



Lithium Iron Phosphate Cell Performance Evaluations for Lunar Extravehicular Activities

by Concha M. Reid

Lithium-ion battery cells are being evaluated for their ability to provide primary power and energy storage for NASA's future Exploration missions. These missions include the Orion Crew Exploration Vehicle, the Ares Crew Launch Vehicle Upper Stage, Extravehicular Activities (EVA, the advanced space suit), the Lunar Surface Ascent Module (LSAM), and the Lunar Precursor and Robotic Program (LPRP), among others. Each of these missions will have different battery requirements. Some missions may require high specific energy and high energy density, while others may require high specific power, wide operating temperature ranges, or a combination of several of these attributes.

EVA is one type of mission that presents particular challenges for today's existing power sources. The Portable Life Support System (PLSS) for the advanced Lunar surface suit will be carried on an astronaut's back during eight hour long sorties, requiring a lightweight power source. Lunar sorties are also expected to occur during varying environmental conditions, requiring a power source that can operate over a wide range of temperatures. Concepts for Lunar EVAs include a primary power source for the PLSS that can recharge rapidly. A power source that can charge quickly could enable a lighter weight system that can be recharged while an astronaut is taking a short break.

Preliminary results of A123 M1 26650 lithium iron phosphate cell performance evaluations for an advanced Lunar surface space suit application are discussed in this paper. These cells exhibit excellent recharge rate capability, however, their specific energy and energy density is lower than typical lithium-ion cell chemistries. The cells were evaluated for their ability to provide primary power in a lightweight battery system while operating at multiple temperatures.



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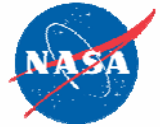
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10th Electrochemical Power Sources R&D Symposium

Williamsburg, VA

20-23 Aug 2007

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- NASA will require energy storage for many of its upcoming Exploration missions
- Lunar and Planetary Exploration will require battery operation under charge and discharge conditions and in environments that differ from LEO and GEO applications
 - Battery requirements vary widely based on the mission
 - Mass reduction is critical to meet launch weight targets
 - Lithium-ion (Li-ion) batteries are baselined for many applications
 - Safety is critical
 - Human-rated systems will be required for crewed missions
 - Stricter qualification processes
 - Safety issues with Li-ion chemistry must be adequately addressed
 - Projected cycle life requirements are not challenging for Li-ion systems, however long shelf life will be required for many missions



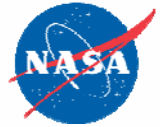
Constellation Elements that will Require Energy Storage

- Lunar Precursor Robotic Program (LPRP)
- Orion Crew Exploration Vehicle (CEV)
 - Service Module, Command Module
 - Human-rated mission
 - Basic requirements - High specific energy and energy density
- Ares I Crew Launch Vehicle (CLV)
 - Upper Stage (US) and Interstage Roll Control
 - Human-rated mission
 - Basic requirements – High specific power
- Ares V Cargo Launch Vehicle (CaLV)
- Extravehicular Activities (EVA)
 - Space suit power system
 - Human-rated mission
 - Basic requirements – High specific energy and energy density, wide operating temperature, low discharge rate, rapid recharge capability
- Lunar Surface Access Module (LSAM)
 - LEO phase, LLO phase, Ascent phase (from Lunar Surface)
 - Human-rated mission
- Rovers
- Landers



- Performance Testing Goals for NASA's Exploration missions
 - Develop a general performance characterization database for Li-ion cells (voltage response, current and temperature capability, impedance)
 - Quantify ability of Li-ion cells to meet projected requirements
 - Perform mission profile testing on cells and batteries
 - Determine gaps in the ability of current technology to meet future needs so research investments can be focused
- Presentation will discuss results of cell performance evaluations for EVA missions
 - Spacesuit Portable Life Support System for Lunar Missions

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EVA Spacesuit Portable Life Support System (PLSS) for Lunar Surface Exploration

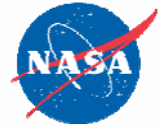
- Will provide power for astronaut life support
- Sorties will last about 8 hours
- Low mass is enabling. Current life support system is heavy, but is used in zero-G. Goal to reduce current PLSS battery mass by about 45%
 - Current battery is silver-zinc
 - Current battery weighs approximately 15 lbs (6.8 kg)
- Notional power profiles were constructed based on current spacesuit life support system requirements and expected lunar surface conditions



Notional EVA PLSS Requirements for Lunar Surface Ops

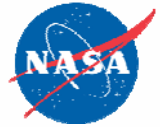
Mission Duration	8 hours
Number of Sorties	500+
Nominal Voltage	18.5 V
Voltage Range	21V to 16V
Operating Temperature Range (discharge)	-60 to 60 degrees Celsius
Average Load	3.8 A continuous
Peak Load	9.5 A pulse for 3 sec
Profile description	Base load of 3.8 A. 9.5 A pulse required at the beginning of discharge to start PLSS fan. Battery must be capable of restarting fan anytime during discharge, so pulse will be repeated every 15 minutes.

❖ Mass minimization is a design goal.



Design Solutions

- Options for attaining 8 hour mission examined
 1. Size battery for 8 hours
 2. Size battery for 4 hours, recharge midway through mission
 3. Size battery for 4 hours, replace with a spare midway through mission
 - 4 hour cases can potentially save battery mass that must be carried by the astronaut
 - Extra batteries or chargers can be transported during or prior to EVA by a rover
 - 4 hour replace option will result in the lowest mass battery
 - 4 hour recharge option will require a rapid recharge battery – Goal to recharge within 15 to 30 minutes
 - For sizing, end of life (EOL) is defined as the point when less than 80% of the capacity delivered on initial discharge is delivered. Therefore initial design was done for nominal discharge to 80% DOD.
 - Design voltage = nominal 18.5 volts
 - Minimum battery voltage = 16 volts
-
- ❖ Study considers 8 hour case and 4 hour rapid recharge case. Replace option not considered in this study
 - ❖ The 8 hour case using is shown for comparison purposes. A battery is typically optimized for the mission, so a high energy cell would be chosen to trade off against a cell that could rapidly recharge.



Battery Performance Evaluation Approach

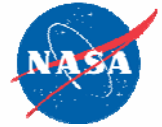
- Candidate cells chosen for performance testing
 - A123 Li-ion cells with iron phosphate cathode chemistry
 - Inherently safer cathode than standard Li-ion cathode
 - Rapid recharge capability could enable mission
 - Cells have a lower specific energy than Li-ion cells with standard cathode. A high specific energy cell would typically be chosen to trade off against a cell that could rapidly recharge. For this paper, the 8 hour case study was performed using A123 cells for comparison purposes.
- Extensive performance testing done initially to determine cell capacity and voltage response at different charge rates, discharge rates, and temperatures
- Results used to size a battery on paper and predict mass and volume
- Scaled mission profiles run on single cells to verify performance (tests to determine if minimum voltage requirements are met)
- Results analyzed, adjustments to cell operating conditions made, and additional tests performed
- Knowledge base formed from results, technology issues to address documented
- Future performance testing as needed



A123 Lithium-Iron Phosphate Cell

Nameplate Capacity	2.3 Ah
Cell Mass	72 grams
Cell Volume	0.035 liters
Nominal Voltage (C/2)	3.3 volts
Voltage Range	3.6* to 2 volts
Operating Temperature Range	-30 to 60 degrees Celsius
Geometry	Cylindrical

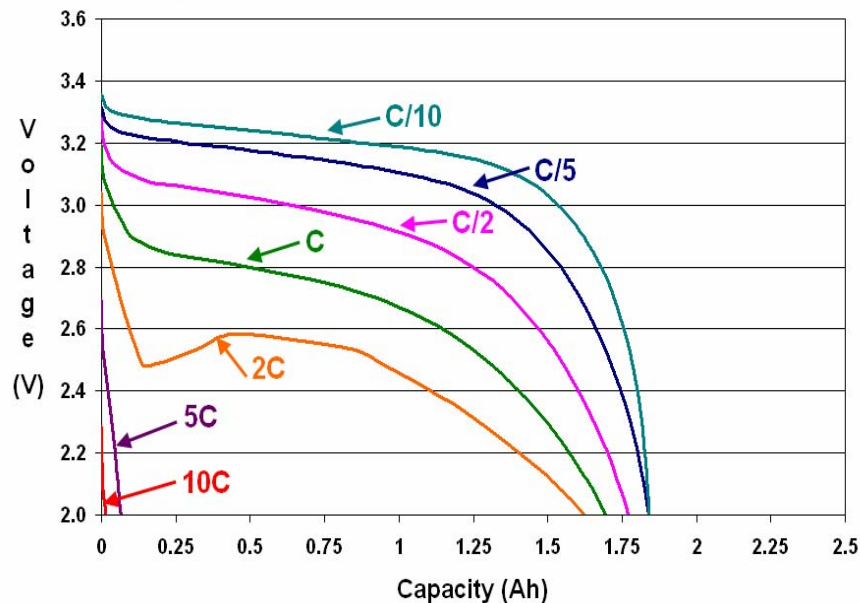
*Higher voltages can be attained, but cycle life is sacrificed



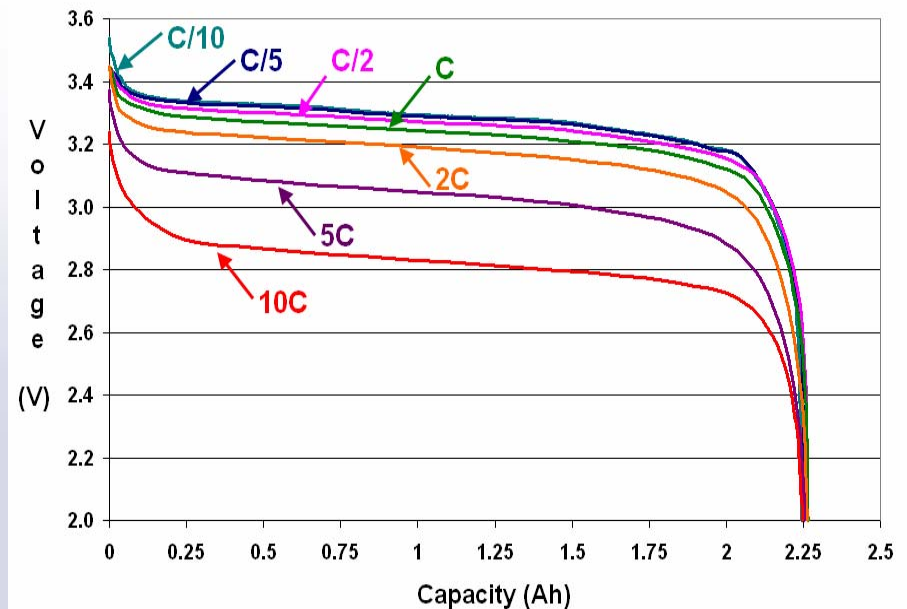
Performance Testing Results

20 and -20 degrees C for Different Discharge Rates

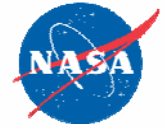
Capacity at -20 Degrees C for Different Rates



Capacity at 20 Degrees C for Different Rates

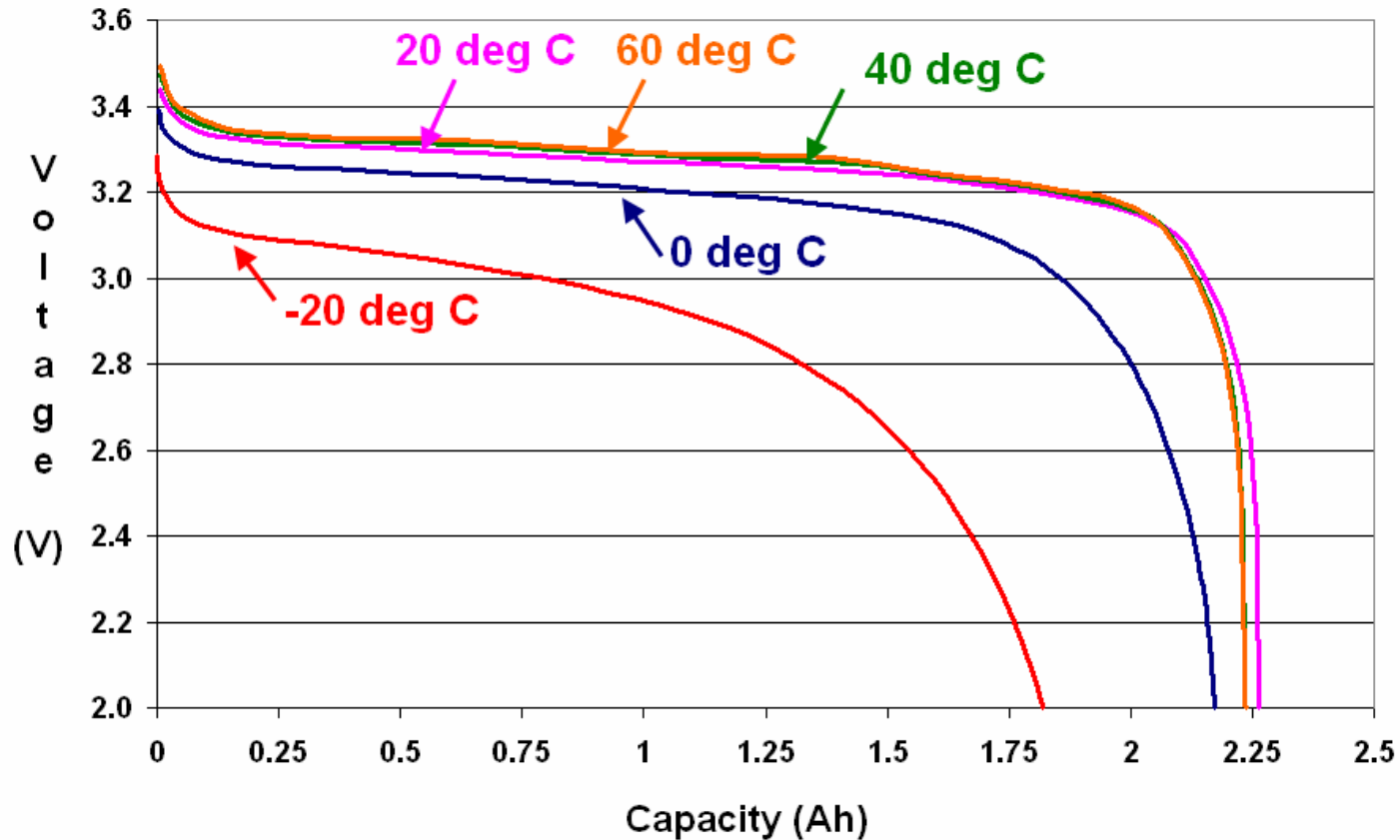


- Charged at C/2 to 3.6V at discharge temperature, voltage held, taper limit of C/50



Performance Testing Results

Capacity at C/2 for Different Temperatures

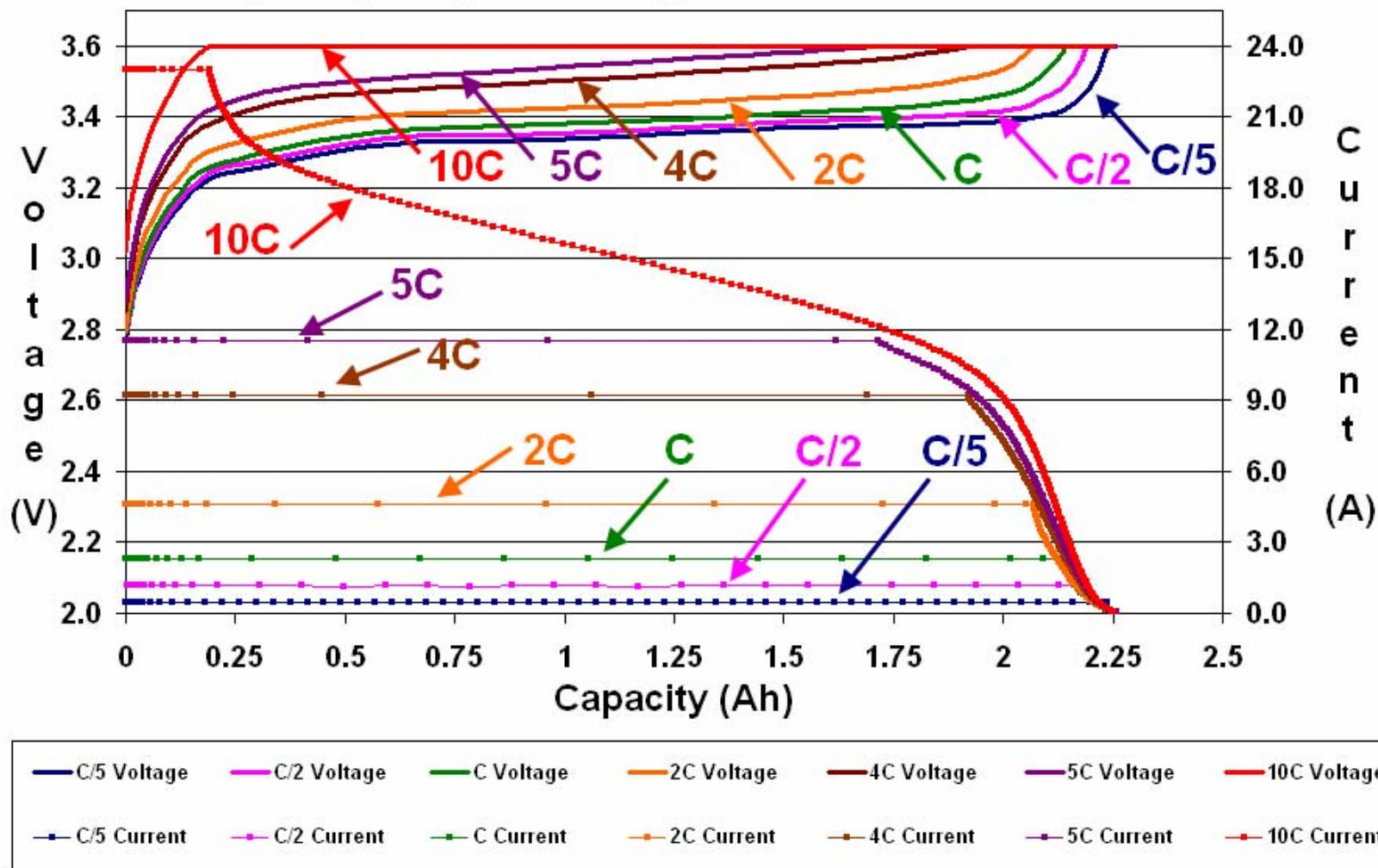


- Charged at C/2 to 3.6V at discharge temperature, voltage held, taper limit of C/50



Performance Testing Results

Charge Capacity at 20 Degrees C for Different Rates

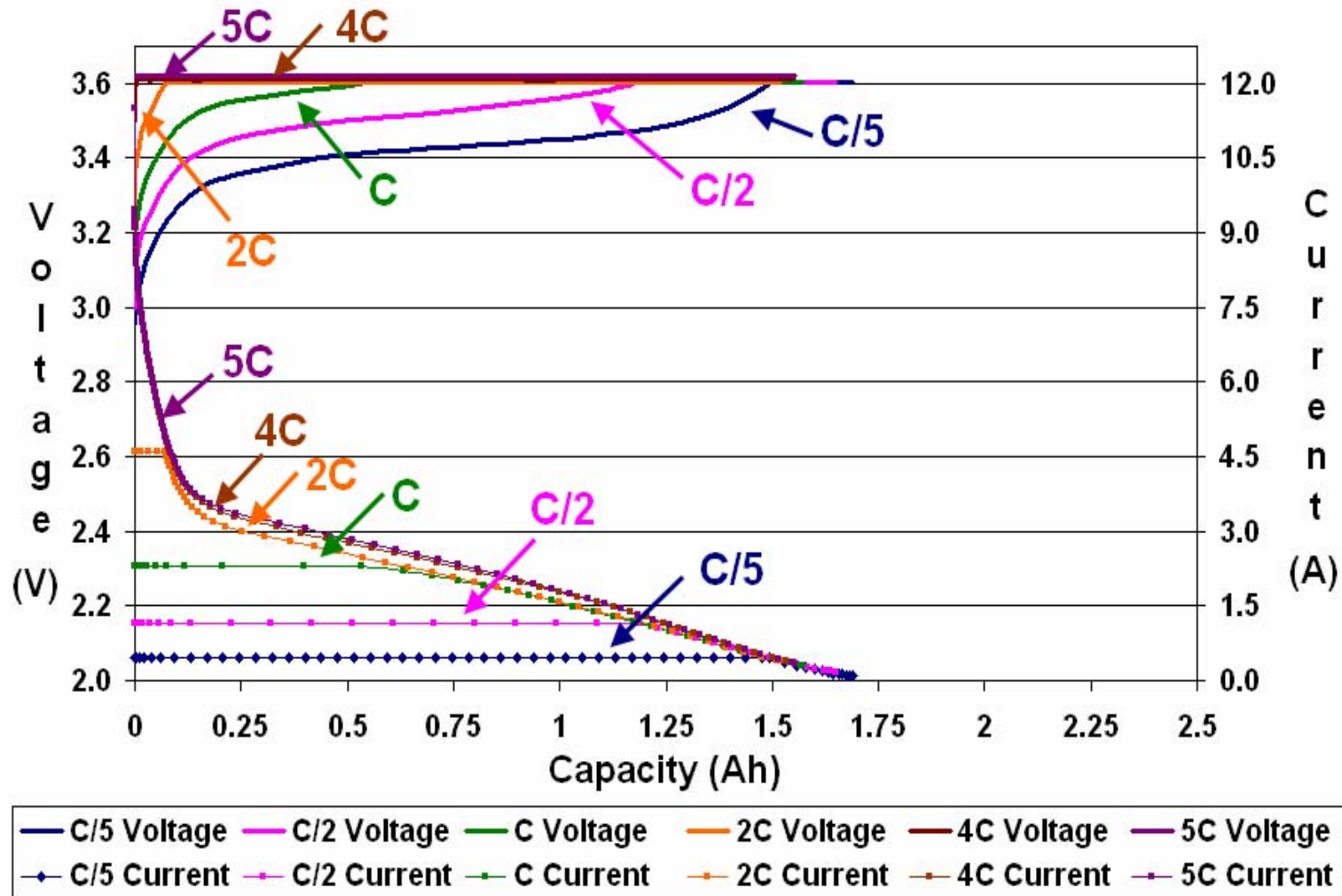


- Charged to 3.6V, voltage held, taper limit of C/50, discharged at C/2 to 2.0V at charge temperature
- C = 2.3A



Performance Testing Results*

Charge Capacity at -20 Degrees C for Different Rates

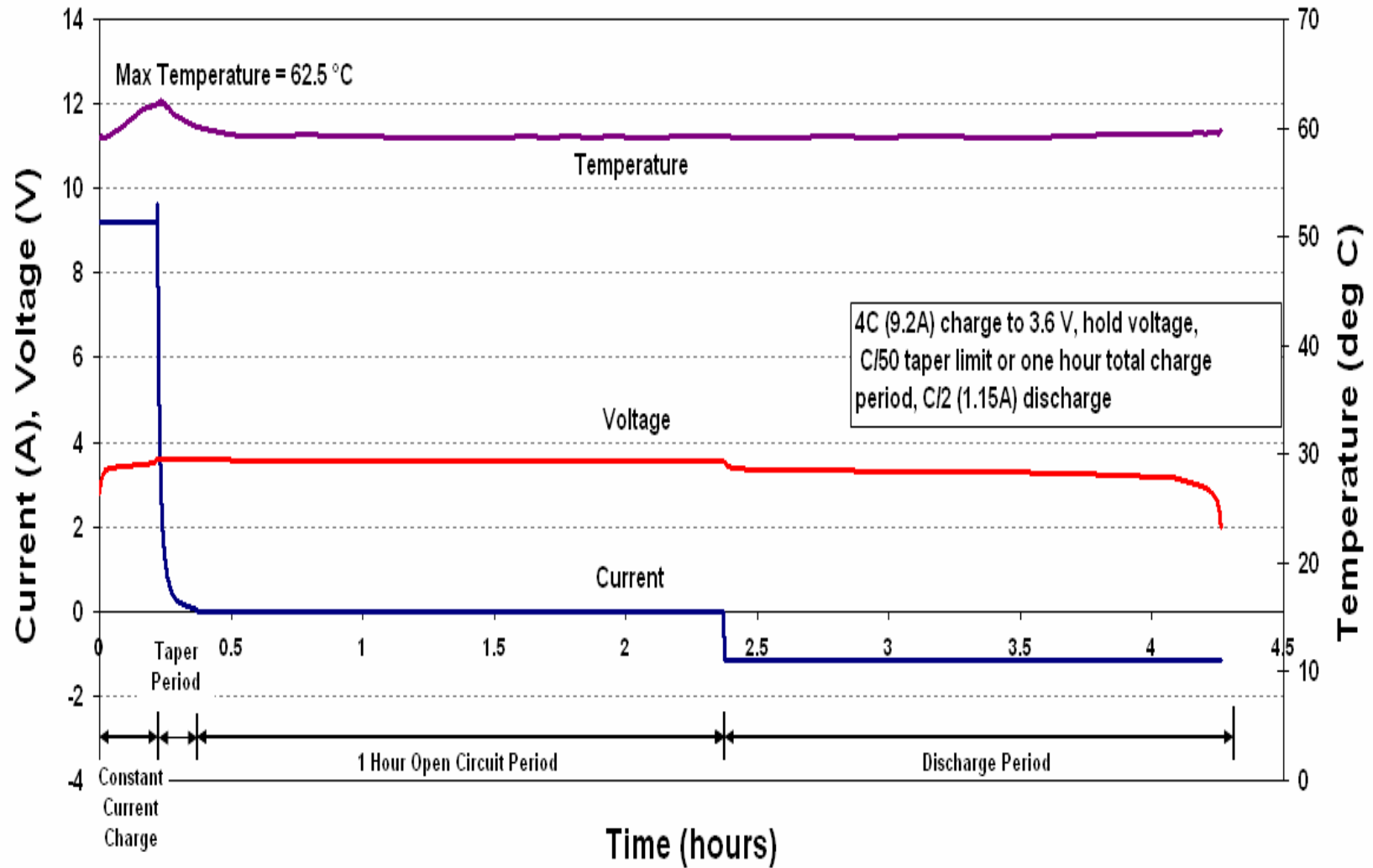


- Charged to 3.6V, voltage held, taper limit of C/50, discharged at C/2 to 2.0V at charge temperature
- C = 2.3 A

*Cell would not charge at 10C at -20 degrees C

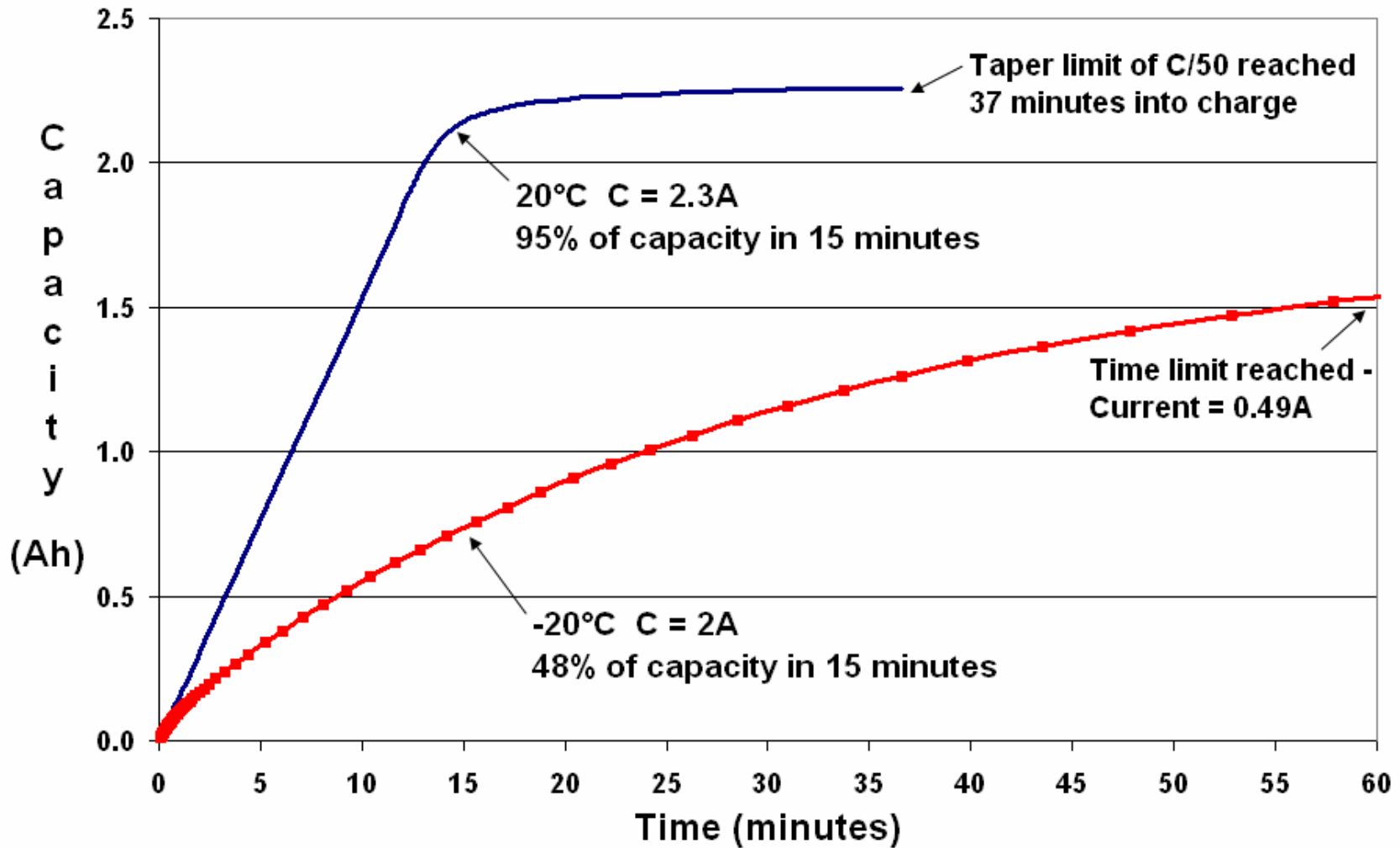


Voltage, Current and Temperature at 4C Charge Rate and 60 Degrees C





Capacity Input at 4C Charge Rate



•C is based on the C/10 capacity at each operating temperature

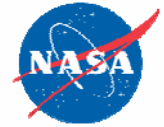


Battery Sizing Results

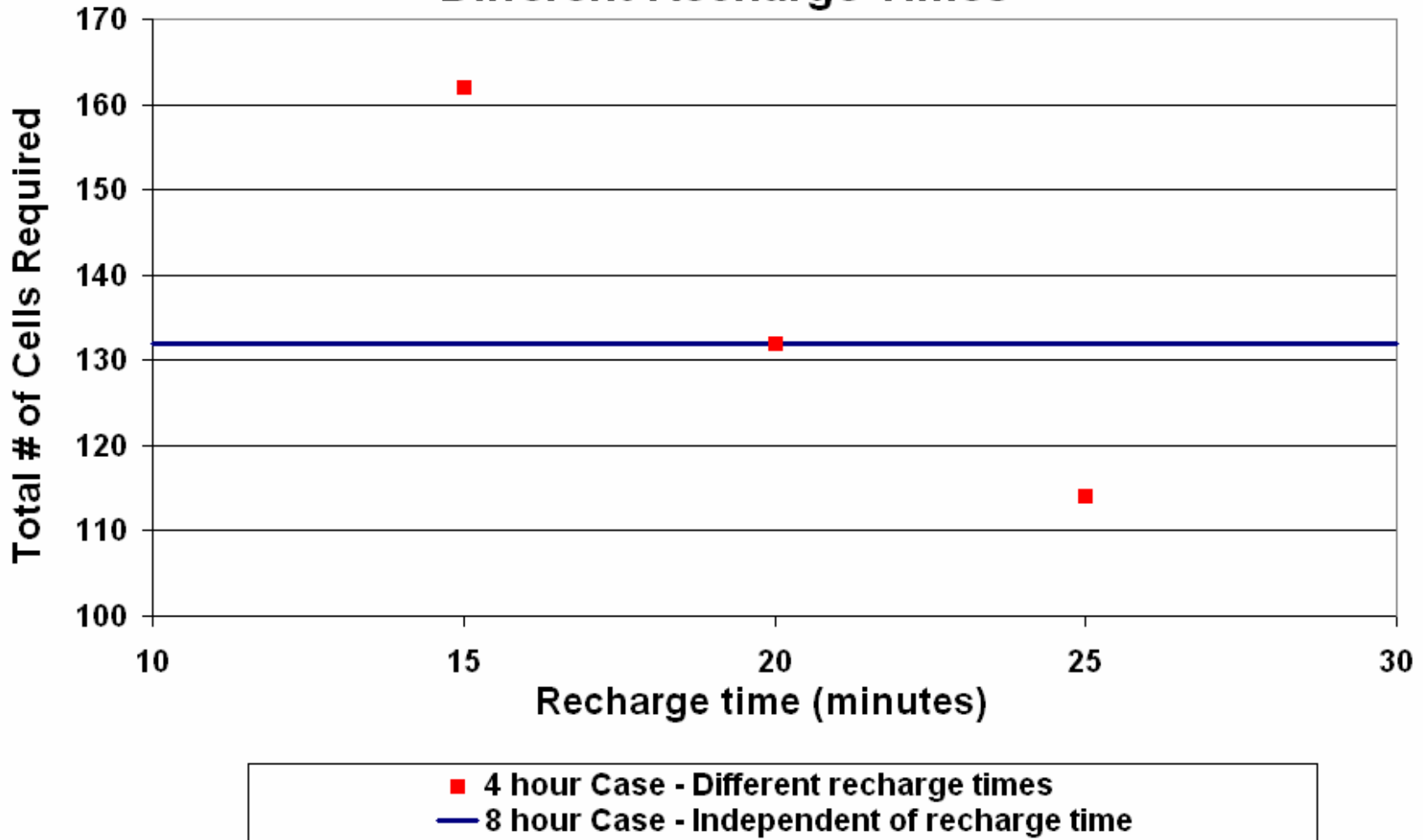
Mission scenario	20°C		-20°C	
	8 Hour	4 Hour w/15 min recharge	8 Hour	4 Hour w/15 min recharge
Expected capacity available per cell (Ah)	2.25	2.14	1.84	0.74
Nominal cell voltage (V)	3.29	3.28	3.19	3.12
Number of cells in series	6	6	6	6
Number of cells in parallel	18	10	22	27
Total number of Cells	108	60	132	162
Battery Mass** (kg)	11	6	13	16
Battery Volume** (liters)	11	6	14	17

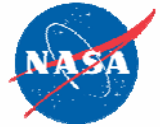
*Sizing based on capacity delivered at the desired operating temperature for a C/10 and C/5 discharge rate for 8 hour and 4 hour case, respectively. Charging was performed at the discharge temperature. Charge conditions: C/2 to 3.6V, taper limit C/50 or one hour total charge time. Rapid recharge conditions: 4C to 3.6V, voltage held, charge terminated after a total of 15 minutes

**Packing factors were applied



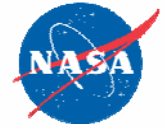
Number of Cells Required at -20 Degrees C for Different Recharge Times





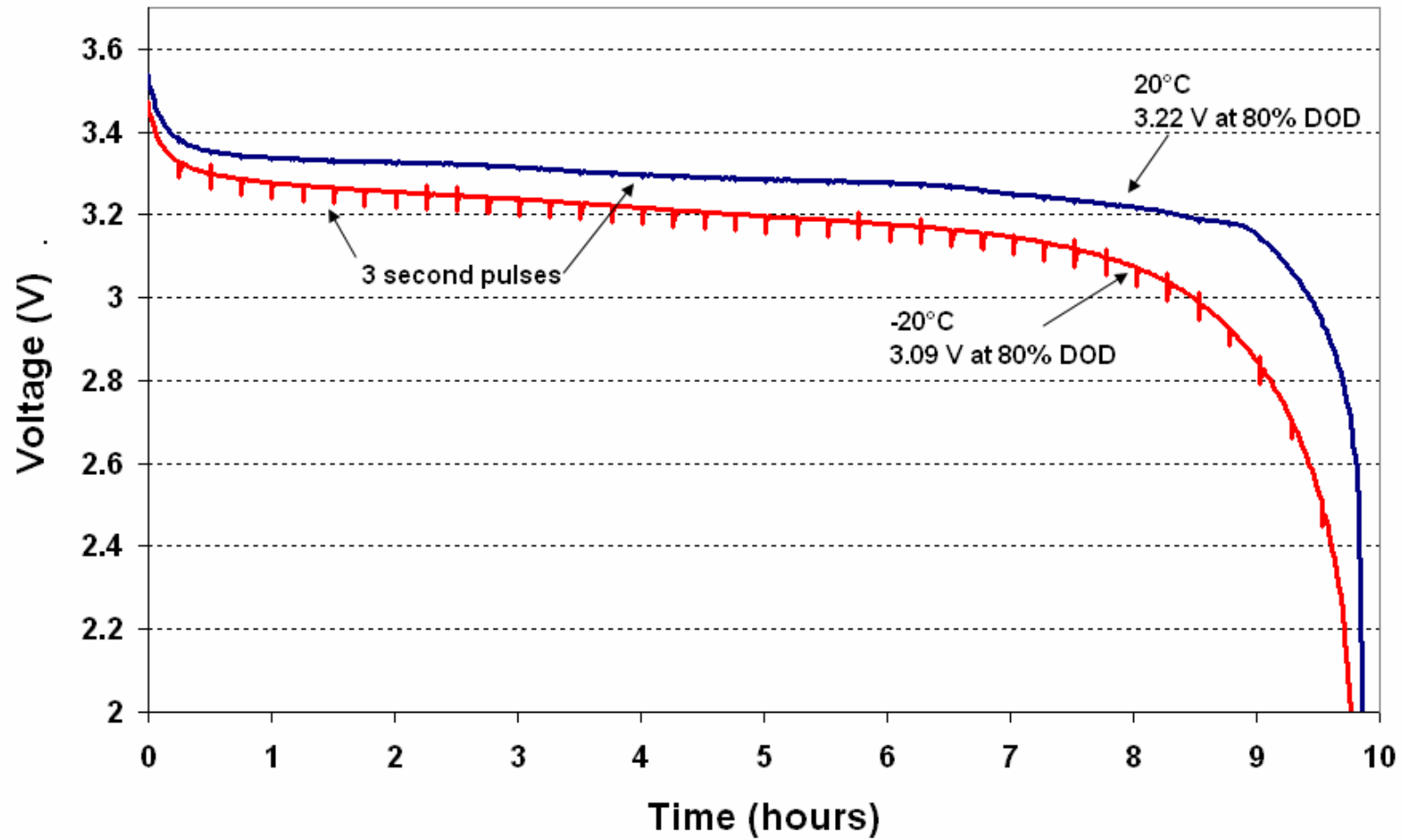
Discussion

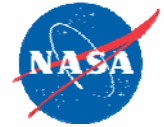
- The A123 cell is not an optimized cell for the 8 hour case. A higher specific energy cell would result in a lower mass battery for the 8 hour case.
- For design for 20°C, the 4 hour rapid recharge case results in a 45% mass savings over the 8 hour case. These mass savings would be lower if a higher specific energy cell is used for the 8 hour case.
 - Operational trade-offs must be performed to weigh the benefit of mass savings versus the added complexity of providing battery recharge capability in the field
- For design for -20°C, the 4 hour rapid recharge case resulted in 23% higher mass than the 8 hour case due to the limited capacity available after the high rate charge at the low temperature
- Incrementally increasing the charge time results in a lighter battery for the 4 hour case at -20°C (due to increased capacity available for subsequent discharge)
- 8 hour and 4 hour mission profile testing at additional temperatures and life testing to quantify cycle life under mission conditions is ongoing



Beginning of Life Mission Profile Results 8 Hour Case at Different Temperatures

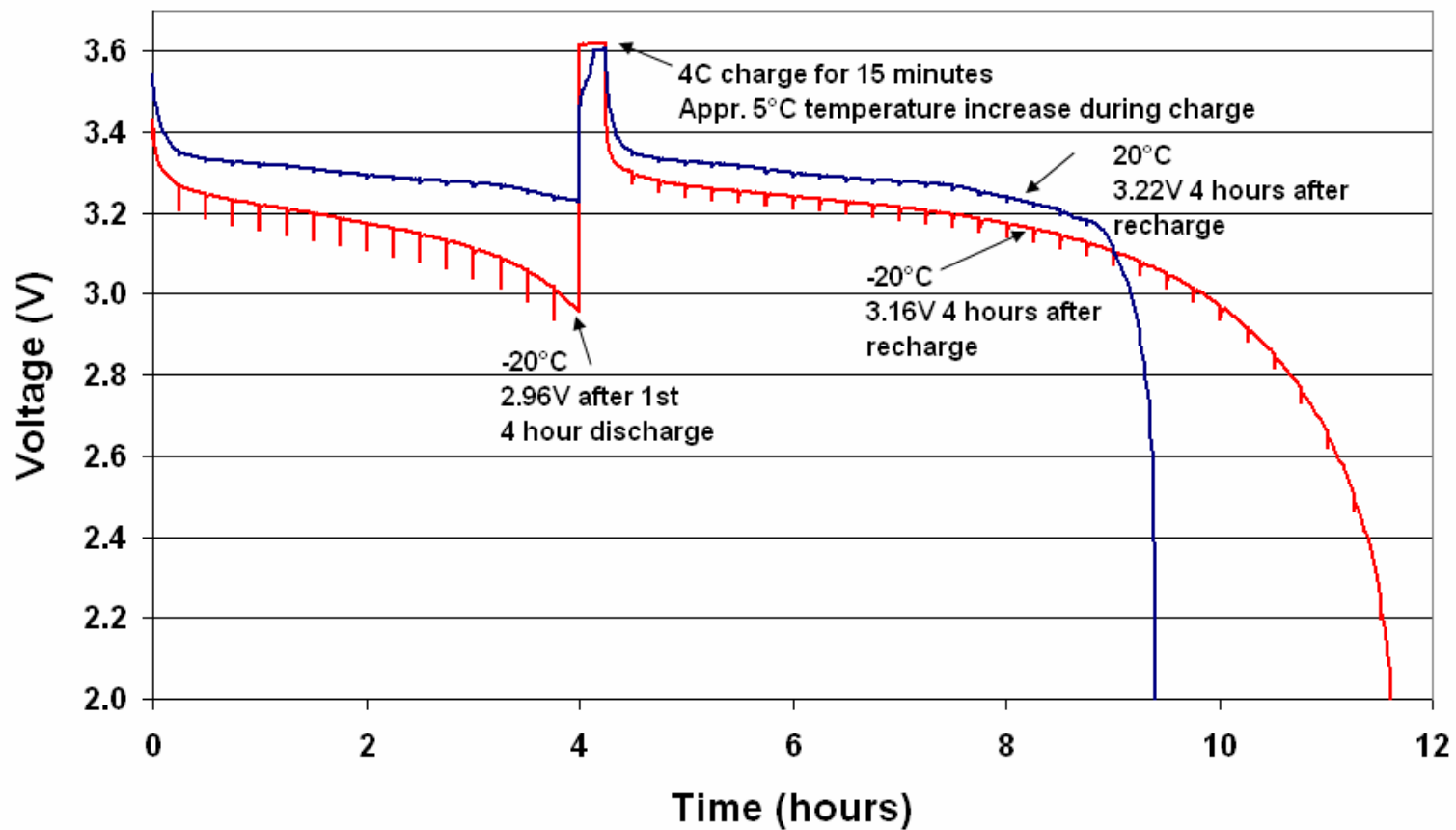
Voltage vs. Mission Time at 20 and -20 Degrees C 8 Hour Case, Single Cell

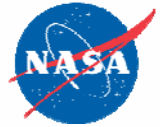




Beginning of Life Mission Profile Results 4 Hour Rapid Recharge Case at Different Temperatures

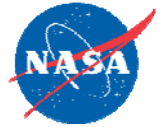
Voltage vs. Mission Time at 20 and -20 Degrees C 4 Hour Case, Single Cell





Summary of EVA Mission Test Results

- A123 Lithium iron phosphate cells can support an EVA mission with a 15 minute recharge at 20°C
 - Results in a lower mass battery for the 4 hour rapid recharge case when compared to the 8 hour case using A123 cells
 - The 8 hour case is not optimized for mass due to the lower specific energy A123 cells offer when compared to standard Li-ion cells
 - Further studies are needed to assess the mass benefit of the 4 hour rapid recharge case using A123 cells versus an 8 hour case with a cell that offers higher specific energy
- A123 Lithium iron phosphate cells cannot support an EVA mission that requires a 15 minute recharge at -20°C
 - Recharge time would need to be greater than 20 minutes to equal the mass of an 8 hour battery using A123 cells
 - A cell that offers higher specific energy than the A123 cells would be even lighter than the battery used for the 8 hour case in this study
 - No significant mass savings would be gained while conforming to the rapid recharge time constraints for the mission
- Cell selection and battery designs can be impacted by mission requirements even within one type of mission
- Testing is ongoing at other temperatures



Summary

- The choice of cell and design of a battery is greatly impacted by the mission requirements and assumptions for testing
- Future NASA Exploration missions will require a wide range of battery capabilities
- Evaluation of candidate technologies helps build database of performance under different operating conditions
- In-depth testing of suitable candidates for particular missions and applications, such as the Lunar EVA PLSS, gives an early indication of ability to meet mission requirements
- Technology development efforts can be focused to target improvements that can enable future missions
- Safe, human-rated, low mass battery systems are key!