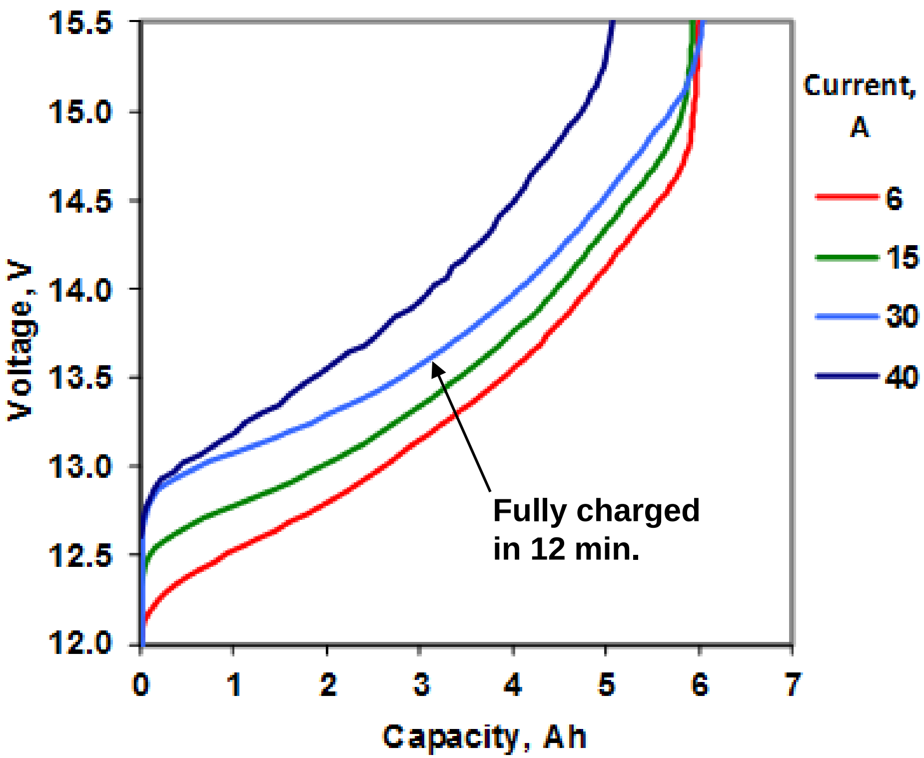
An initial stand-alone system based on a 6-series cell, 6 Ah, 15V module, fully integrated with electronics, was assembled with CAM-7/LTO cells.



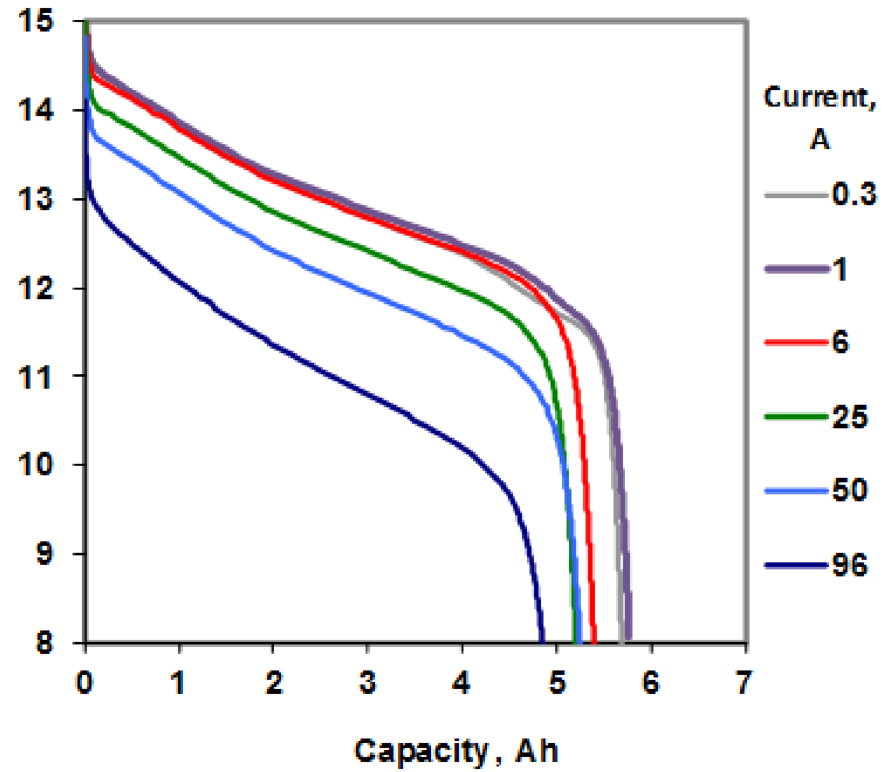


The 15.5 V, 6 Ah module can be charged and discharged at high rates.

RT charge of 6 Ah pack



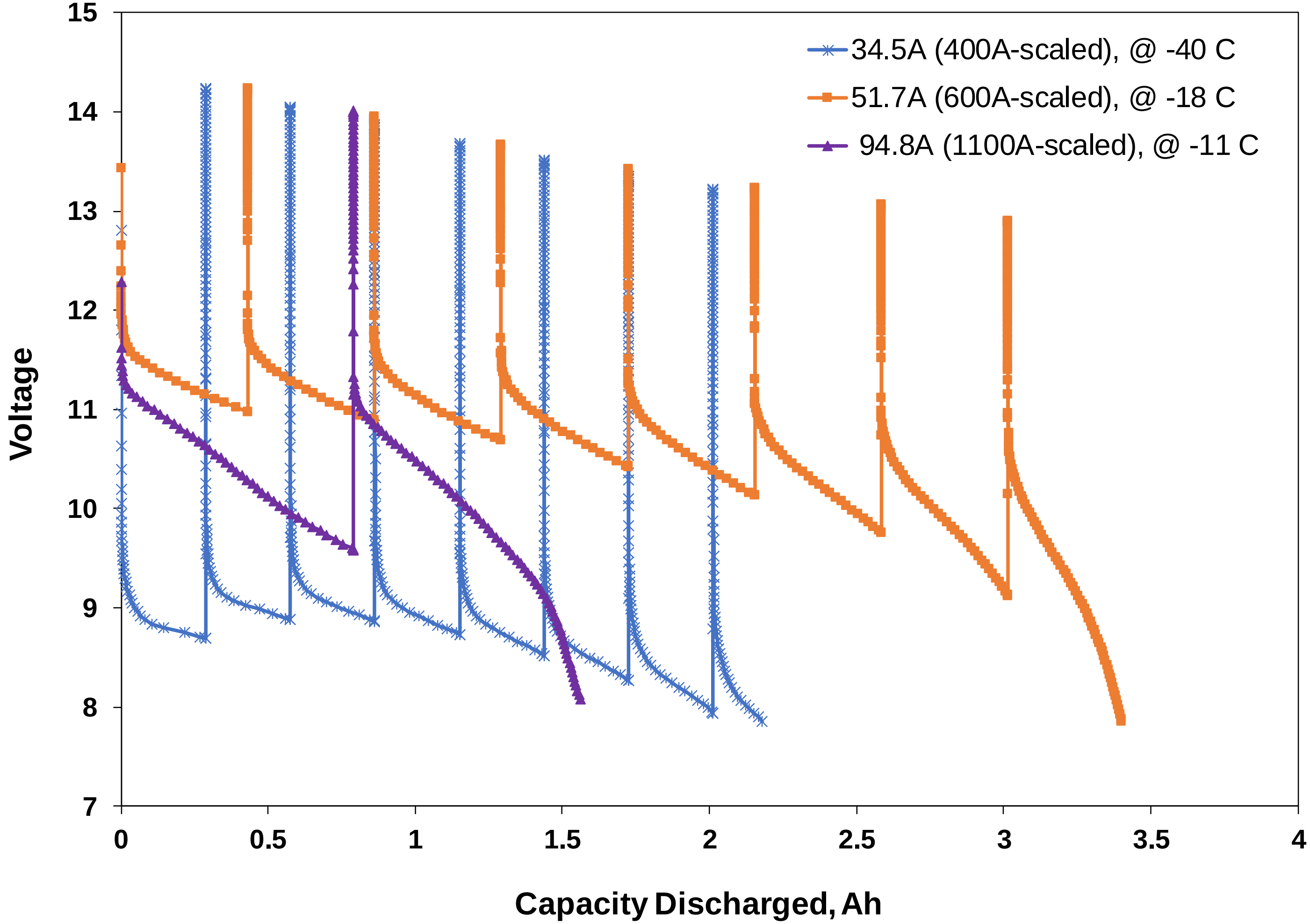
RT discharge of 6 Ah pack



15.55 V - 7.86 V module cycling limits are scaled to 6T limits of 28.5V - 14.4V.

73 Wh max. discharge energy corresponds to 78 Wh/kg at cell level, and projects to 70 Ah and 1550 Wh for 6T with 62% of volume occupied by cells.

Module meets scaled cold-cranking requirements of Li-ion 6T draft specification.

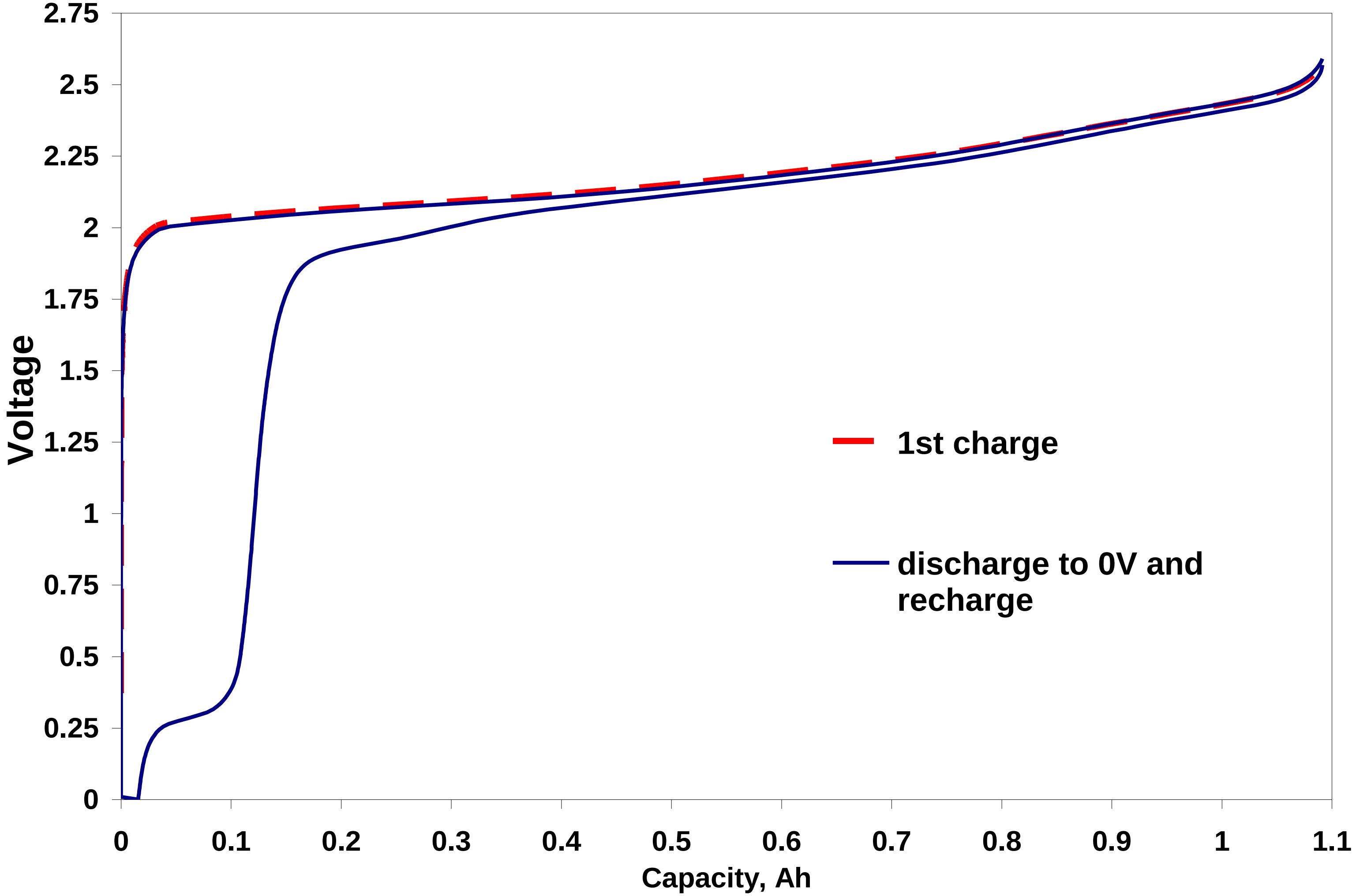


30 second pulses: 30 minutes rest between pulses to negate self-heating.

CAM-7/LTO cells can be reversibly stored at 0V, thereby easing logistical burdens.

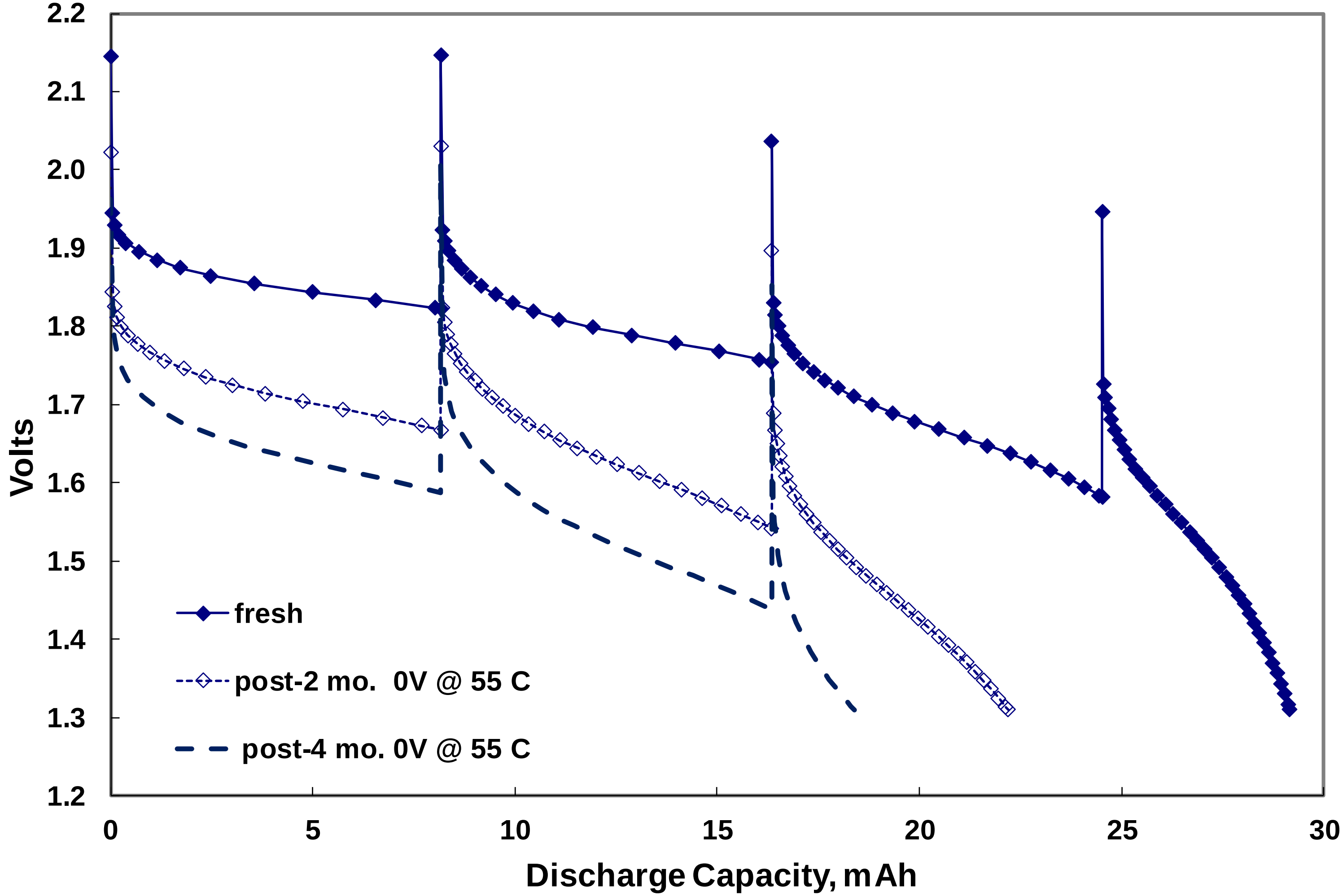
- Completely de-energized batteries can greatly ease logistical burdens by:
  - Being fundamentally safer.
  - Having longer shelf life (even if exposed to high temperatures).
  - Enabling close-packing in bulk for transportation and storage.
  - Eliminating burdensome monitoring and maintenance.

Charging after discharge to 0V reproduces 1st charge; cell is unchanged.



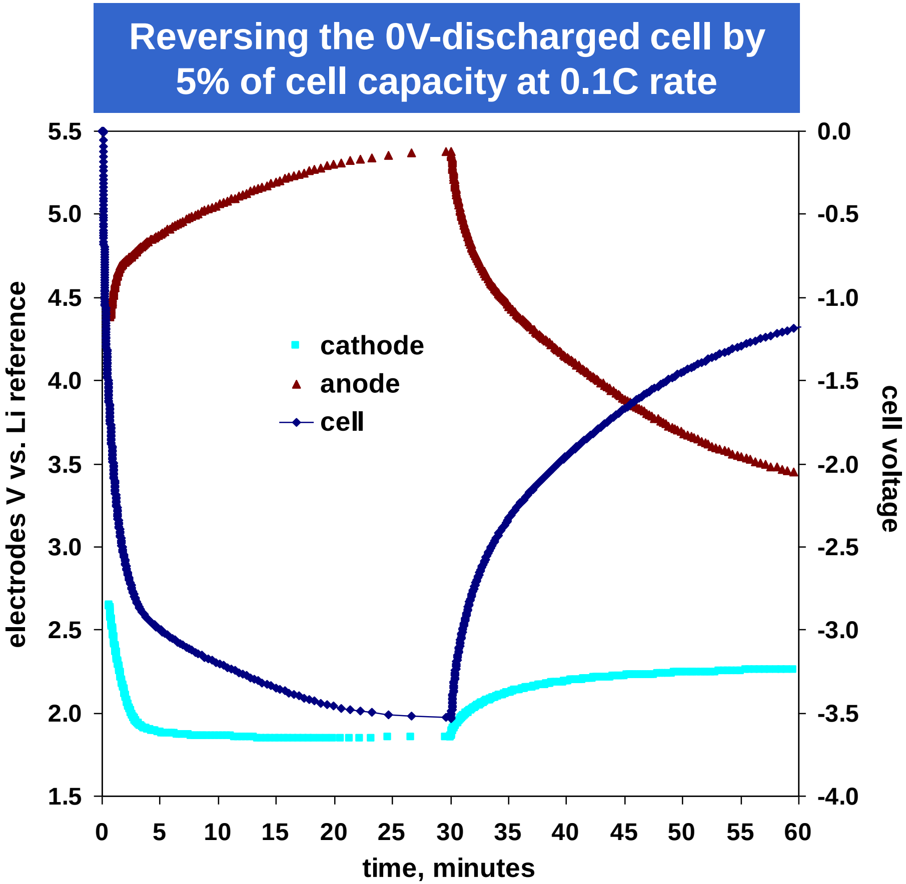
1.1 Ah pouch cell

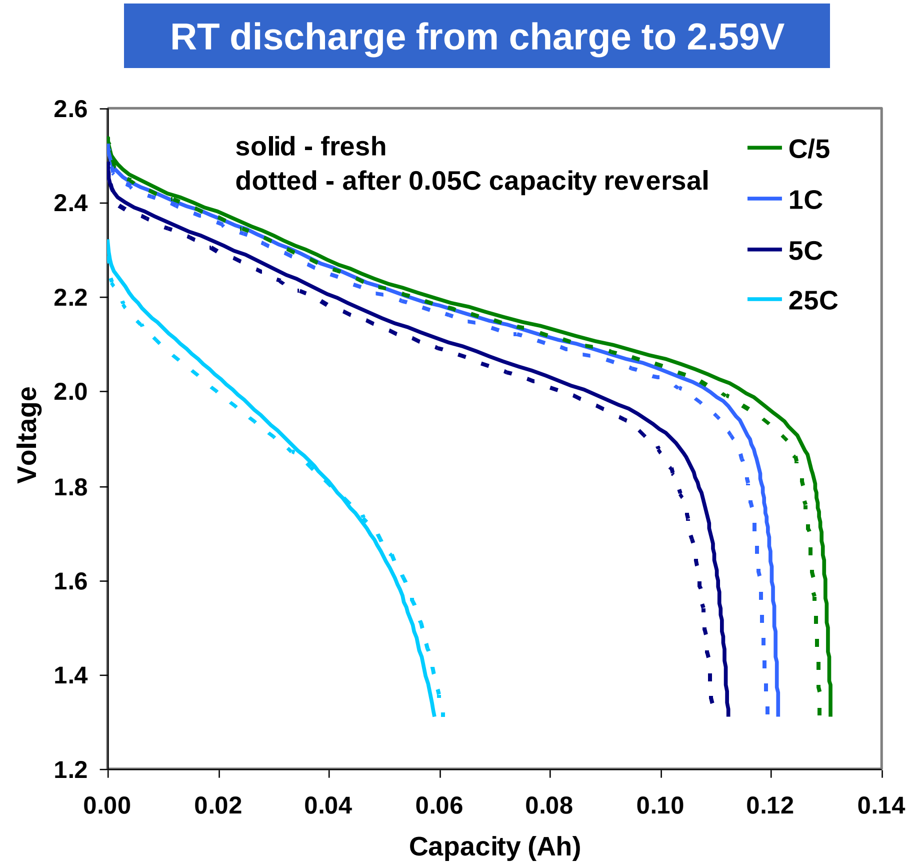
Ability to support 20C pulse discharge at -18 °C is retained after storage for 4 months at 55 °C (131 °F) in 0V condition.



Unsupported 50 mAh pouch cell: 0.98 A, 30 second pulse/30 minute rest at -18 °C (0 °F).

Cell chemistry's tolerance of cell reversal enables 0V-discharge of series-contacted cell strings.



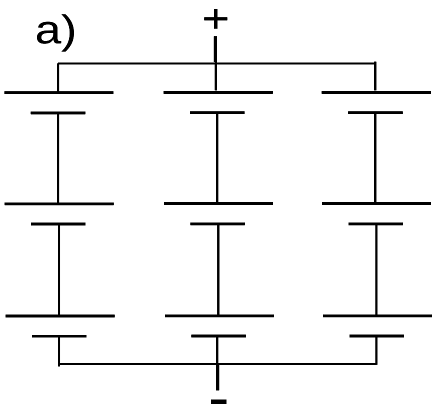


Unfixtured 130 mAh cell with Li metal reference electrode

Structural integration and distribution of batteries beneath armor on military vehicle surfaces poses special challenges.

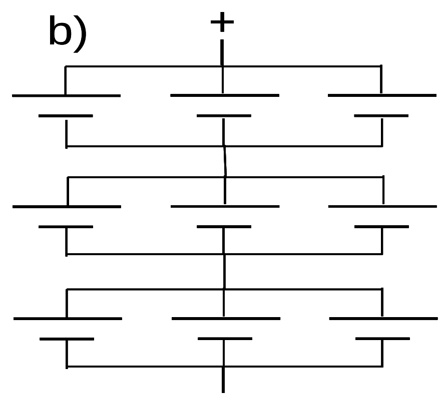
- Batteries are likely to undergo prolonged extreme temperature exposures.
  - Cells must be particularly tolerant of high temperatures, which ordinarily will rapidly degrade Li-ion cells.
- Batteries are highly likely to sustain localized damage in battle conditions.
  - Battery must incorporate redundancy and/or be capable of maintaining functionality with some level of damage/disablement to individual cells.
- Current-carrying elements and battery management elements can be more critically vulnerable than cells themselves.
  - Current collection should be as distributed as possible.
  - Current cutoff requirements should be minimized.
  - Battery management should be minimized.

Cell connection topology impacts a structurally distributed battery’s durability.



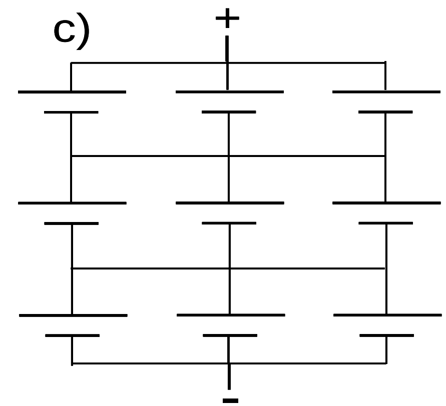
S-P

- **Less vulnerable current distribution**
- **String lost to cell fail open**
- **Hard short: series cell overcharge**
- **Soft short: cell reversal**



P-S

- **More vulnerable current distribution**
- **Parallel cells stressed by cell fail open**
- **Hard short: large fault current**
- **Soft short: cell reversal**



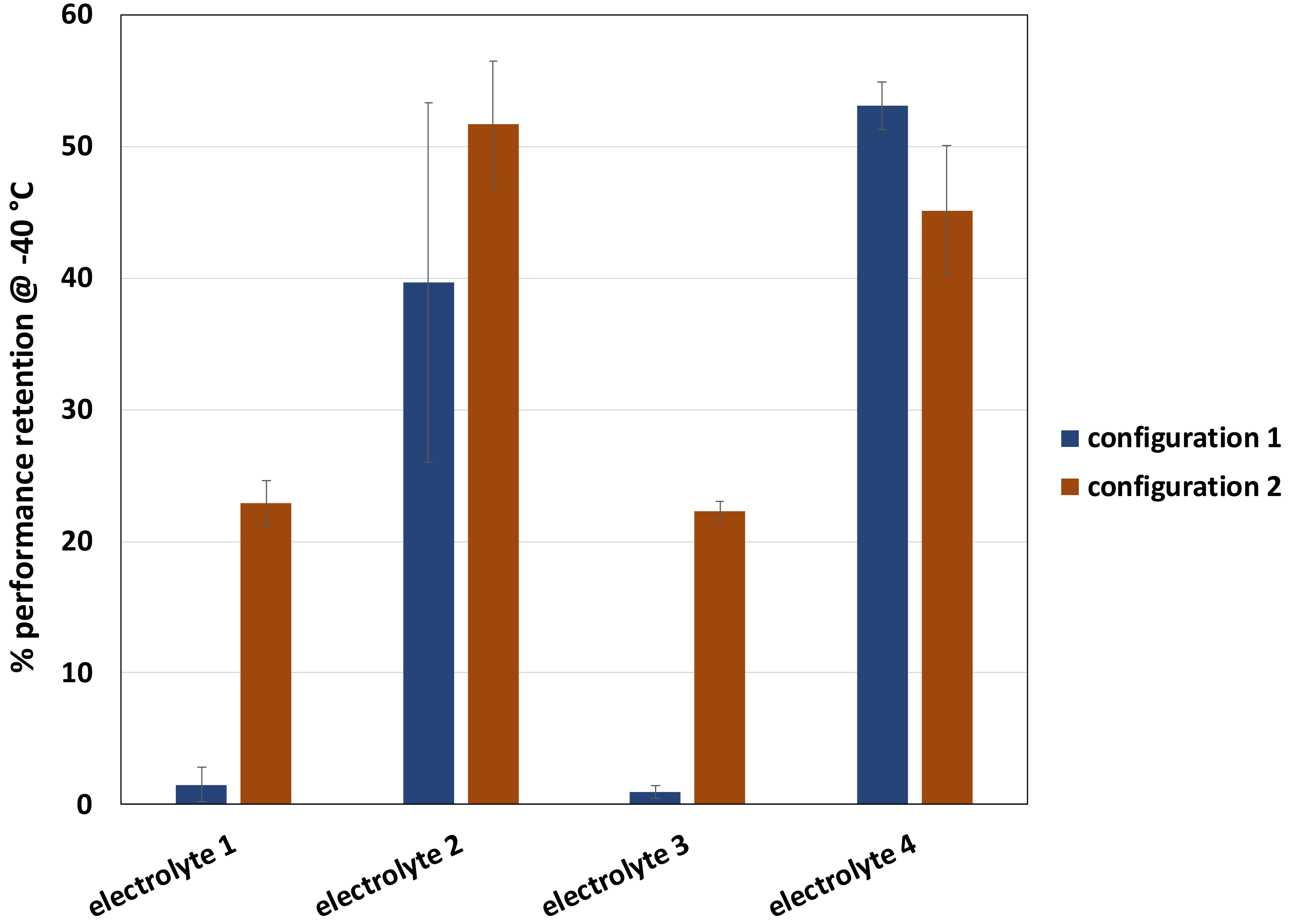
matrix

- **Less vulnerable current distribution**
- **Parallel cells stressed by cell fail open**
- **Hard short: large fault current**
- **Soft short: cell reversal**

Consideration of cell topology's role in damage tolerance leads to some general conclusions:

- CAM-7/LTO cells have excellent properties for damage-tolerant batteries.
  - Tolerant of overcharge.
  - Tolerant of cell reversal.
  - Electrolyte can be tailored for enhanced elevated-temperature tolerance.
- Each armor battery unit should interface with the vehicle bus at full voltage (24V).
- Use of electronics within armor battery units should be minimized.
- Fusing would be preferred method of electrical isolation.
  - More easily implemented at module interconnect level than at individual cell level.
- A uniform module design small enough to meet above parameters should be used.

Elevated-temperature tolerance is optimized by selection of electrolyte and design of battery's cell configuration.



Retention of -40 °C 1C pulse performance by un-fixtured 130 mAh pouch cells after storage in charged state at 78 °C (172 °F) for 40 days.

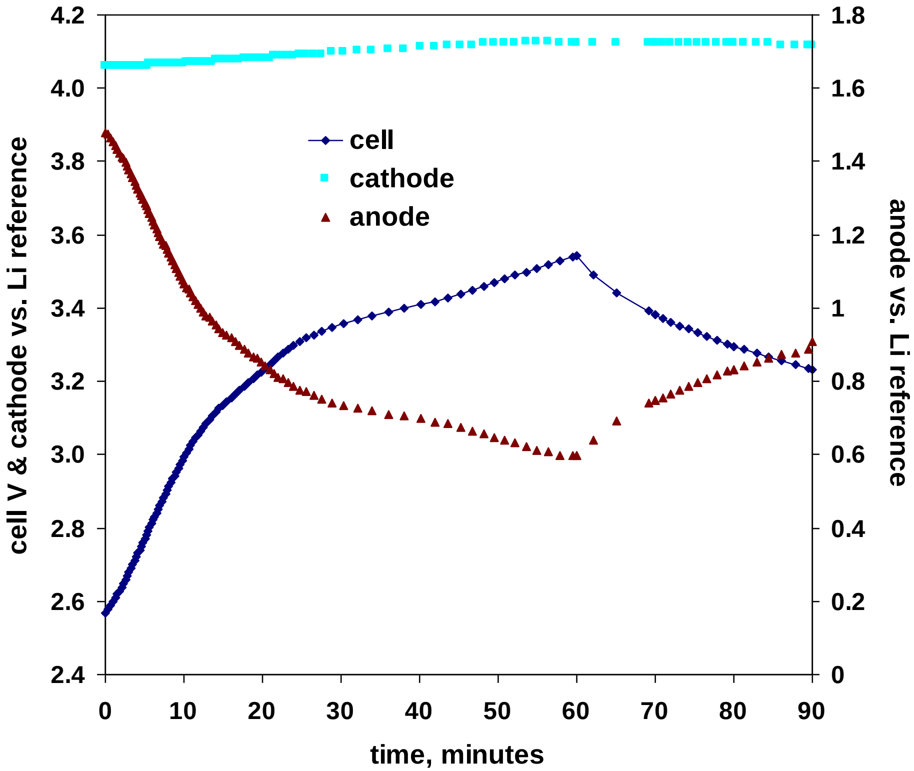
28.5 V charging of a series string containing shorted cells subjects the other cells in the string to overcharge.

# of cells shorted	Remaining cells’ charge V	
	11-S	12-S
0	2.591	2.371
1	2.850	2.591
2	3.167	2.850
3	3.563	3.167
4	4.071	3.563
5	4.750	4.071

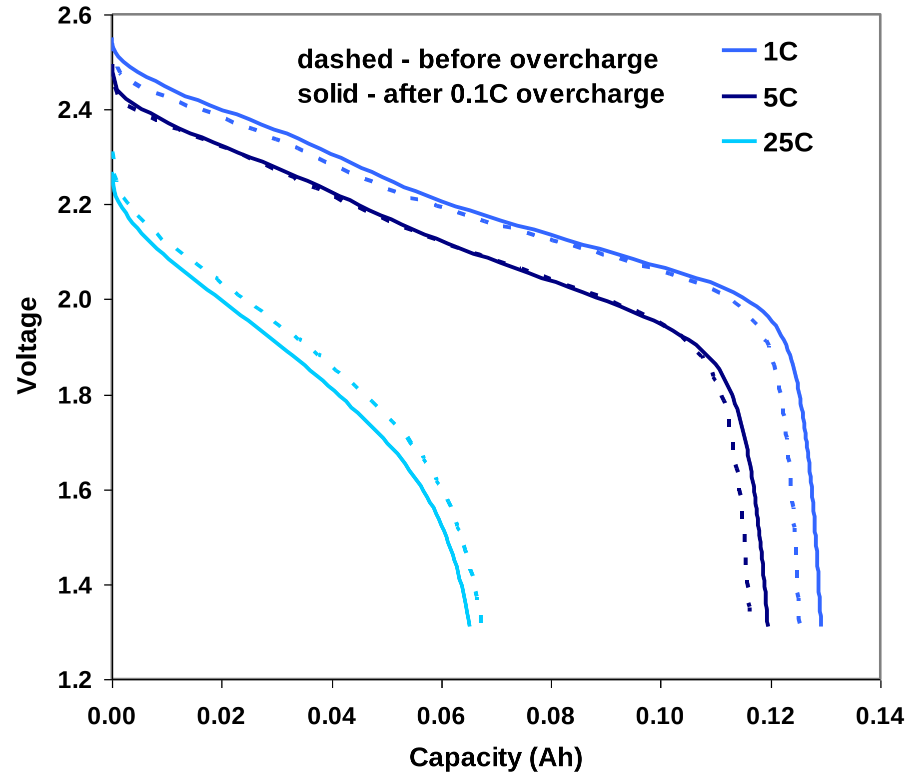
The higher the cells’ overcharge tolerance, the greater the number of shorted cells with which the series string can still function.

CAM-7/LTO cells are highly tolerant of overcharge, e.g., a negligible impact of 3 cells shorted in 11-S configuration or 4 cells shorted in 12-S configuration.

Overcharging the 2.59V-charged cell by 10% of cell capacity at 0.1C rate

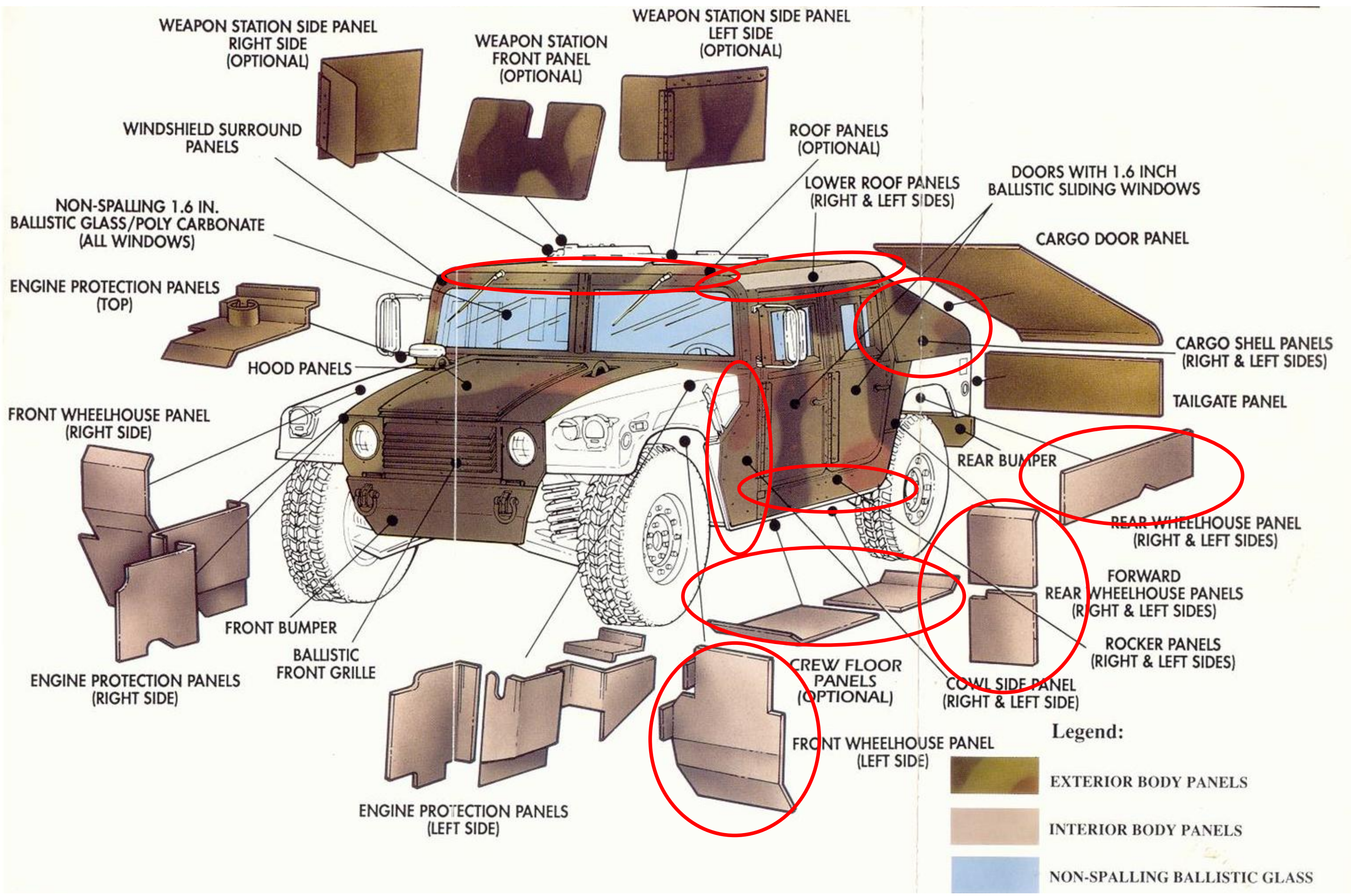


RT discharge from charge to 2.59V



Unfixtured 130 mAh pouch cell with Li metal reference electrode

Estimated area behind selected non-hinged armor pieces of M1100 HMMWV is up to ~7 m^2: at 2-3 cm thick, could provide over 140 liters for 20+ kWh battery.



Properties and performance of CAM-7/LTO pouch cells can enable novel military vehicle battery designs and operational profiles.

- Low-temperature capabilities and long life are well-suited to 6T batteries for Silent Watch missions.
- 0V capability, reversal tolerance and elevated-temperature tolerance are well-suited to 6T batteries with minimized logistical burden.
- Elevated-temperature tolerance and configurational flexibility are well-suited to batteries that are structurally integrated beneath vehicle armor.
- Overcharge and reversal tolerance and safety are well-suited to battle damage-tolerant structural batteries.

Acknowledgements: This material is based upon work supported by the following agencies under the following Contract Numbers:

- US Army (TARDEC) SBIR Phase II contract # W56HZV-12-C-0065
  - TPOC: Laurence Toomey
- US Navy (NAVFAC) SBIR Phase II contract # N39430-14-C-1506
  - TPOC: Ken Ho
- US Defense Logistics Agency SBIR Phase I contract # HQ0147-15-C-8003
  - TPOC: Traci Myers
- US Army (TARDEC) SBIR Phase I contract # W56HZV-16-C-0143
  - TPOC: Alex Hundich

Disclaimer: Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the above funding agencies.