Performance Testing of Li-ion Cells and Batteries at JPL in Support of Present and Future NASA Missions

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Outline

- ***Performance Testing of Yardney Li-Ion Cells for MSL***
  - ***Objectives, approach and mission requirements***
  - ***Mission simulation testing of Yardney 20 Ah cells***
  - ***Mission simulation testing of Yardney 43 Ah cells***
  - ***MMPAT related performance testing***
- ***Performance Testing of Yardney 25 Ah Li-Ion Cells for InSight***
  - ***Objectives, approach and mission requirements***
  - ***Effect of high temperature exposure; Mission relevant cycle life testing (Group 1)***
  - ***Impact of accelerated cycling at high temperature (Group 3)***
  - ***NCA-based cells with different electrolytes (Heritage vs. LTE) (Group 4)***
  - ***Mission simulation testing of NCA-based cells with LTE (Group 5)***
- ***Performance Testing of 18650-Size Li-Ion Cells for the Planned Europa Mission***
  - ***Objectives, approach and mission requirements***
  - ***Results of high temperature storage testing***
  - ***Results of module level long term storage testing***
  - ***Results of module 100% DOD cycle life testing***
- ***Conclusions***

Objective:

• Assess viability of using Yardney lithium-ion cells/batteries for the Mars Science Laboratory (MSL) Curiosity Rover Mission.
• Assess whether lithium-ion cells/batteries manufactured by Yardney Technical Products, Inc. can meet all MSL mission requirements.
• **Support the MSL mission by providing capacity fade and impedance growth projections to assist in the determination of the health of the Curiosity battery.**

Approach:

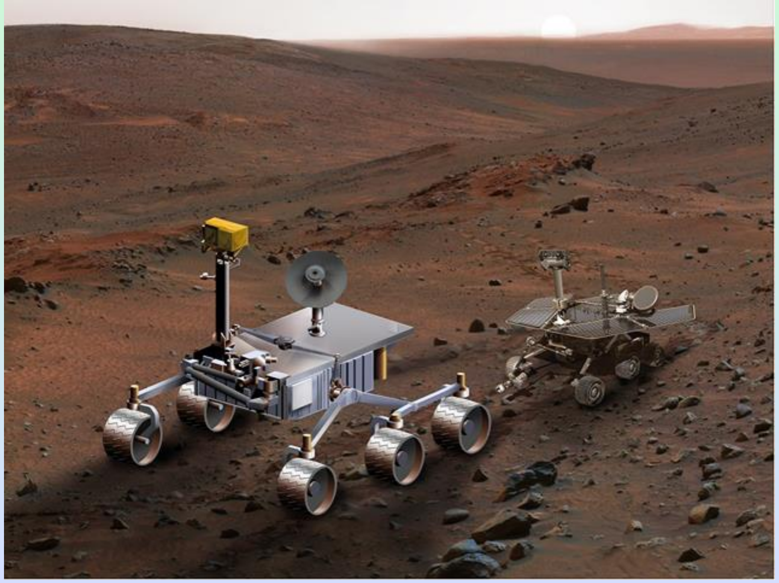
• **Perform a number of mission specific characterization tests to determine technological readiness and ability to meet mission requirements for the MSL project.**
• ***Perform acceptance testing of flight and "flight-type" cells and Rover Battery Assembly Units (RBAUs) for the MSL project.***
•***Perform mission simulation testing on 20Ah and 43 Ah Yardney Li-ion cells fabricated for the MSL project:***

- **Launch load profile simulation**
- **Launch pad and cruise period simulation**
- **Cruise period trajectory correction maneuvers**
- **Entry, descent, and landing (EDL) pulse load profile simulation**
- **Surface operation temperature and load profile simulation**
    - **Periodic diagnostic determination of capacity and impedance under various conditions.**

Mars Science Laboratory (MSL) Curiosity Rover

- **Launch Date: November 26, 2011**
- **Landing Date: August 6, 2012**

- **Science Goals**: To assess habitability: whether Mars ever was an environment able to support microbial life.
  - The biggest, most advanced suite of instruments ever sent to the Martian surface.
  - Analyze dozens of samples scooped from the soil and cored from rocks in the onboard laboratory to detect chemical building blocks of life (e.g., forms of carbon) on Mars.
- Landing: Parachute assisted and powered descent, lowered on tether like sky crane.
- **Programmatic Goals** : To demonstrate the:
  - Ability to land a very large, heavy rover to the surface of Mars (future Mars Sample Return)
  - Ability to land more precisely in a 20-kilometer (12.4-mile) landing circle
  - long-range mobility (5-20 kilometers or about 3 to 12 miles)
- **Highlights:**
  - **Curiosity has operated over 1500 Sols to-date**
  - After 2 years and almost 9 km of driving, Curiosity has reached the base of Mount Sharp
  - During the first year, the rover fulfilled its major science goal of determining whether Mars ever offered conditions favorable for microbial life.
  - **As of Sol 1507, Curiosity has driven 9.16 miles (or 14.75 kilometers)**



Battery Details

- Two 8-cell batteries in parallel (8s2p).
- 24-32.8 V, 86 Ah (MER, Grail, Juno Chemistry)
- Qualification Temperature range: -30^o to $+40^oC$.
- Operating Temperature Range: -20^o to $+30^oC$
- **Required Life: ~ 4 years**
- **Surface Life: 670 Sols of operation.**
- Battery temperature controlled with a combination of heaters and radiators

Performance Requirements for MSL Rover Mission

- Operation for more than 40 months after launch and a calendar life of > 4 years.
- Consist of two Li-ion rechargeable batteries, each with a nameplate capacity rating of 43 Ah for redundancy.
- Surface Operation Capability:
  - Support 670 sols of surface operations with two discharge cycles per sol, with one cycle being 1000Wh at 0°C and 17.2A
  - Possess capability of meeting the performance requirements with an average battery temperature of +15°C and an absolute maximum of +30°C on the surface of Mars.
  - The Rover Battery provides a capacity of > 59 Ah at 0°C and C/5 end of life.
- Launch Capability:
  - The Rover Battery supports 1300 Wh during launch at 20° and 30°C at a 34 A max discharge current.
- EDL Capability:
  - Provides capability of supporting a 21 A load for 18 mSec (each battery).
  - Supports sequential (grouped) pyro events as close together as 120 mSec.

Performance Demonstration of Yardney Li-Ion Cells for MSL
Overview of Test Plan

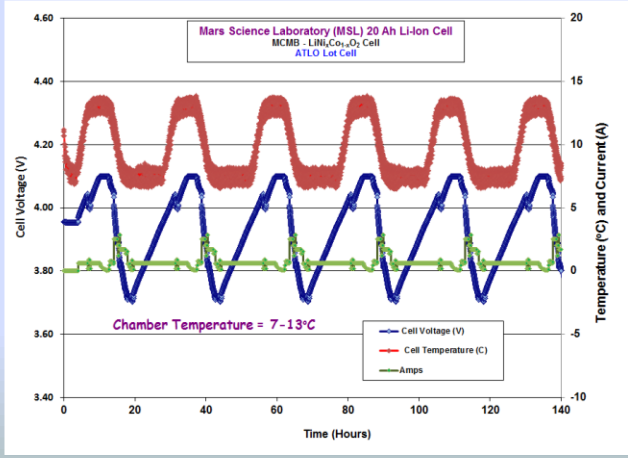
- *Yardney 20 Ah Li-ion Cells (1st Generation MSL Cell Design):*
  - Initial characterization over a number of temperatures (20°, 0°, -10°, and -20°C)
  - Discharge rate characterization
    - Up to C rate discharge, at 30°, 20°, 10°, 0°, -10°, -20°, -30°, -40°C
  - Charge rate characterization
  - Launch characterization
  - Cycle life characterization (100 % DOD) at different temperatures
  - Surface operation mission simulation testing
- *Yardney 43 Ah Li-ion Cells (2nd Generation MSL Cell Design):*
  - Initial characterization over a number of temperatures (20°, 0°, -10°, and -20°C)
  - Discharge rate characterization
    - Up to C rate discharge, at 30°, 20°, 10°, 0°, -10°, -20°, -30°, -40°C
  - Cycle life characterization (100 % DOD) at different temperatures
  - Accelerated shallow DOD (40-60%) cycle life testing
  - Mission simulation testing
    - On-pad storage characterization
    - Cruise simulation testing
    - Surface operation mission simulation testing

Performance Testing of Yardney MSL 20 Ah Li-Ion Cells
Mission Simulation Testing

- **Cell Group 1 (Cells: MSL-147, MSL-150, MSL-153)**
  - **Cells subjected to 30°C for only 10.5 days (removed and stored at ambient)**
  - **Cells in full SOC under OCV conditions**
  - **360 Days at 25-30°C Cruise condition, 50% SOC bus storage**

- **Cell Group 2 (Cells: MSL-141, MSL-142, MSL-143)**
  - **Cells subjected to 30°C for full 21 day period**
  - **Cells in full SOC under OCV conditions**
  - **360 Days at 25-30°C Cruise condition, 70% SOC bus storage**

- **After completing the cruise simulation and characterization, all of the cells were subjected to surface operation mission simulation testing.**

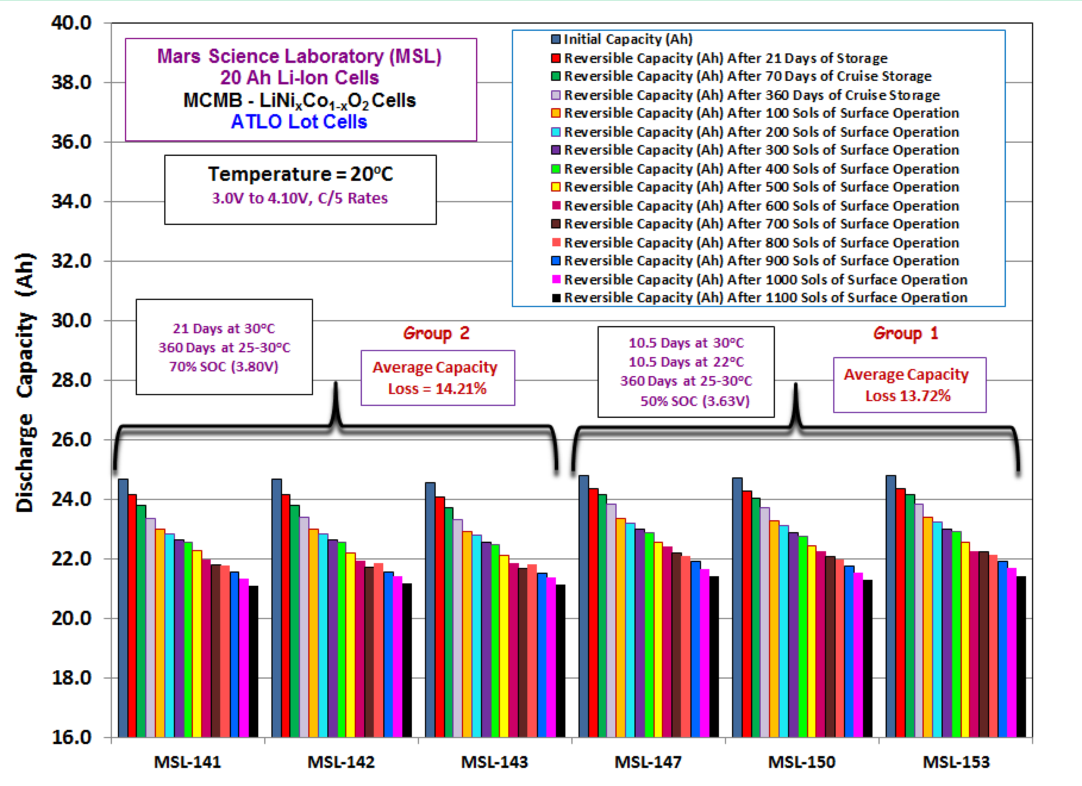


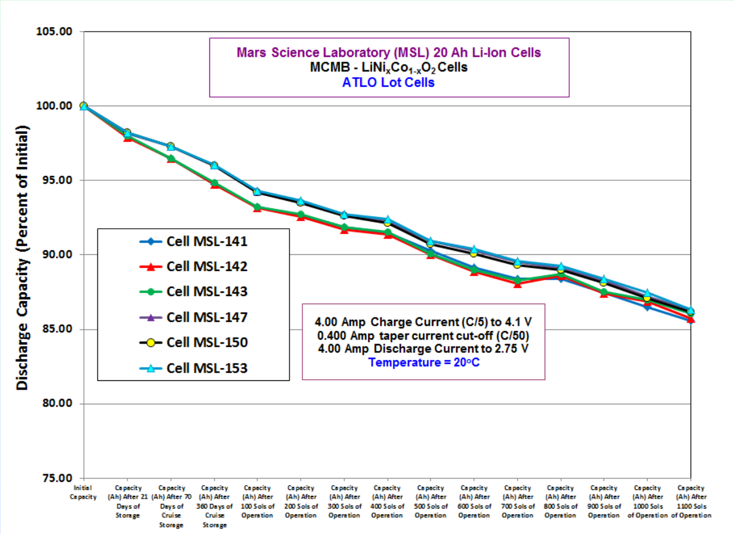
- **The health of the cells is periodically determined throughout the life at various temperatures:**
  - **+20°C, 0°C, -10°C, and -20°C.**

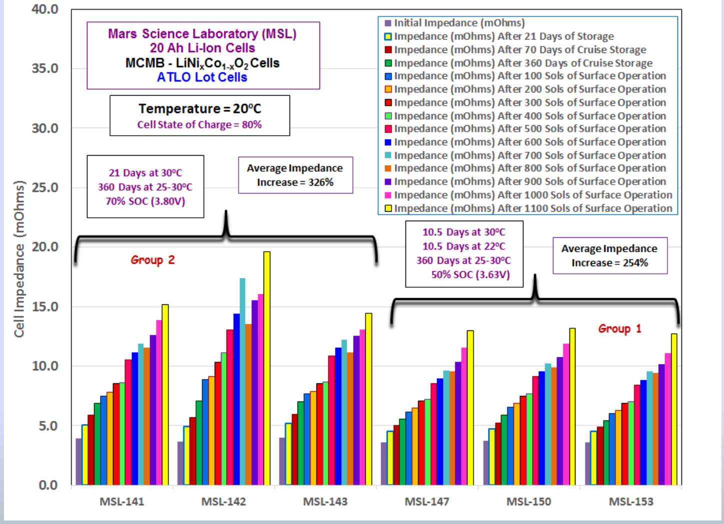
Performance of Yardney MSL 20 Ah Li-Ion Cells

Characterization Testing at 20°C

After Completing Pad Storage, Cruise Storage and 1100 Sols on the Surface







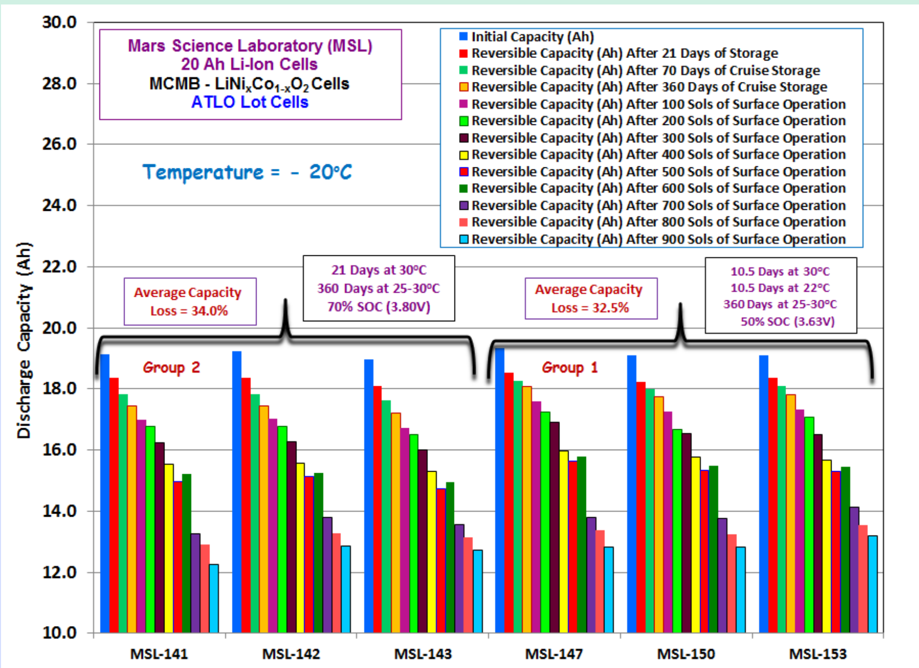
- ***Approximately 13.7% capacity loss has been observed at +20°C (with the Group 1 cells) after completing pad storage + cruise + 1100 sols of operation.***
- ***More impedance growth was observed for the Group 2 cells, which is attributed to high pad storage temperature and high SOC during cruise.***

Performance of Yardney MSL 20 Ah Li-Ion Cells

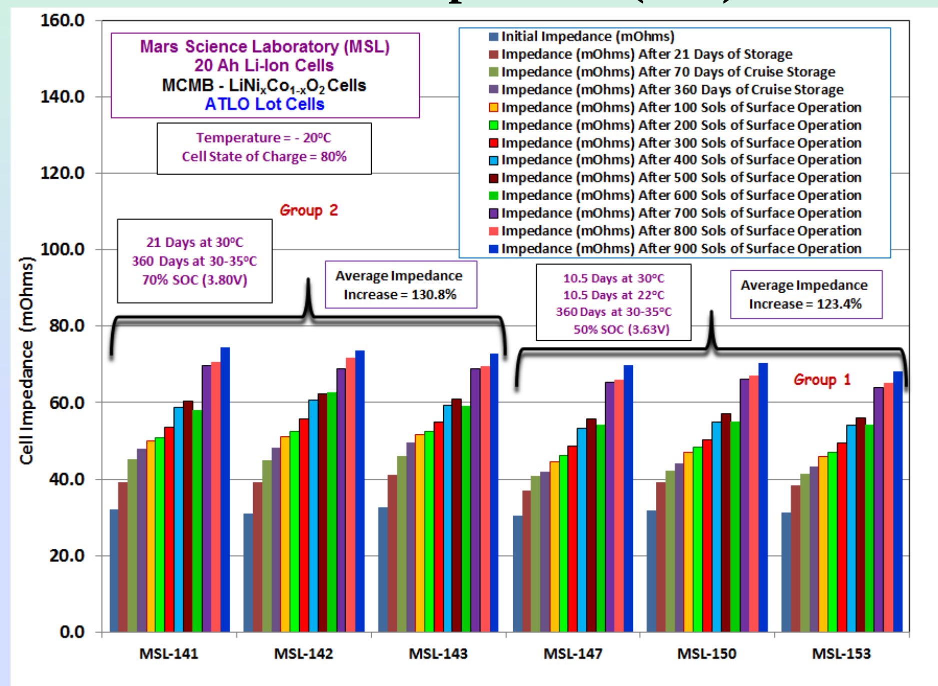
Characterization Testing at - 20°C

After Completing Pad Storage, Cruise Storage and 900 Sols on the Surface

Discharge Capacity (Ah)



Cell Impedance (mΩ)

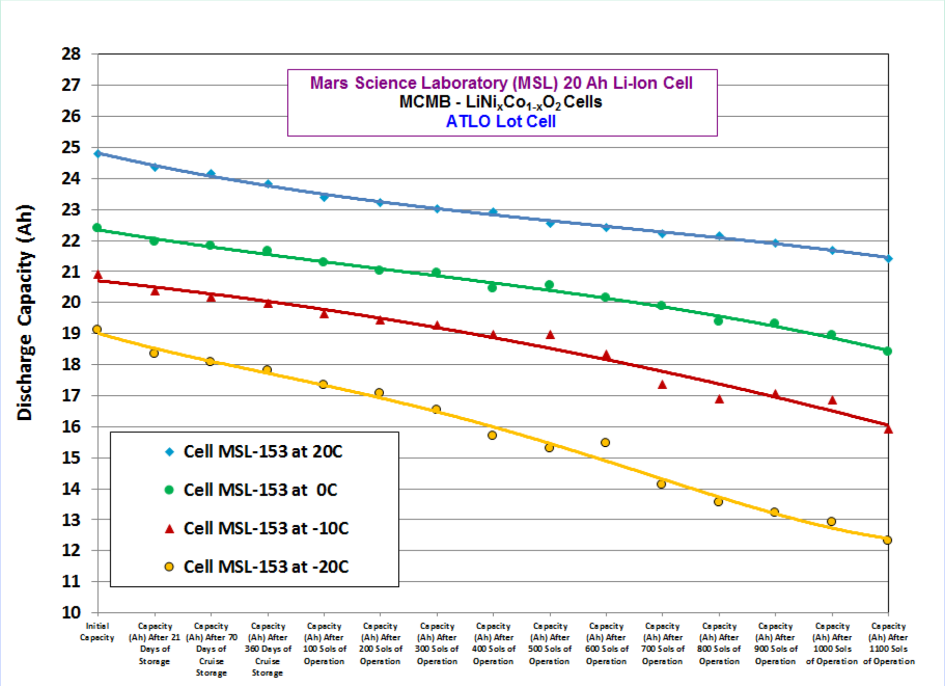


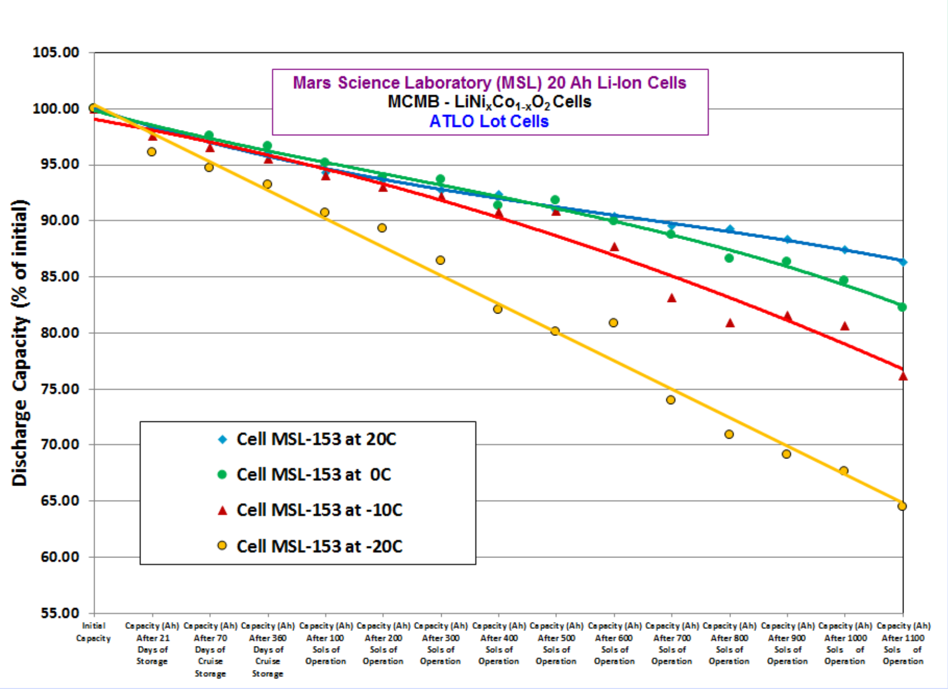
- ***Larger capacity fade characteristics for Group 1 and Group 2 were observed at -20°C compared with the warmer temperatures.***
- ***Approximately 32.5% capacity loss has been observed at - 20°C (with the Group 1 cells) after completing pad storage + cruise + 900 sols of operation.***

Performance of Yardney MSL 20 Ah Li-Ion Cells

Characterization Testing at Various Temperatures

After Completing Pad Storage, Cruise Storage and 1,100 Sols on the Surface



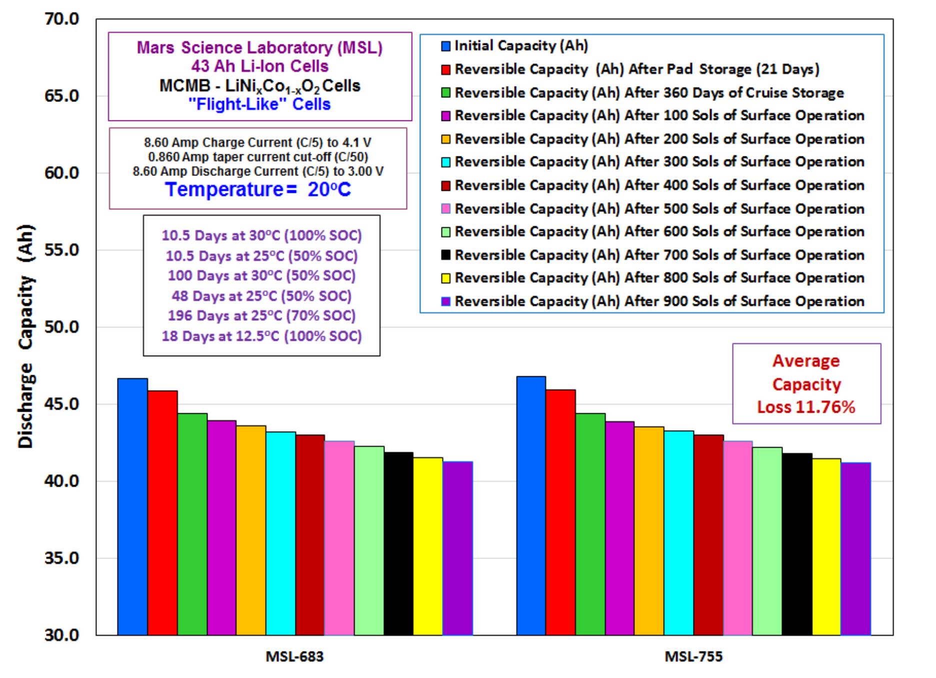


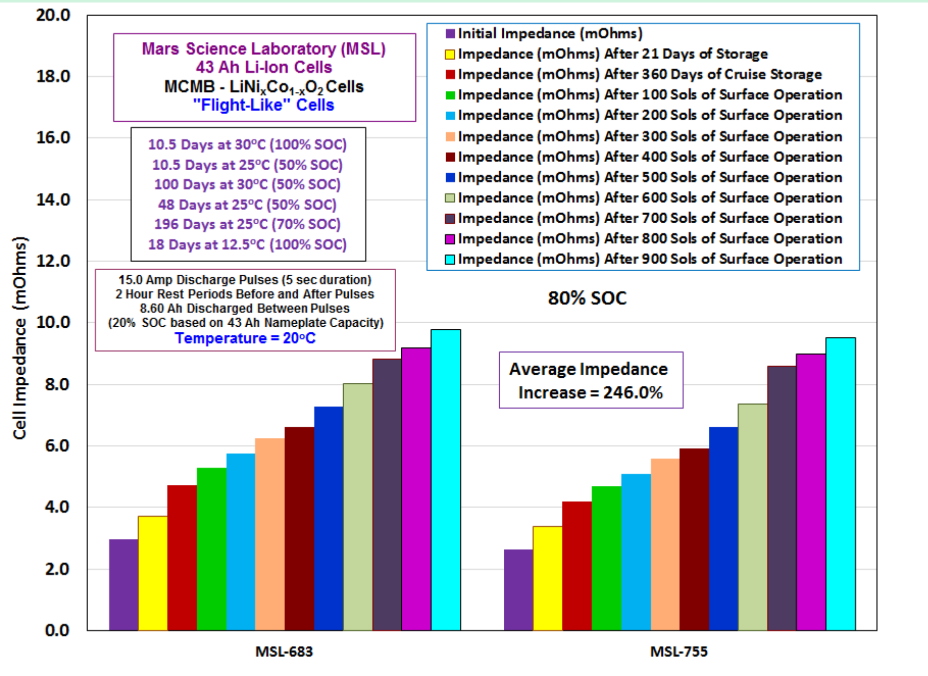
- ***The capacity loss observed is more significant at low temperatures.***

Performance of Yardney MSL 43 Ah Li-Ion Cells

Characterization Testing at 20°C

After Completing Pad Storage, Cruise Storage and 900 Sols on the Surface





- **The capacity fade and impedance growth observed with the 43 Ah cells as a result of the cruise period was somewhat greater than seen with the 20 Ah. This is primarily attributed to the more realistic cruise simulation conditions (including temperature and cell SOC).**

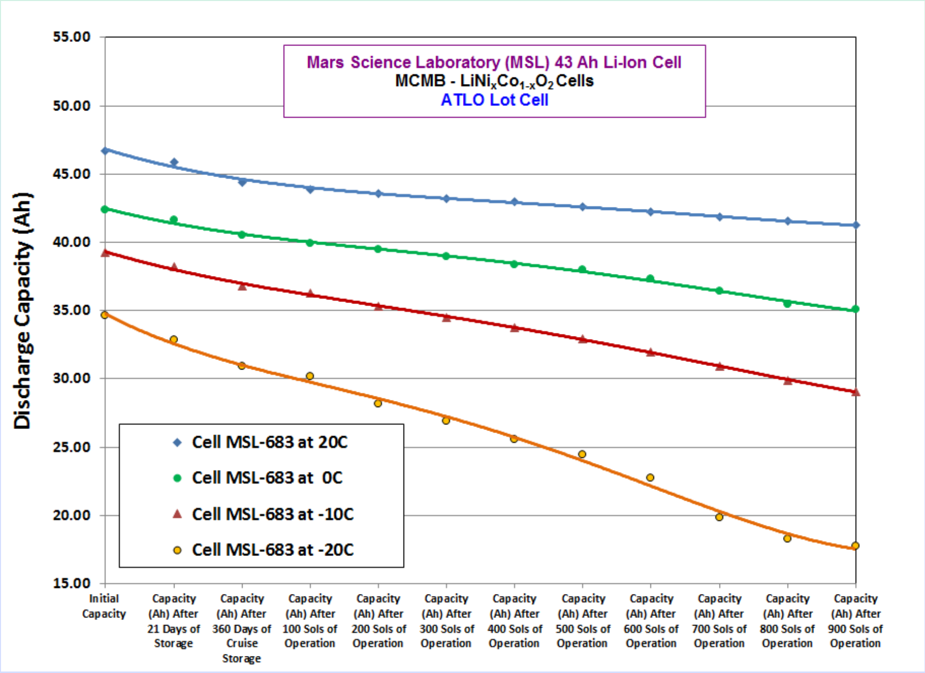
- **Pad Characterization:**
  - **Cells subjected to 30°C for 10.5 days (cells at 100% SOC, OCV conditions)**
  - **Cells subjected to 25°C for 10.5 days (cells at 50% SOC, OCV conditions)**

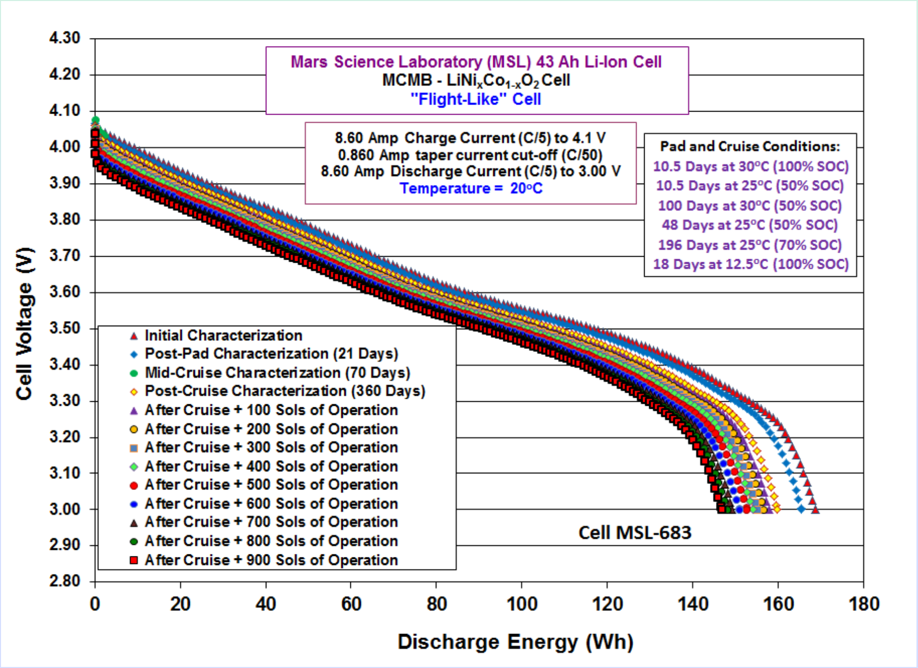
- **Cruise Characterization:**
  - **100 days at 30°C (50% SOC), 48 days at 25°C (50% SOC), 196 days at 25°C (70% SOC), 18 days at 12.5°C (70% SOC)**

Performance of Yardney MSL 43 Ah Li-Ion Cells

Characterization Testing at 20°C

After Completing Pad Storage, Cruise Storage and 900 Sols on the Surface

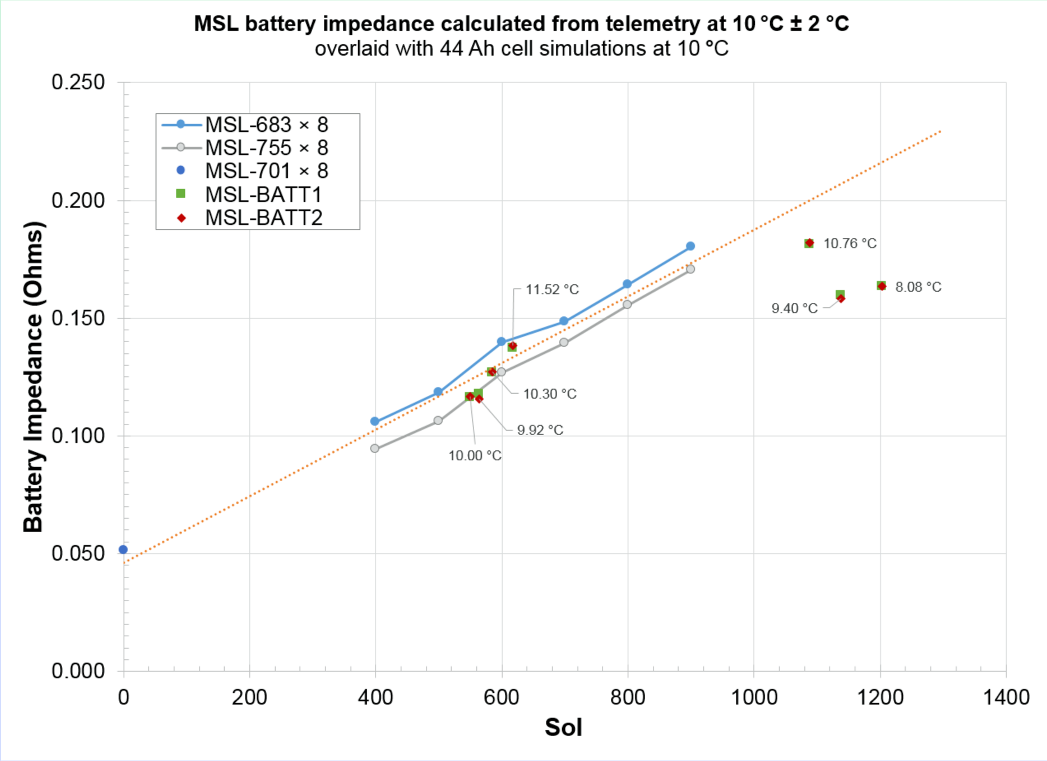




- The capacity fade and impedance growth observed with the 43 Ah cells as a result of the cruise period was somewhat greater than seen with the 20 Ah. This is primarily attributed to the more realistic cruise simulation conditions (including temperature and cell SOC).

Performance of Yardney MSL 43 Ah Li-Ion Cells

Summary of Calculated Impedance of MSL Curiosity Batteries Obtained From Telemetry Data and Simulated Ground Test Data (Heater Operation)

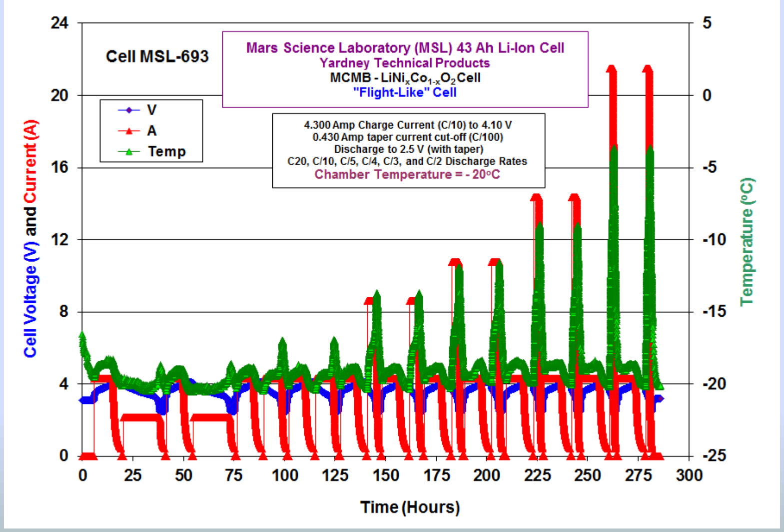


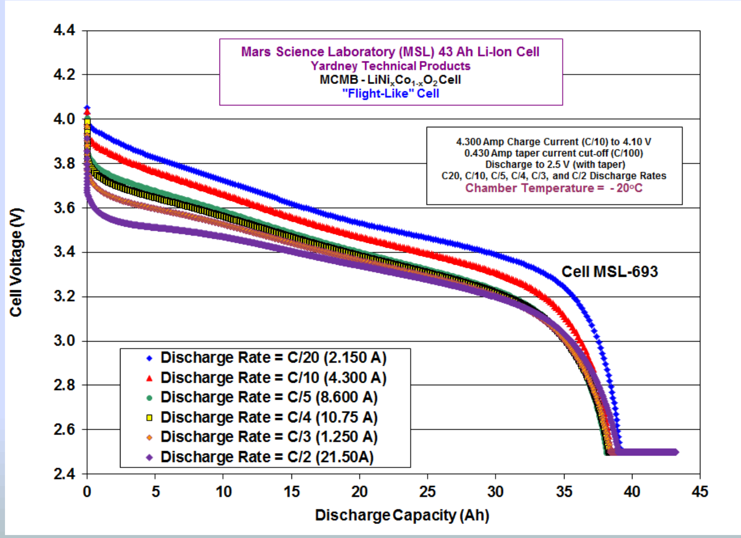
- Current efforts are focused on evaluating the impedance of the flight batteries determined from telemetry data and comparing it with comparable data generated on the ground test units subjected to mission simulation cycling.
- By briefly enabling the mobility heaters on the rover, we are able to estimate the internal resistance under controlled conditions (i.e., current injection/interruption measurements).
- Simulated heater operation was performed on 43 Ah cells undergoing mission simulation testing.
- Generally, good agreement was observed when comparing comparable measurements at 10^{o}C (i.e., ~ 125-140 mOhms was observed after completing 600 sols for both the flight batteries and ground test cells.
- Measurements help to validate relevance of ground testing data.

Performance of Yardney MSL 43 Ah Li-Ion Cells

Performance Testing in Support of MMPAT

- **In support of the JPL developed Multi-Mission Power Analysis Tool (MMPAT), we have completed a number of performance characterization tests that have been designed to aid in the creation of detailed cell polarization tables:**
  - **Discharge rate characterization testing:**
    - Six different discharge rates evaluated = C20, C/10, C/5, C/4, C/3, and C/2
    - Five different temperatures evaluated = 25°, 20°, 10°, 0°, -10°, and –20°C
    - Taper charge and taper discharge implemented
    - Cells discharged to 2.50 V (with taper discharge to C/100 in all cases)
  - **Charge rate characterization testing:**
    - Six different discharge rates evaluated = C20, C/10, C/5, C/4, C/3, and C/2
    - Five different temperatures evaluated = 25°, 20°, 10°, 0°, -10°, and –20°C
    - Taper charge and taper discharge implemented





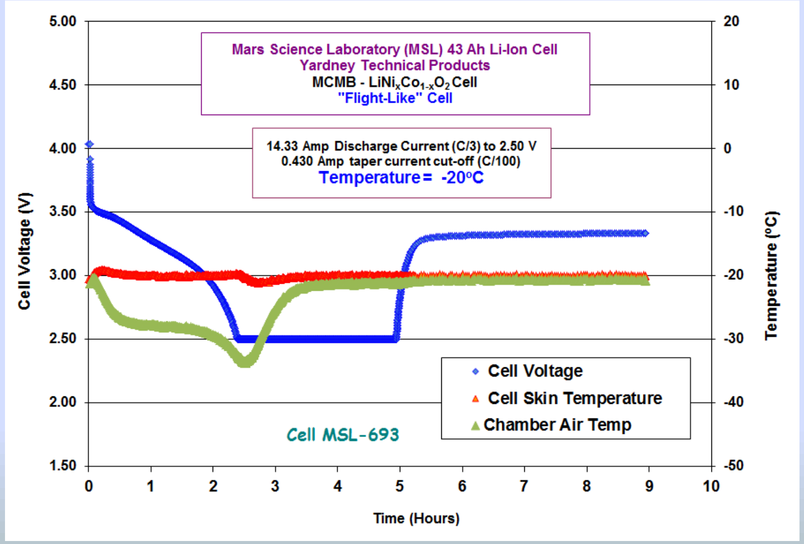
Performance of Yardney MSL 43 Ah Li-Ion Cells

Performance Testing in Support of MMPAT

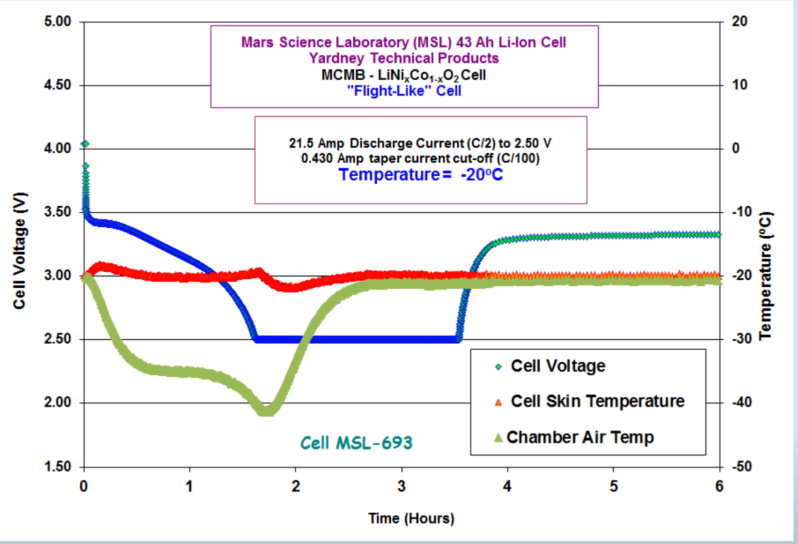
- After completing the discharge and charge rate testing, a determination was made as to which rates and at which temperatures result in the cell skin temperature readings that deviate significantly from the defined characterization temperature.
- If the cell temperature deviates during any part of the cycle by more than ~ > 2°C from the desired temperature, the test will be repeated at these charge and discharge rates with the product controlling the chamber temperature to compensate for the cell heat generation.

Product Controlled Temperature Testing

C/3 Discharge at -20°C



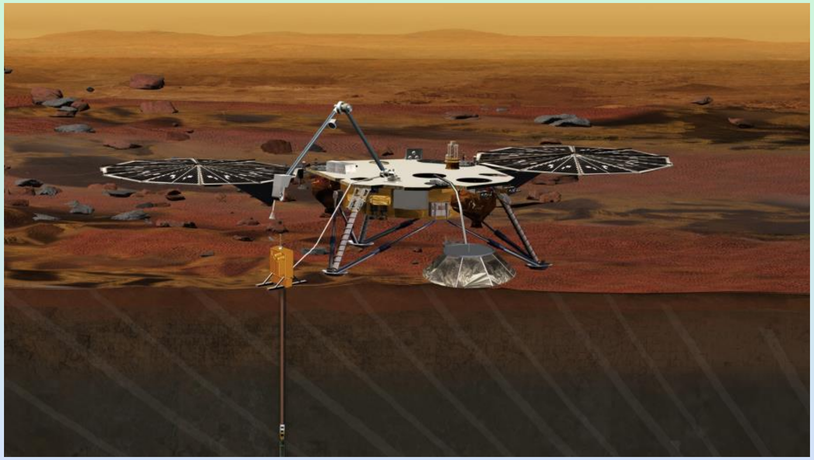
C/2 Discharge at -20°C



NASA's Mars InSight Lander

- **Anticipated Launch Date: May 2018**
- **InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) is a NASA Discovery Program mission that will place a single geophysical lander on Mars to study its deep interior.**
- **Mission will consist of a spacecraft built by Lockheed Martin Space Systems Company based on a design that was successfully used for NASA's Phoenix Mars lander mission**
- Science Goals:.
  - InSight is a terrestrial planet explorer that will address the processes that shaped the rocky planets of the inner solar system (including Earth) more than four billion years ago
  - InSight will probe beneath the surface of Mars, detecting the fingerprints of the processes of terrestrial planet formation

– **In January 2016, the March 2016 launch date of InSight mission was suspended to allow the repair of a leak in a section of the prime instrument in the science payload.**



Battery Details

- Two 8-cell batteries (connected in parallel)
- Manufactured by Eagle-Picher Technologies / Yardney Division
- 24-32.8 V (Phoenix Battery Design)
- Qualification Temperature range: - 40°C to +50°C.
- **Operating Temperature Range: -30° to +35°C**
- **Required Life: ~ 4 years**
- **Surface Life: 709 Sols of operation.**

Objective:

- **The primary objective of this test program is to characterize four different cell chemistries across the range of temperatures, with an emphasis upon the low temperature performance.**
- **Test objective is to down select cell chemistry that meets mission requirements most successfully.**
- **Test program serves as technology validation activity if down-selection deviates from the heritage chemistry.**
- **Goal is to characterize the cells under flight-relevant conditions to enable an informed decision for the technology down-selection prior to the CDR, and provide sufficient information to determine if all requirements are met.**

Approach:

- **Obtain prototype cells consisting of four different cell chemistries from Yardney Technical Products.**
- **Cell design is based on the format utilized for the Mars Phoenix Lander**
- ***Implement a long term testing program, focused on determining: (i) the charge and discharge characteristics over a wide temperature, (ii) cycle life performance under mission relevant conditions, and (iii) accelerated cycling at high temperatures.***

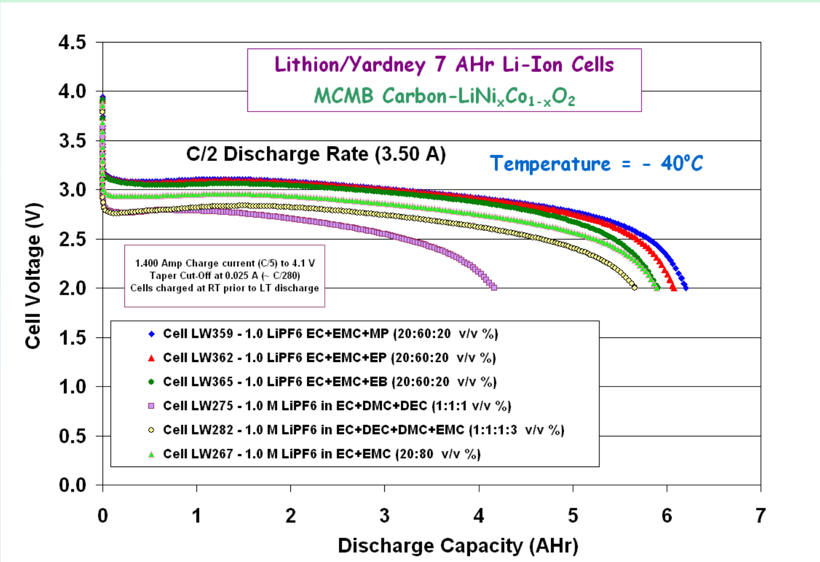
Key Battery Performance Requirements for InSight

- Operation for more than 40 months after launch and a calendar life of > 4 years.
- Consist of two Li-ion rechargeable batteries (connected in parallel)
- Surface Operation Capability:
  - The battery shall support 709 sols of surface operations over a temperature range of -30°C to +35°C
  - Each 8-cell battery shall be able to support a 5A charge rate over the entire allowable flight temperature range of-30°C to +35°C
  - Each 8-cell battery shall provide at least 25 Ah at -25°C beginning of life over the voltage range of 24.0V to 32.80V using a C/5 rate (5.0A)

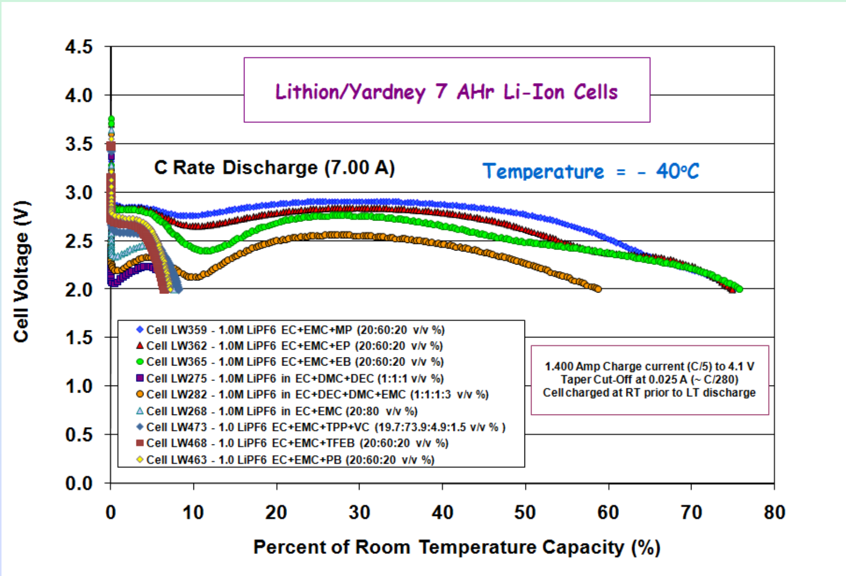
Development of Advanced Low Temperature Electrolytes

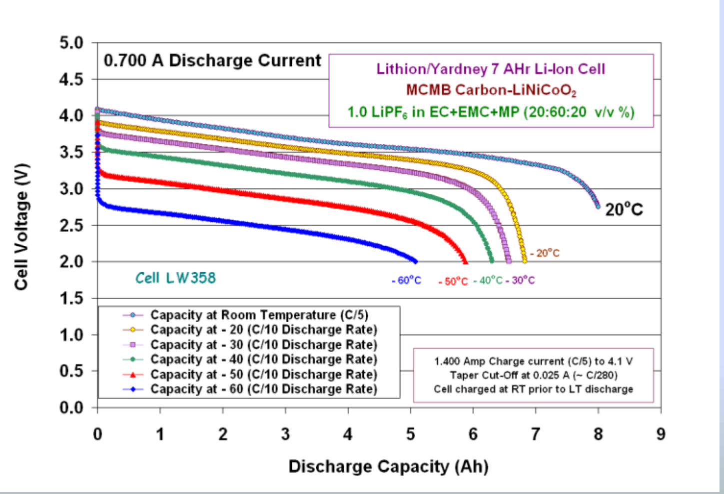
Demonstration of Ester-Based Electrolytes in Yardney Prototype Cells

Performance at -40°C (C/2 Rate)



Performance at -40°C (C Rate)





An electrolyte formulation containing methyl propionate, 1.0M LiPF$_6$ EC+EMC+MP (20:60:20 v/v %) was demonstrated to provide improved low temperature performance over baseline all carbonate-based electrolytes (including the heritage blend), while still providing reasonable high temperature resilience.

- M.C. Smart, and B.V. Ratnakumar, L.D. Whitcanack, K.A. Smith, S. Santee, R. Gitzendanner, V. Yevoli, "Li-Ion Electrolytes Containing Ester Co-Solvents for Wide Operating Temperature Range", *ECS Trans.* **11**, (29) 99 (2008).
- M. C. Smart, B. V. Ratnakumar, K. B. Chin, and L. D. Whitcanack, "Lithium-Ion Electrolytes Containing Ester Co-solvents for Improved Low Temperature Performance", *J. Electrochem. Soc.*, **157 (12)**, A1361-A1374 (2010).

Performance Testing of Yardney NCP-25x Lithium-Ion Cells

Summary of Test Plan for InSight

- Next Generation Yardney NCP-25x Li-Ion Cells
  - **18 Cells are currently on test possessing four chemistry variations**
  - **Cell are 25 Ah Nameplate capacity (based on Yardney NCP-25-1 design)**
  - **Cells are being subjected to performance testing to determine applicability to InSight**

Cell Group (Quantity)	Cell Definition	Cathode	Anode	Material Loading	Electrolyte
Chemistry A (5 Cells)	Heritage (Control / Phoenix Baseline)	$LiNiCoO_2$ (NCO)	MCMB	Nominal	Standard Heritage Electrolyte 1.0M $LiPF_6$ in EC+DEC+DMC (1:1:1)
Chemistry B (5 Cells)	Heritage, Low-Temperature Electrolyte	$LiNiCoO_2$ (NCO)	MCMB	Nominal	Low-Ester, Low-Temperature 1.0M $LiPF_6$ in EC+EMC+MP (20:60:20)
Chemistry C (5 Cells)	**NextGen Chemistry, Low-Temperature Electrolyte**	**$LiNiCoAlO_2$ (NCA)**	**Modified Graphite**	**Nominal**	**Low-Ester, Low-Temperature 1.0M $LiPF_6$ in EC+EMC+MP (20:60:20)**
Chemistry D (3 Cells)	NextGen Chemistry, Heritage Electrolyte	$LiNiCoAlO_2$ (NCA)	Modified Graphite	Nominal	Standard Heritage Electrolyte 1.0M $LiPF_6$ in EC+DEC+DMC (1:1:1)

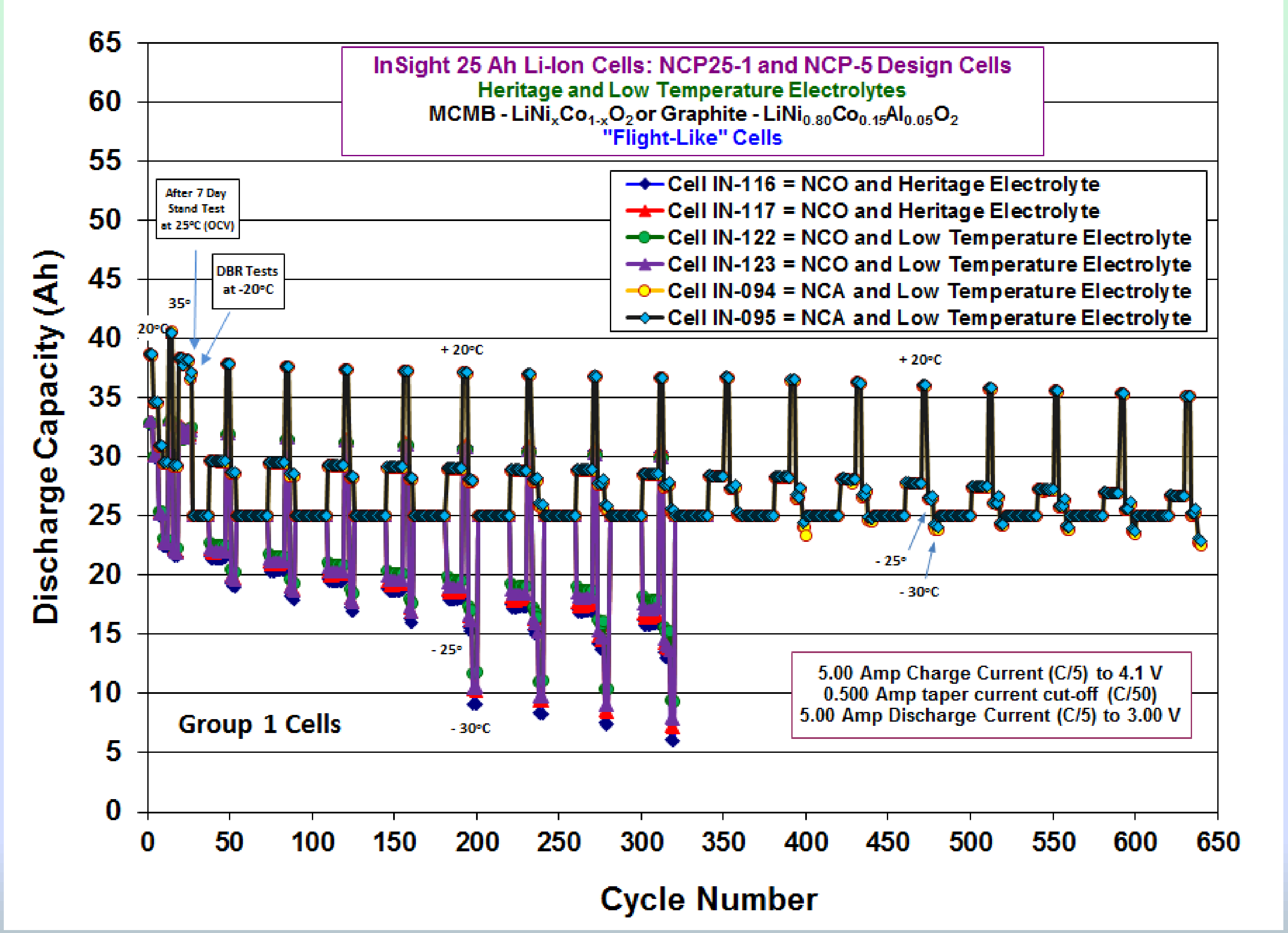
Performance Testing of InSight Yardney NCP-25-6 Li-Ion Cells

Status of Group 1 Cell Testing

- **Status of Group 1 Cells (6 Cells):**
- **Undergoing mission-like cycling at +30°C, +20°C, and -25°C (one cycle per sol) (Performed in groups of 10 cycles at each temperature)**
  - Subjected to +35°C cycling, 7 day stand test at +25°C, and DBR characterization
  - NCA cells completed over **640 cycles;** NCO cells discontinued after completing 340 cycles
  - To date, the flight like cells have completed the following:
    - 160 cycles at +30°C using low rate (capacity = 25 Ah)
    - 150 cycles at +20°C using low rate (capacity = 25 Ah)
    - 160 cycles at - 25°C using low rate (full DOD cycling, 3.0V to 4.10V)
  - Characterization cycling performed at different temperatures periodically to gauge performance and determine health: (Full DOD C/5 rates used in all cases, 3.0V to 4.1V):
    - Temperature = +20°C; Total number of cycles = 54
    - Temperature = - 25°C; Total number of cycles = 54
    - Temperature = - 30°C; Total number of cycles = 40

Results of Group 1 Cell Testing

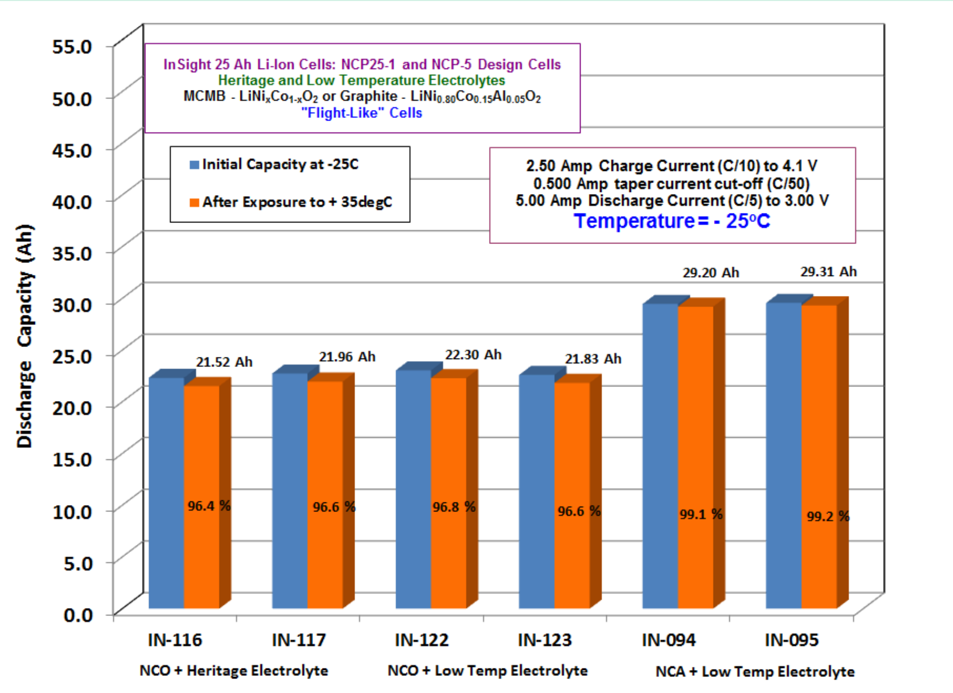
Summary of Results (Discharge Capacity, Ah)

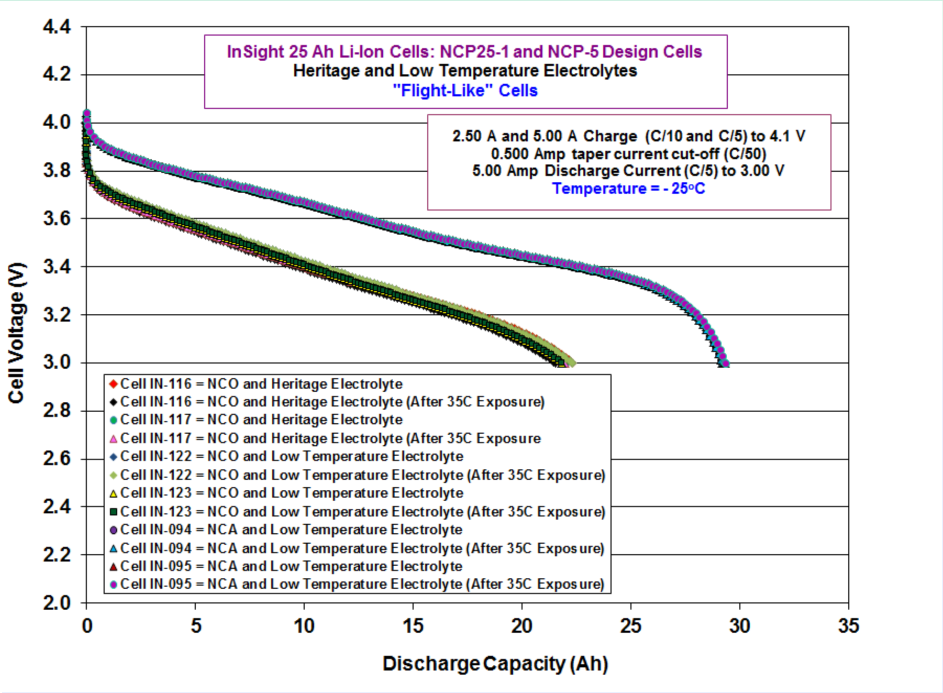


Results of Group 1 Cell Testing

Performance at -25°C After Initial Exposure to +35°C

Comparison of Different Chemistries



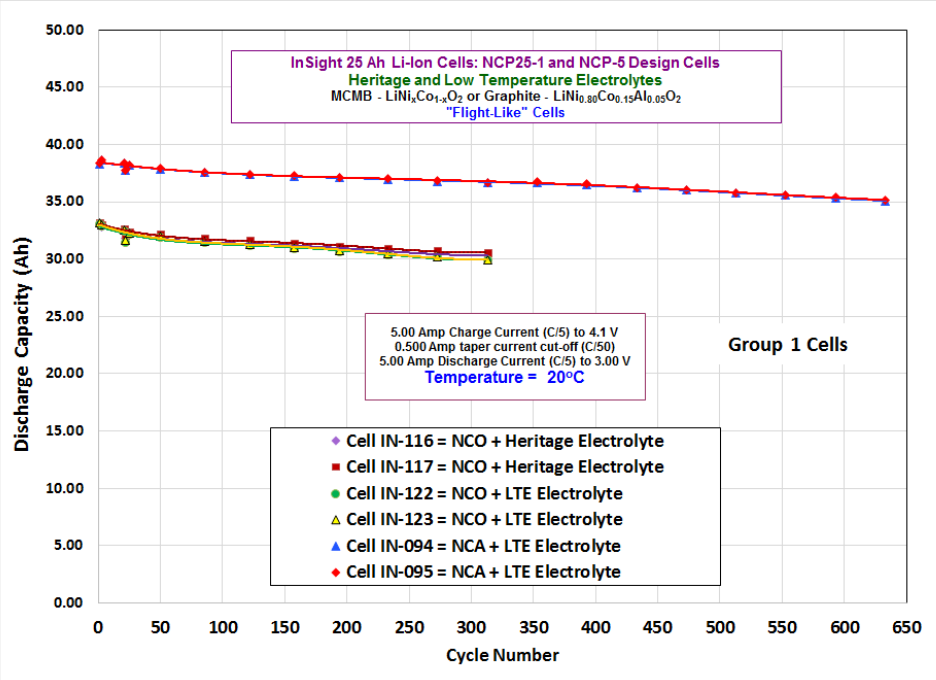


- Cells with NCA and Low Temperature Electrolyte deliver 31% more capacity at -25°C compared with heritage chemistry and display much higher operating voltage throughout the discharge.
  - The NCA-based cells display enhanced resilience to high temperatures.

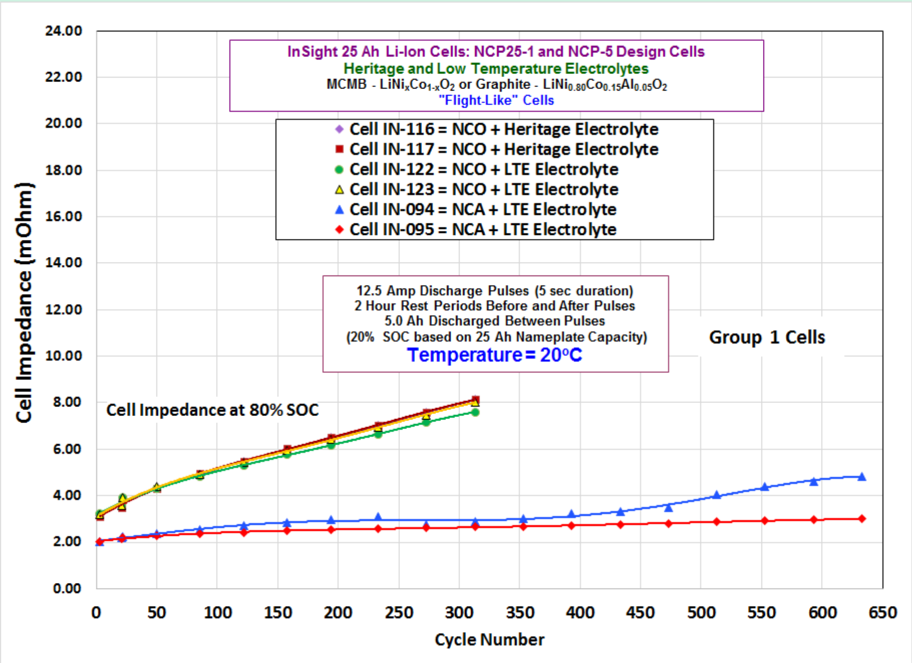
Results of Group 1 Cell Testing

Summary of Results (Discharge Capacity at 20°C)

Discharge Capacity (Ah) at 20°C



Cell Impedance (mΩ) at 20°C

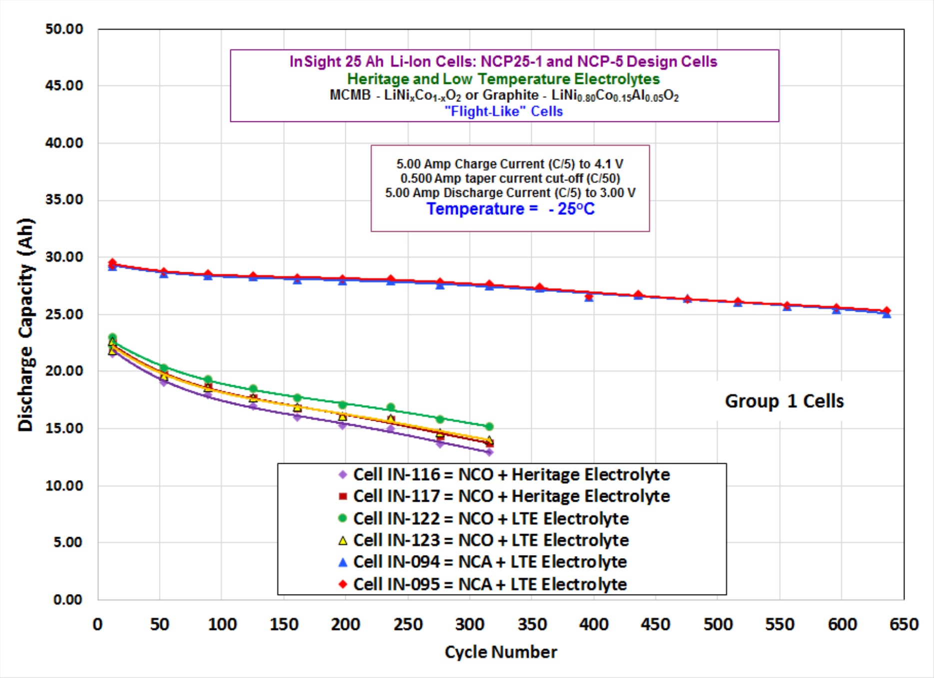


- Good capacity retention and low impedance growth was observed with the NCA+LTE cells
  - NCA+LTE cells delivered > 91% of the initial capacity after completing 633 cycles (> 2.35 years)
  - NCA+LTE cells displayed less than half the impedance of the NCO systems, and the impedance growth is much lower

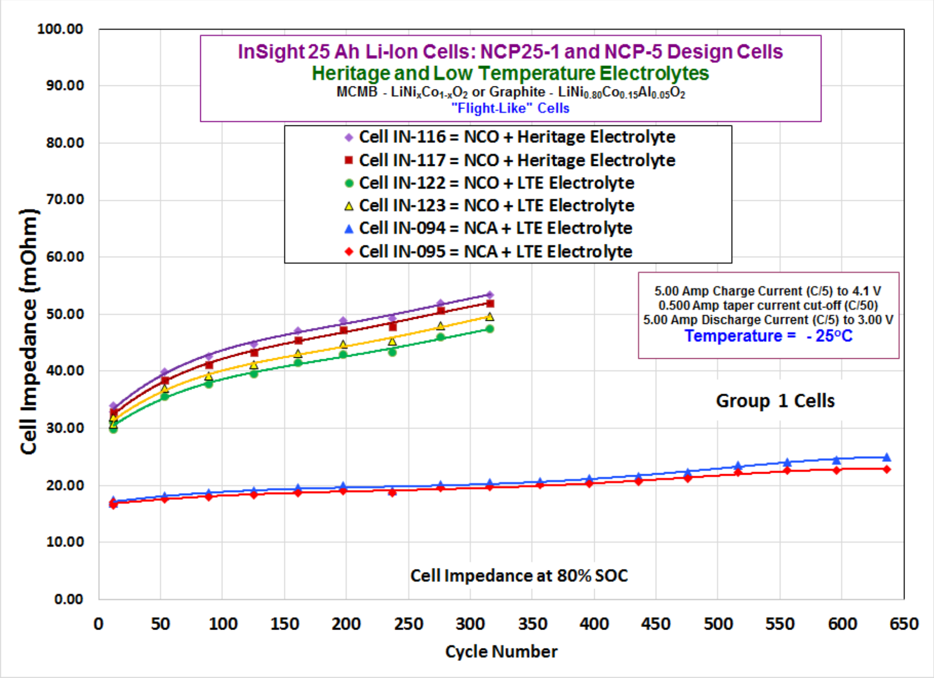
Results of Group 1 Cell Testing

Summary of Results (Discharge Capacity at -25°C)

Discharge Capacity (Ah) at -25°C



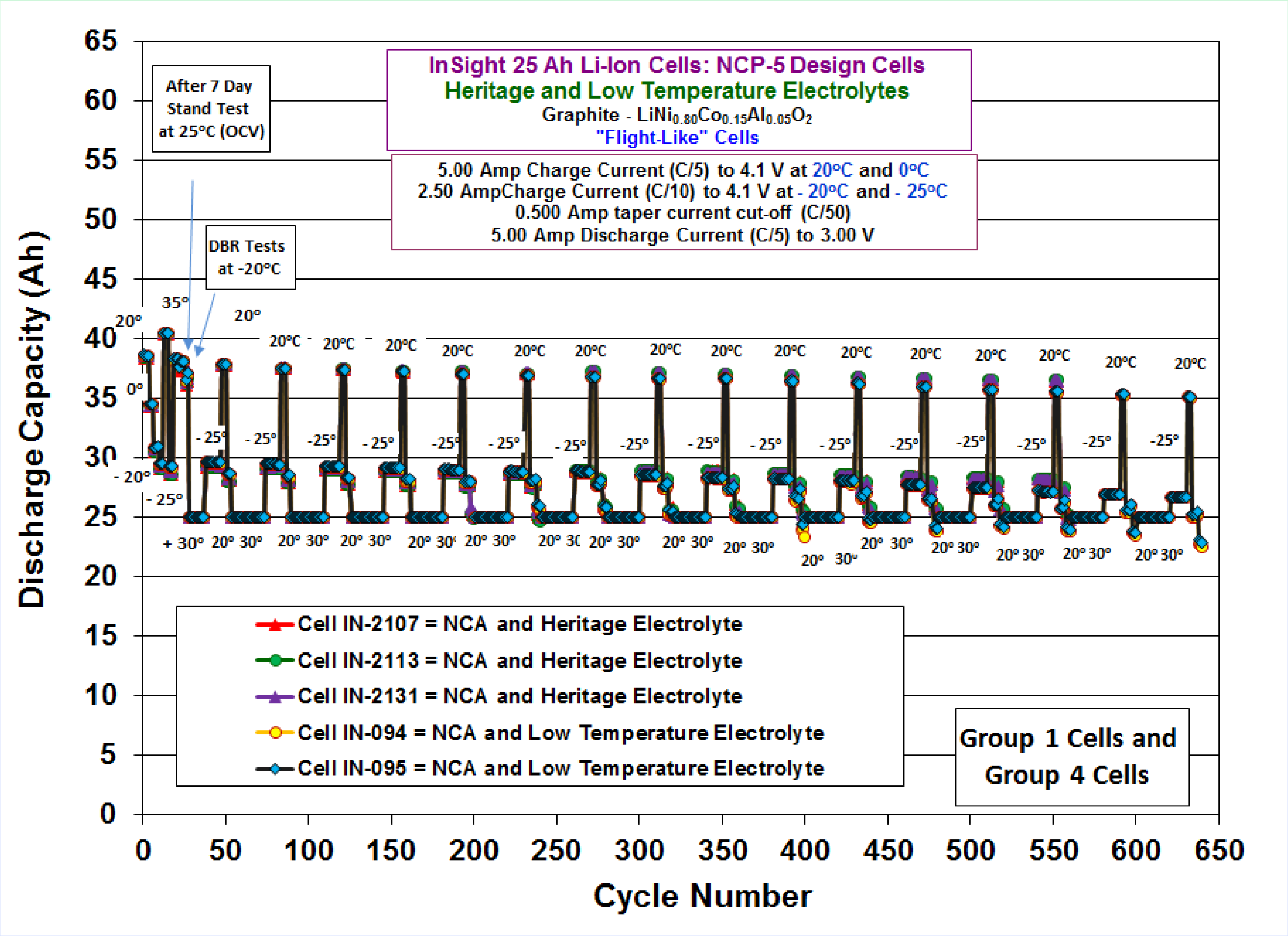
Cell Impedance (mΩ) at -25°C



- *The NCA+ Low Temperature Electrolyte chemistry delivers improved capacity at -25°C compared with the NCO heritage and displays dramatically better low temperature capacity retention throughout the life of the cells.*

Results of Group 4 Cell Testing

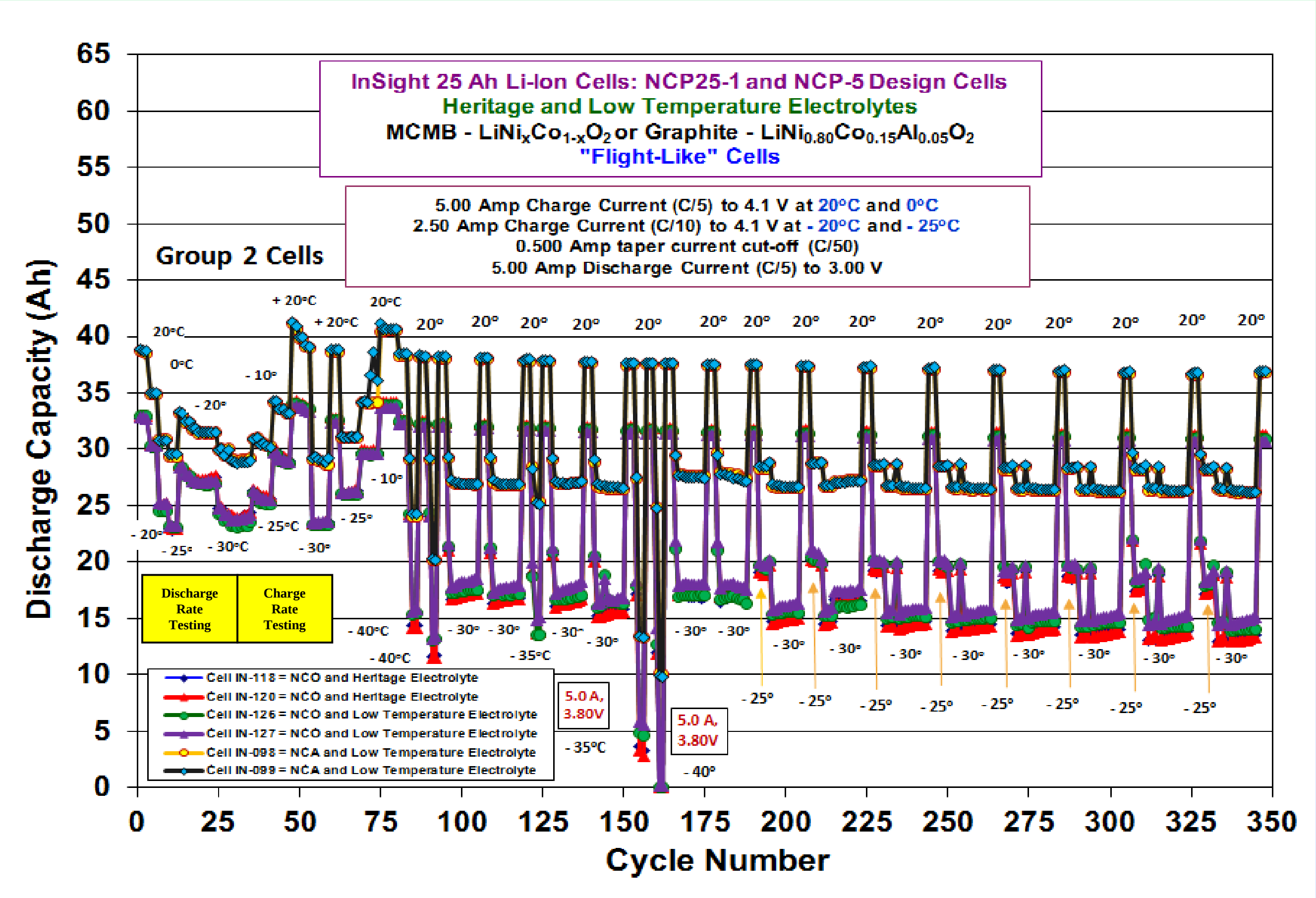
Summary of Results (Discharge Capacity, Ah)



- ***NCA-based cells that contain the low temperature MP-based electrolyte and the heritage all carbonate-based electrolyte performed very comparably throughout the testing.***

Results of Group 2 Cell Testing

Summary of Results (Discharge Capacity, Ah)



- *After (a) initial characterization at different temperatures (20, 0, -20, and -25°C), (b) discharge rate characterization (down to -30°C), (c) charge rate characterization (down to -30°C), and (d) diagnostic testing at -40°C, the cells have been subjected to (e) continuous cycling at -30°C to assess robustness. Over 140 cycles completed at flight-like conditions at -30°C*
- Cells still display > 95% of original capacity at +20°C (Testing discontinued to accommodate other tests)
- Completed over **345 cycles and displayed excellent resilience to cycling at -30°C**

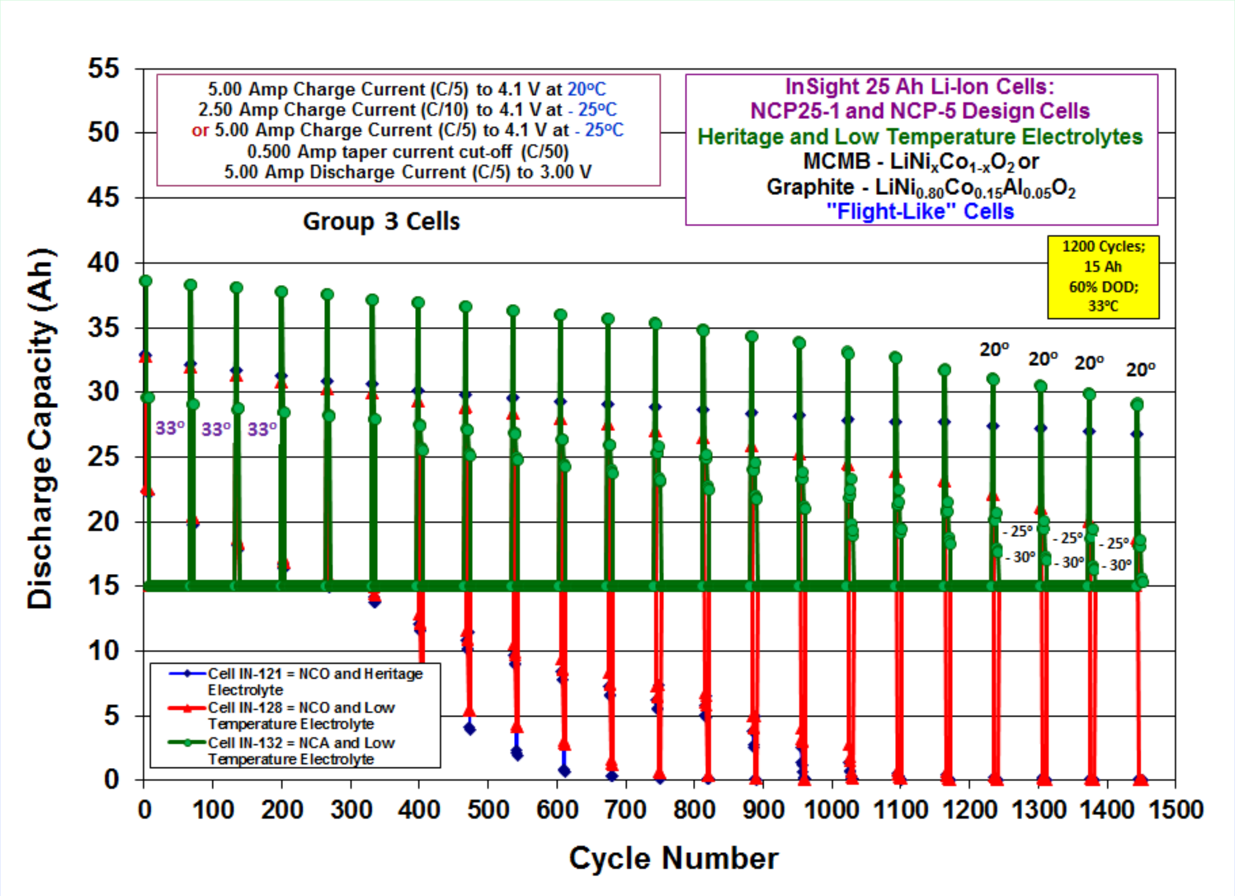
Performance Testing of InSight Yardney NCP-25-6 Li-Ion Cells

Status of Group 3 Cell Testing

- **Status of Group 3 Cells (3 Cells):**
  - **Accelerated partial DOD (60%) cycling at high temperature (+33°C)**
  - Completed over **1,382 cycles** (1,200 cycles at 60% DOD at +33°C)
  - Accelerated cycling at +33°C represents worst case thermal environment
  - Cycle life performance does not reflect cruise and calendar fade

Results of Group 3 Cell Testing

Summary of Results (Discharge Capacity, Ah)

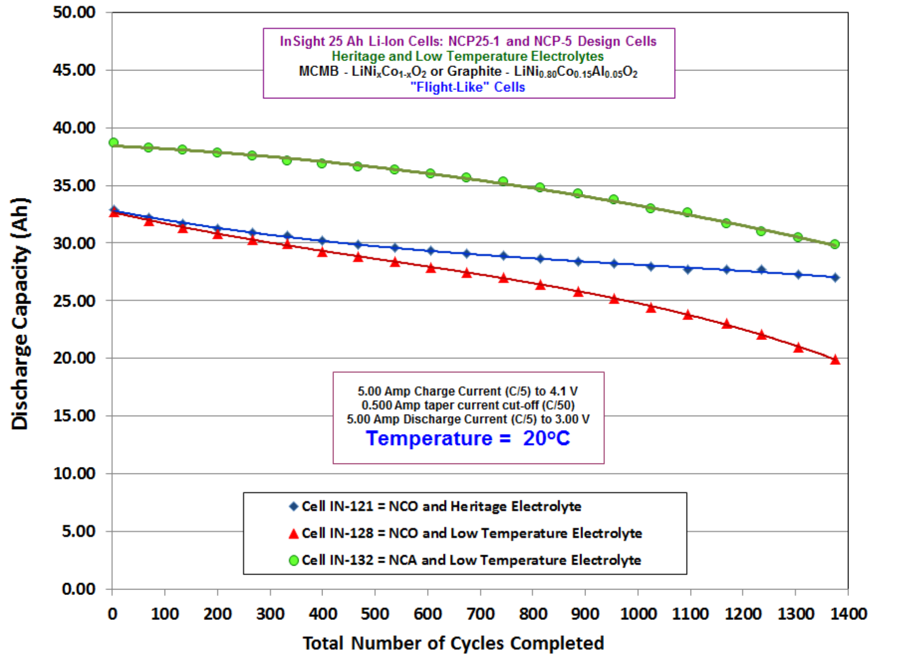


- *The Group 3 cells were cycled at high temperature +33°C and periodically characterized at +20°, -25°, and-30°C*
- *The NCA+LTE cell IN-132 delivered 18.79 Ah at -25°C (cycle 1,378) and 16.31 Ah at -30°C (cycle 1,382)*
  In contrast, the NCO+Heritage only delivered 0.100 Ah and the NCO+LTE delivered 0.084Ah at -25°C (cycle 1,378)
- *Cells cycled under flight-like conditions (i.e., C/5 charge rate to 4.10V)*
- *Cells have completed 1,200 accelerated cycles at high temperature (i.e., 33°C)*

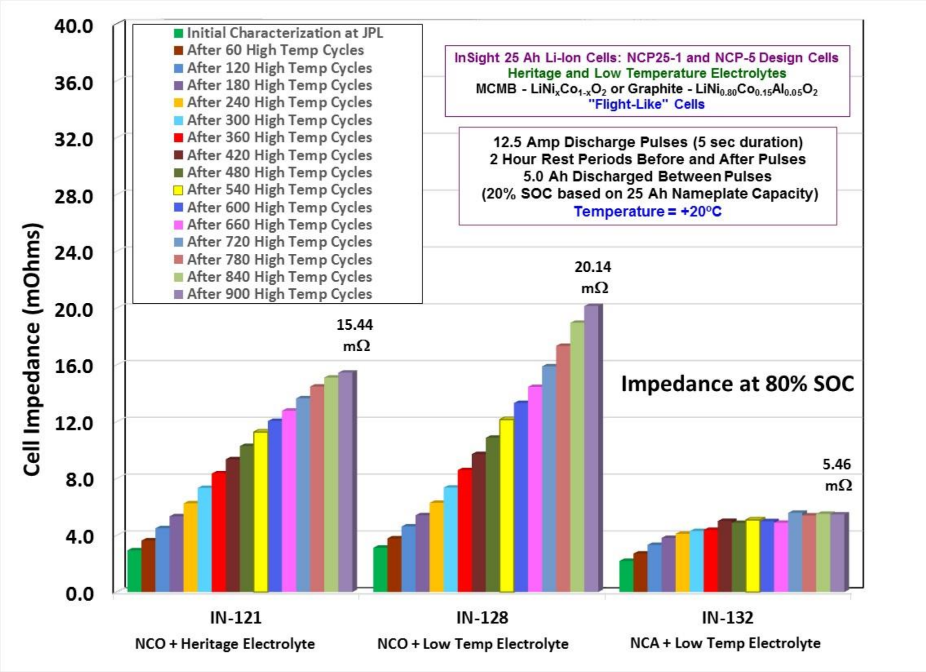
Results of Group 3 Cell Testing

Summary of Results (Capacity and Impedance at 20°C)

Discharge Capacity (Ah) at +20°C



Cell Impedance at +20°C

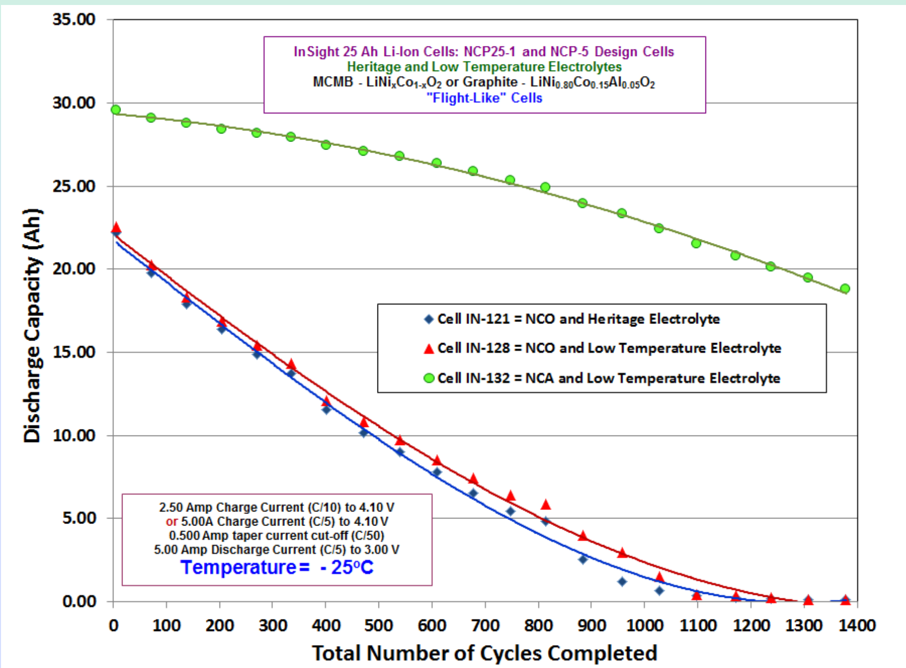


- *The NCA +LTE cell displays good tolerance to high temperatures (i.e., 33°C) and lower impedance growth compared to the NCO heritage cell.*
- *The trend in the capacity retained as a result of the high temperature cycling is the following:*
  - *NCO+Heritage (27.43 Ah, 83.4%) > NCA+LTE (31.0 Ah, 80.2%) > NCO+LTE (22.07 Ah, 67.5%)*
- *After > 900 cycles, the NCA cell impedance is roughly a third of the NCO heritage chemistry.*

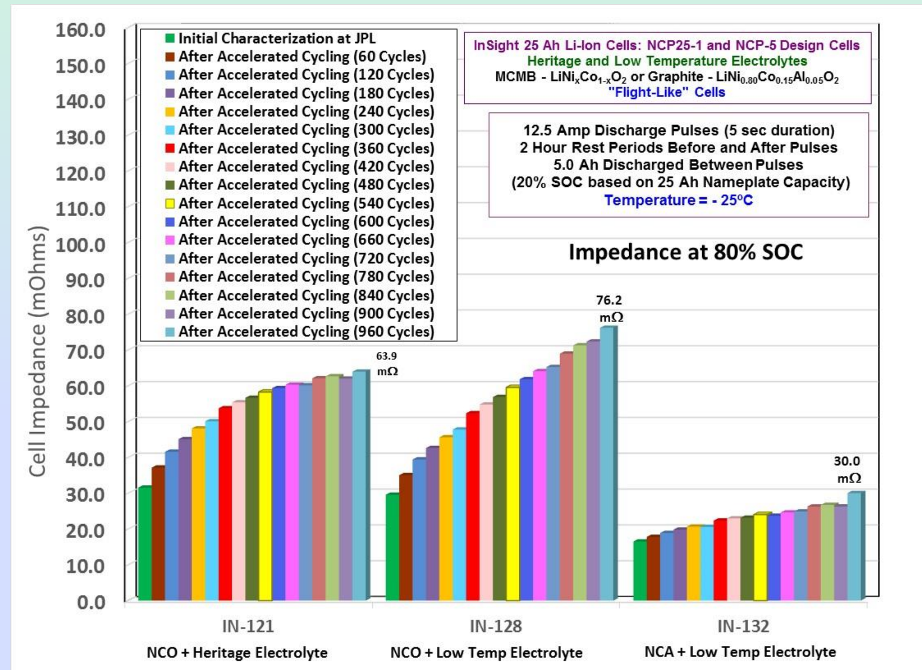
Results of Group 3 Cell Testing

Summary of Results (Discharge Capacity at -25°C)

Discharge Capacity (Ah) at -25°C



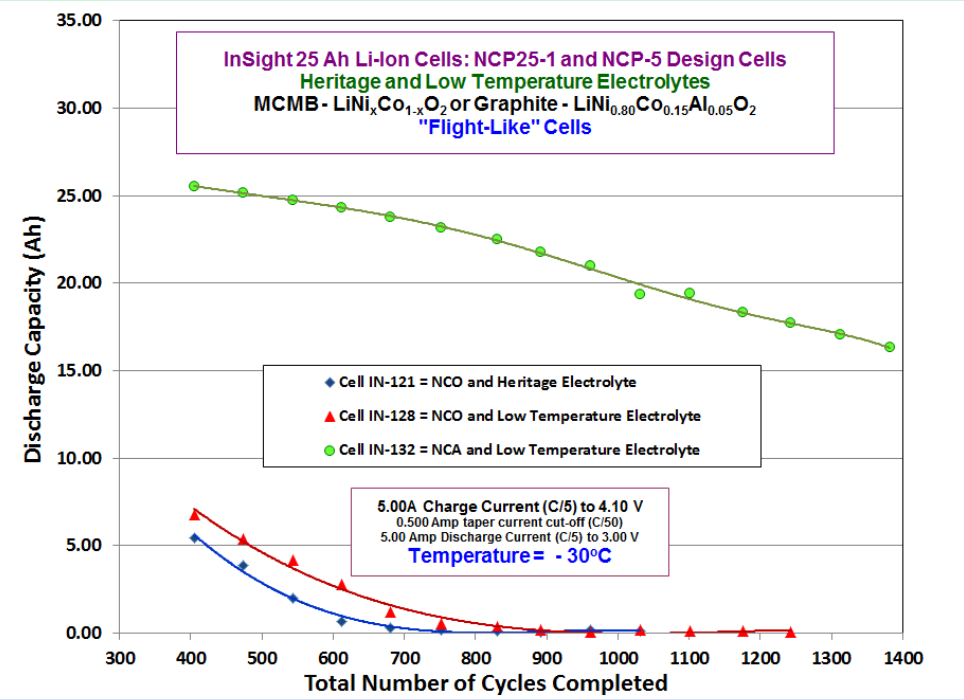
Cell Impedance at -25°C

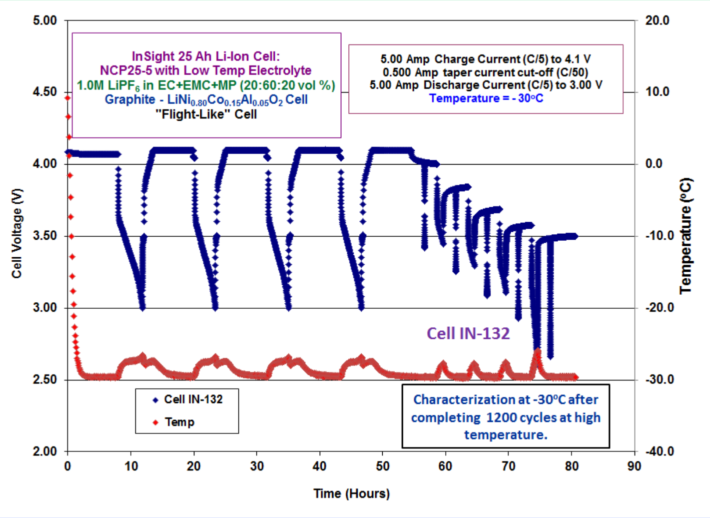


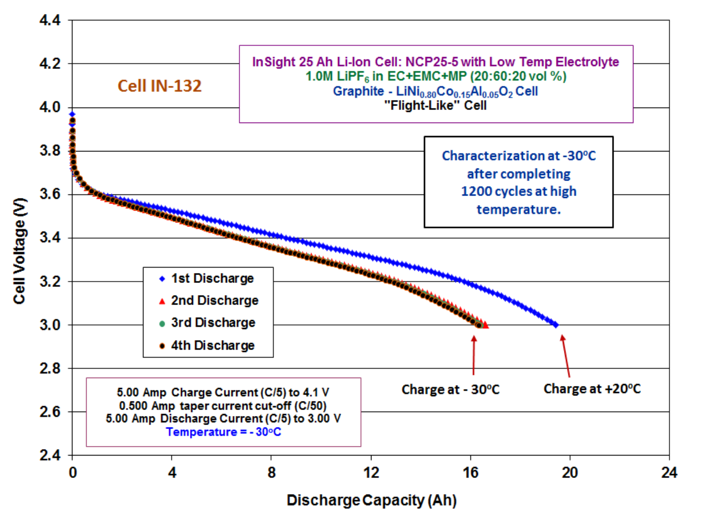
- *The low temperature performance of the NCA +LTE cell was superior to that of the NCO-based cells, and that capability was preserved much better after being subjected to high temperature cycling.*
- *After completing over 1,200 total cycles, the NCA +LTE cell delivered over 90 times the capacity of either NCO cell*
- *The trend in the capacity delivered at -25°C after extensive cycling is the following:*
  - *NCA+LTE (20.11 Ah, 67.0%) > NCO+LTE (0.210Ah, 0.93%) > NCO+Heritage (0.176Ah, 0.80%)*

Results of Group 3 Cell Testing

Summary of Results (Performance at -30^{o}C)







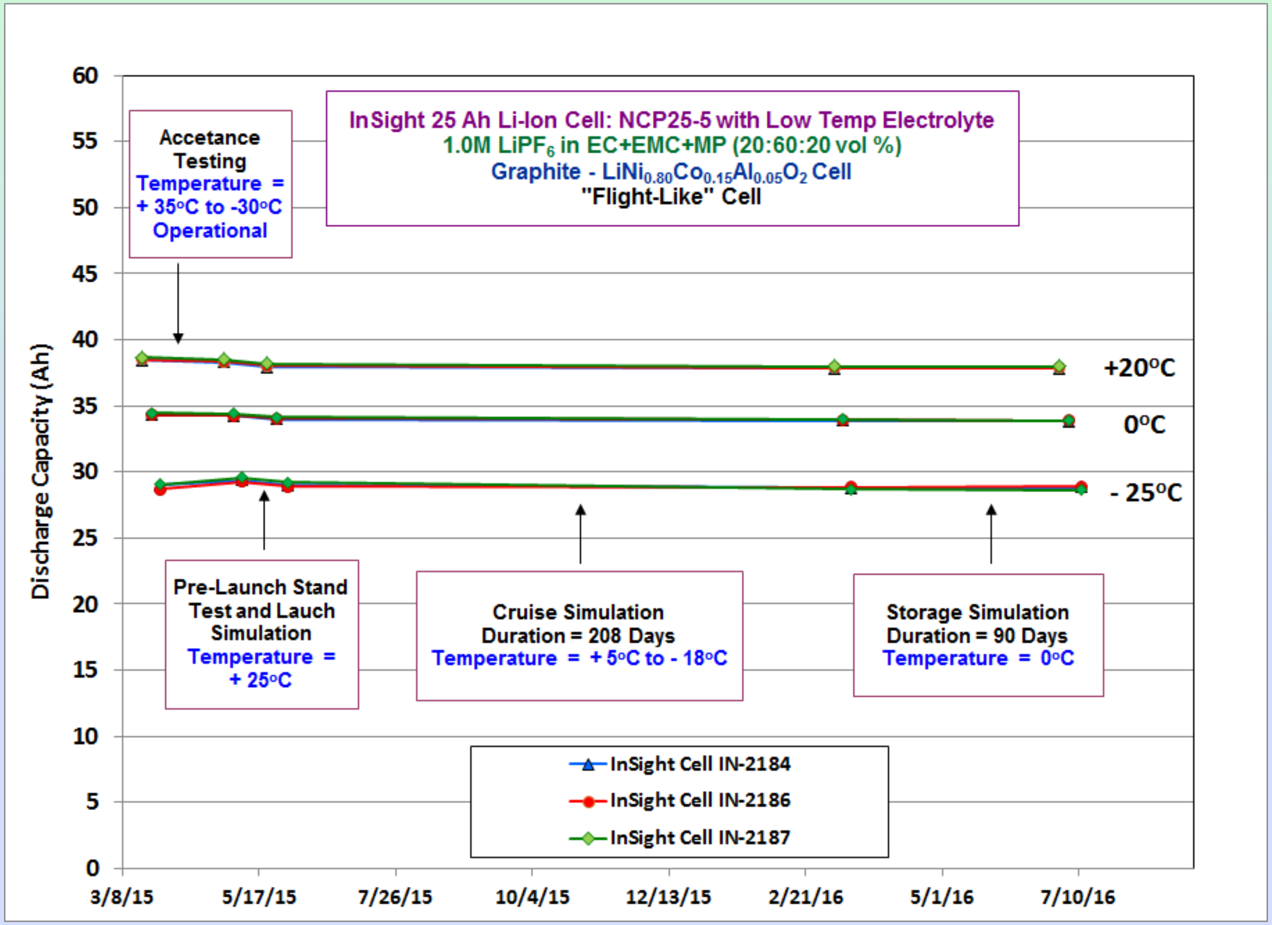
- After completing 1080 high temperature cycles (and over 1240 total cycles), the NCA+LTE dramatically outperforms the heritage chemistry at -30^{o}C (i.e., delivering 17.5 Ah compared with negligible capacity for the heritage cell)
- No evidence of Li plating was observed with the cells using a C/5 charge rate (5.0A) at -30^{o}C.

Performance Testing of InSight Yardney NCP-25-6 Li-Ion Cells
Status of Group 5 Cell Testing

- **Mission Simulation Testing (3 Cells)**
  - **Initial Characterization at +20°C, 0°C, and -25°C**
  - **Flight-like Acceptance Testing**
    - **Capacity Verification at +20°C**
    - **High Current Battery Capacity at +0°C (2 Cycles)**
    - **Charge Retention Test at + 20°C (2 Cycles)**
    - **Battery Impedance Test at 50% SOC at +20°C**
    - **Battery Acceptance Random Vibration Test**
    - **Post Random Vibration Capacity Verification at +20°C (2 Cycles)**
    - **Battery TVAC Cycling (2 Non-Op TVAC Cycles, 6 Op/Non-Op Cycles**
    - **Post Thermal Vacuum/Thermal Cycle Battery Capacity at +20°C**
  - **Repeat of Characterization at +20°C, 0°C, and -25°C**
  - **Pre-Launch Stand Test at +25°C (100% SOC)**
  - **Launch Simulation at +25°C**
  - **Repeat of Characterization at +20°C, 0°C, and -25°C**
  - **Cruise Simulation Testing Test (70% - 100% SOC, +5°C to -18°C)**
  - **Repeat of Characterization at +20°C, 0°C, and -25°C**
  - **Storage Simulation Testing**

Performance Testing of InSight Yardney Li-Ion Cells

Status of Group 5 Cell Testing



- *Less than 1.8 % capacity loss was observed at all three temperatures after being subjected to acceptance testing, long term cruise simulation, and 3 months of post-cruise storage.*

Performance Testing of InSight Yardney Li-Ion Cells

Status of Group 5 Cell Testing

Capacity and Impedance at +20°C

	InSight Cell IN-2184					InSight Cell IN-2186					InSight Cell IN-2187				
	Ah	Percent of Initial (%)	Wh	Percent of Initial (%)	mOhms	Ah	Percent of Initial (%)	Wh	Percent of Initial (%)	mOhms	Ah	Percent of Initial (%)	Wh	Percent of Initial (%)	mOhms
Initial Performance at +20°C	38.459	100	140.6	100	2.197	38.5250	100	140.81	100	2.142	38.643	100	141.26	100	2.081
Performance at +20°C After Acceptance Testing	38.292	99.57	139.91	99.51	2.417	38.351	99.55	140.11	99.50	2.283	38.507	99.65	140.69	99.60	2.185
Performance at +20°C After Pre-Launch Stand Test and Launch Simulation	37.955	98.69	138.72	98.66	2.643	38.051	98.77	139.07	98.77	2.399	38.181	98.80	139.56	98.80	2.301
Performance at +20°C After Cruise Simulation	37.839	98.39	138.23	98.32	3.052	37.894	98.36	138.51	98.37	2.515	37.997	98.33	138.93	98.35	2.368
Performance at +20°C After 3 Months of Storage	37.807	98.30	138.07	98.20	3.210	37.898	98.37	138.49	98.35	2.606	37.959	98.23	138.77	98.24	2.441

- ***Less than 1.8 % capacity loss was observed at all three temperatures after being subjected to acceptance testing, long term cruise simulation, and 3 months of post-cruise storage.***

Performance Testing of InSight Yardney Li-Ion Cells

Status of Group 5 Cell Testing

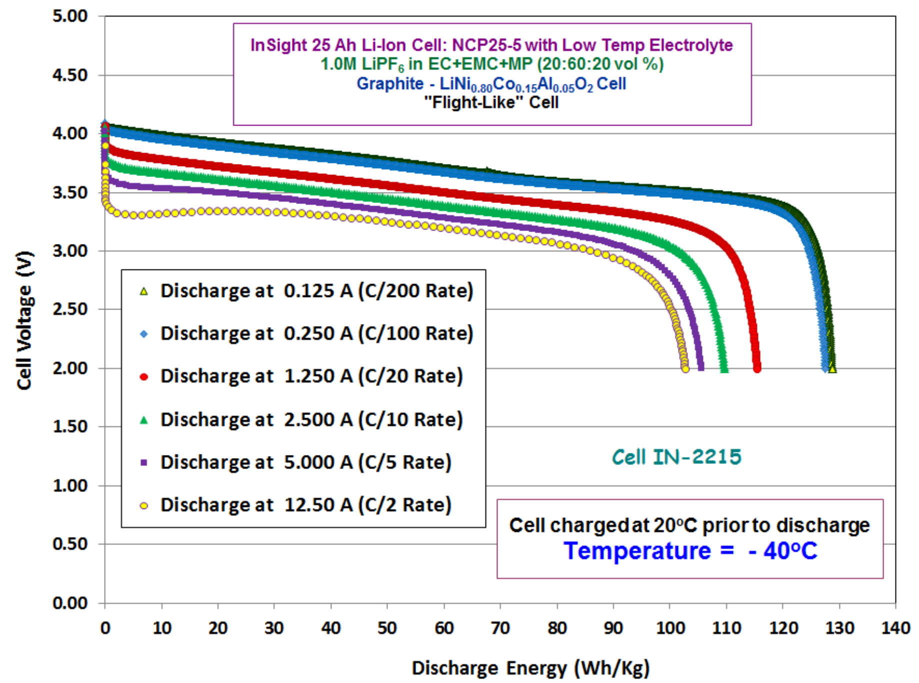
Capacity and Impedance at - 25°C

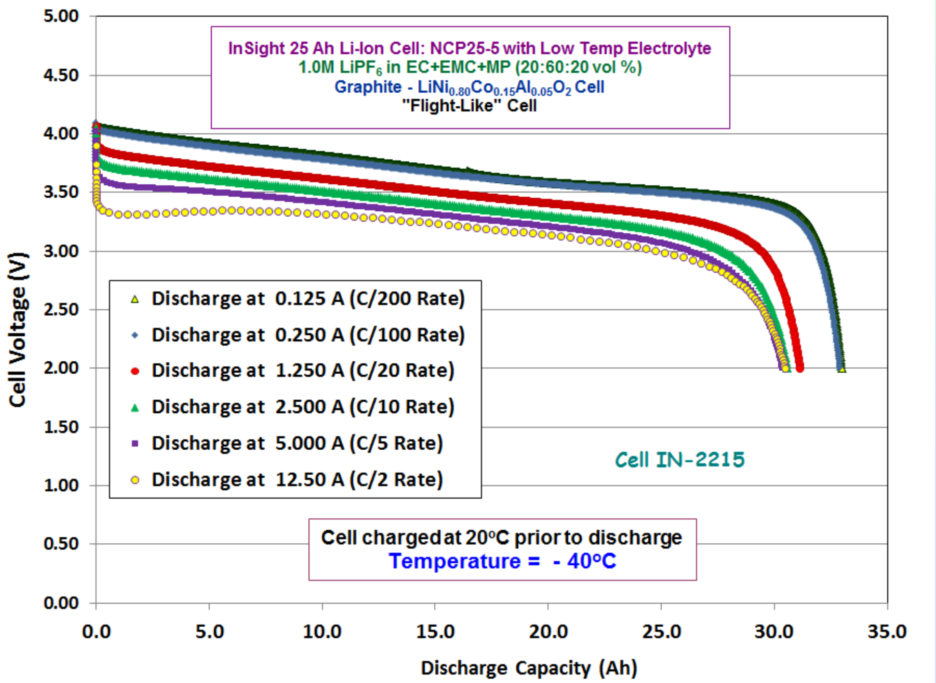
	InSight Cell IN-2184					InSight Cell IN-2186					InSight Cell IN-2187				
	Ah	Percent of Initial (%)	Wh	Percent of Initial (%)	mOhms	Ah	Percent of Initial (%)	Wh	Percent of Initial (%)	mOhms	Ah	Percent of Initial (%)	Wh	Percent of Initial (%)	mOhms
Initial Performance at - 25°C	28.993	100	102.65	100	18.054	28.6807	100	101.21	100	18.976	29.035	100	102.73	100	18.109
Performance at - 25°C After Acceptance Testing	29.367	101.29	104.64	101.93	16.089	29.2640	102.03	104.10	102.86	16.400	29.556	101.79	105.39	102.59	15.552
Performance at - 25°C After Pre-Launch Stand Test and Launch Simulation	29.016	100.08	103.19	100.52	16.938	28.8975	100.76	102.61	101.39	17.237	29.192	100.54	103.9	101.14	16.425
Performance at - 25°C After Cruise Simulation	28.819	99.40	102.30	99.65	18.146	28.8725	100.67	102.55	101.32	17.908	28.690	98.81	101.64	98.94	18.360
Performance at - 25°C After 3 Months of Storage	28.835	99.46	102.38	99.73	17.951	28.8802	100.70	102.62	101.39	17.780	28.649	98.67	101.48	98.78	18.268

- ***Less than 1.8 % capacity loss was observed at all three temperatures after being subjected to acceptance testing, long term cruise simulation, and 3 months of post-cruise storage.***

Performance Testing of InSight Yardney NCP-25-6 Cells

Evaluation of Low Temperature Performance for Future Potential NASA Missions to Icy Moons





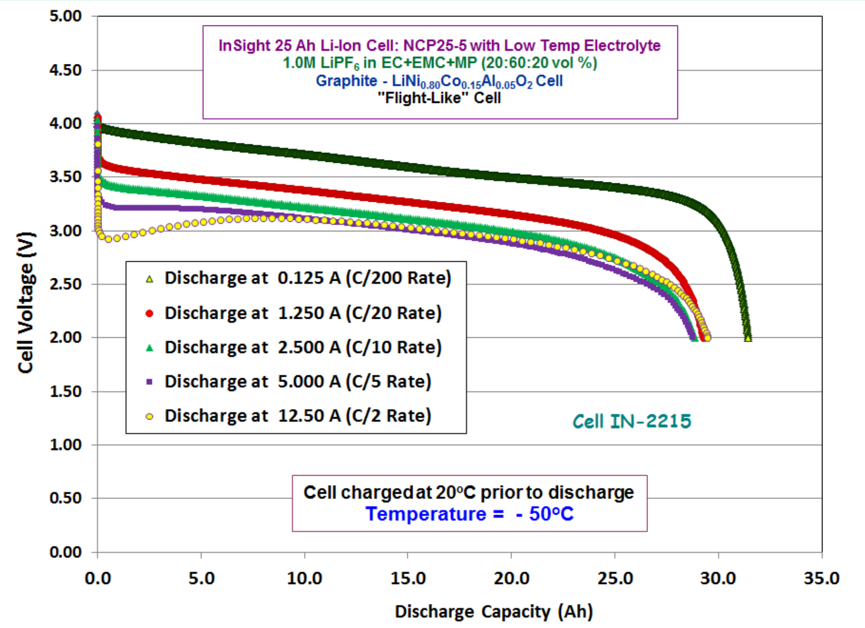
- The next generation InSight chemistry containing the MP-based low temperature electrolytes delivers good rate capability at -40°C , delivering over 102 Wh/kg at a C/2 rate (or 12.50A).
- Demonstrates that technology is well suited to support high power transmission events.

M. C. Smart. et al., "The Use of Low Temperature Electrolytes in High Specific Energy Li-Ion Cells for Future NASA Missions to Icy Moons", 229th Meeting of the Electrochemical Society, San Diego, California, June 1, 2016.

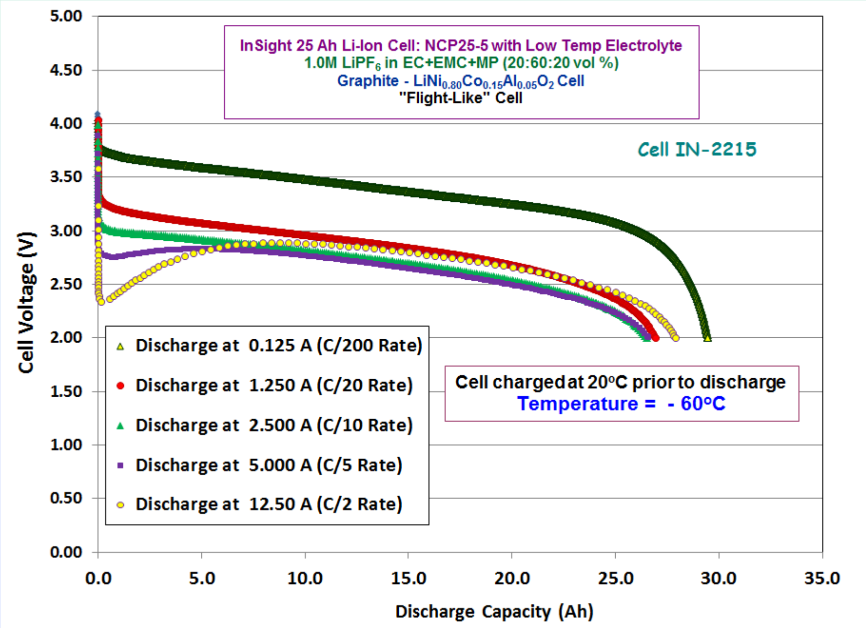
Performance Testing of InSight Yardney NCP-25-6 Cells

Evaluation of Low Temperature Performance for Future Potential NASA Missions to Icy Moons

Temperature = - 50°C



Temperature = - 60°C



- The next generation InSight chemistry containing the MP-based low temperature electrolytes delivers good rate capability at -50°C , delivering over 90 Wh/kg at a C/2 rate (or 12.50A).
- Good performance also demonstrated at -60°C

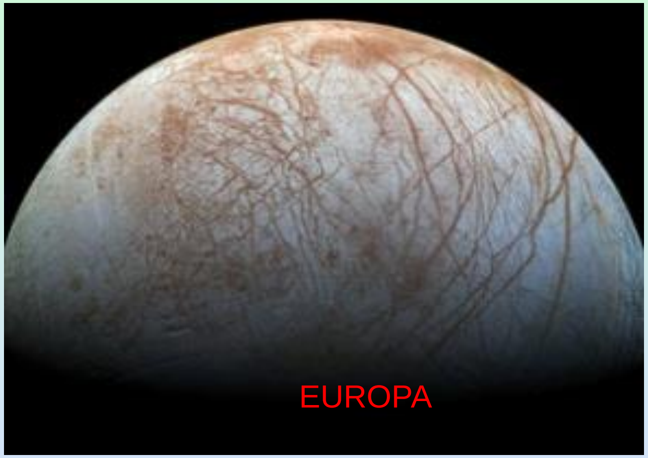
NASA's Planned Europa Mission

- **Anticipated Launch Date: TBD (2020's)**

- **NASA's planned Europa mission would conduct a detailed reconnaissance of Jupiter's moon Europa and to investigate its habitability for life.**
- **The mission would send a radiation tolerant spacecraft into a long, looping orbit of Europa to perform repeated close flybys.**

- **Planned NASA-selected Instruments**:.

1) Plasma Instrument for Magnetic Sounding (PIMS)
2) Interior Characterization of Europa using Magnetometry (ICEMAG)
3) Mapping Imaging Spectrometer for Europa (MISE)
4) Europa Imaging System (EIS)
5) Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON)
6) Europa Thermal Emission Imaging System (E-THEMIS)
7) Mass Spectrometer for Planetary Exploration/Europa (MASPEX)
8) Ultraviolet Spectrograph/Europa (UVS)
9) Surface Dust Mass Analyzer (SUDA)



Key Driving Battery Requirements

- **Long life = 11 years (long cruise period)**
- **High radiation tolerance**
- **High specific energy**
- **Operating Temperature Range: 0° to +30°C**
- **The preliminary architecture for the Europa mission is to use a battery design consisting of high specific energy small 18650-size Li-ion cells, to capitalize on their internal safety functions, high capacity, and excellent cell-to-cell reproducibility.**

NASA's Planned Europa Mission:
Lithium-Ion 18650 Cell Chemistry Assessment

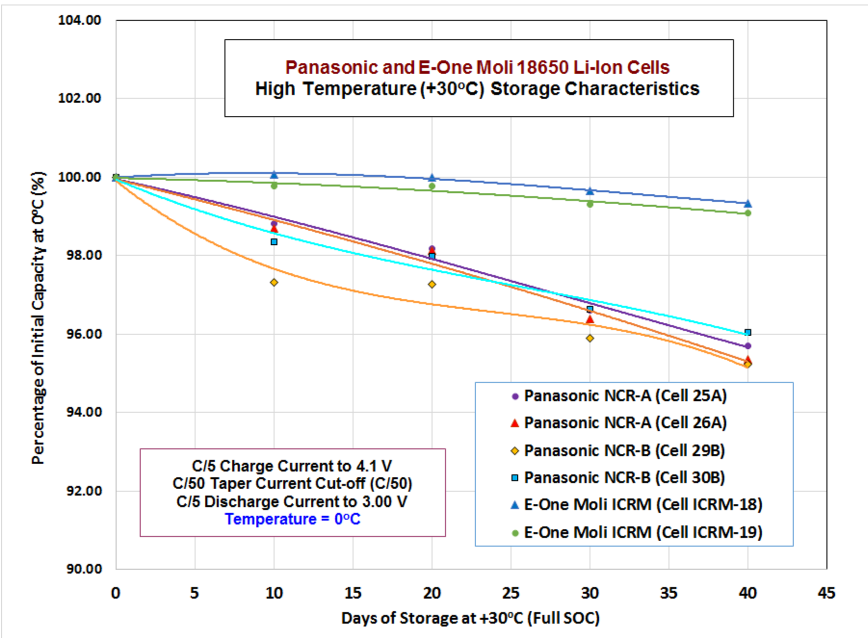
- The Europa Mission has identified a number of viable small cell Li-ion options that are good candidates for the project, which provide high specific energy and good performance characteristics.
  - Molicel ICR-M 18650 Cells
  - Molicel ICR-J 18650 Cells
  - Panasonic NCR-B 18650 Cells
  - Panasonic NCR-A 18650 Cells

- An in-house performance assessment program has been initiated to determine the viability for the Europa project, which includes the following:
  - Radiation tolerance (subjected to Co^{60} gamma rays)
  - Cycle life performance under various conditions
  - Storage life testing at the cell level (at 0^oC and $+25^oC$)
  - High temperature storage characterization ($+30^oC$)
  - 8-Cell module 100% DOD cycle life testing at $+20^oC$
  - 8-Cell module long term storage life testing at $+0^oC$

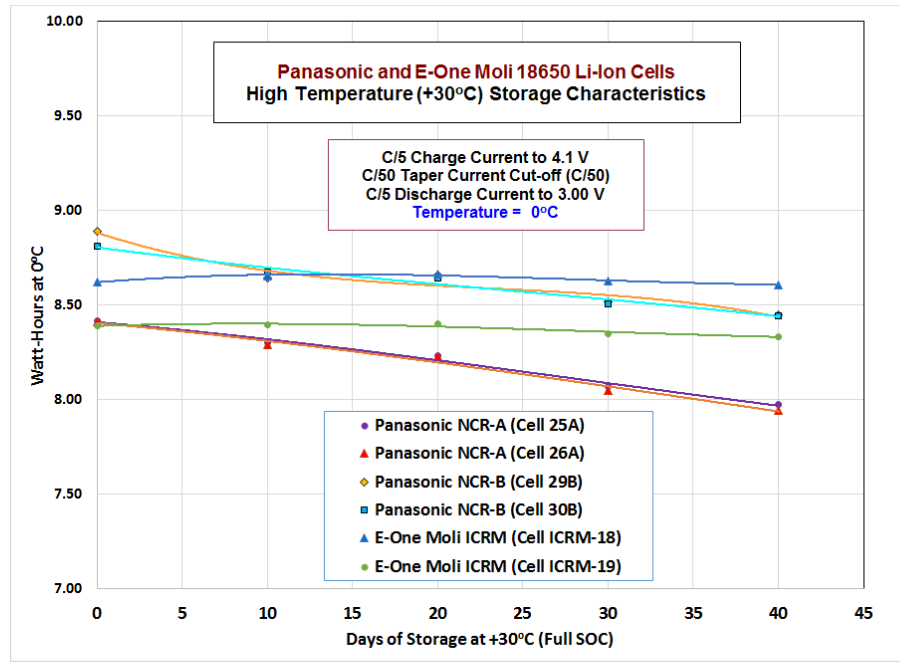
NASA's Planned Europa Mission:
Lithium-Ion 18650 Cell Chemistry Assessment

- ***Summary of cell high temperature storage results: characterization at +0°C***

Percentage of Initial Capacity (Ah) at 0°C



Watt Hours Delivered (Wh) at 0°C

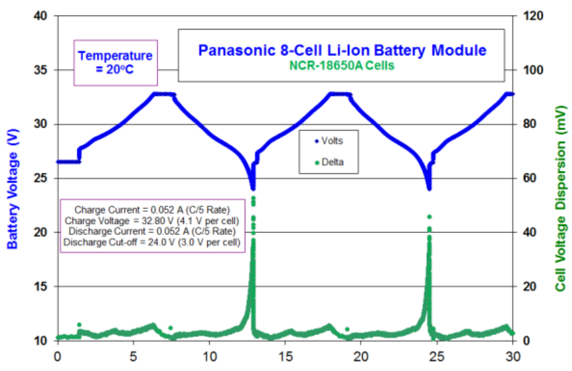


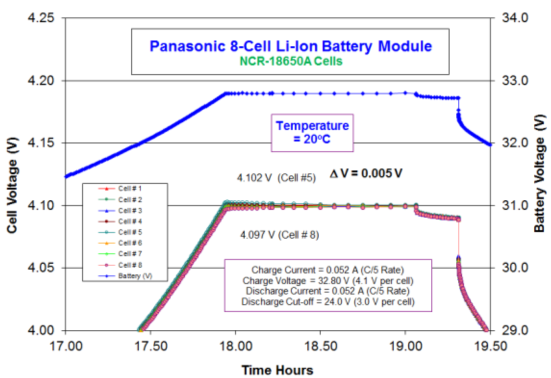
- E-One Moli cells have displayed the least amount of permanent capacity fade.
- **Cells subjected to 40 days of storage at +30°C**.

NASA's Planned Europa Mission:
Lithium-Ion 18650 Cell Chemistry Assessment

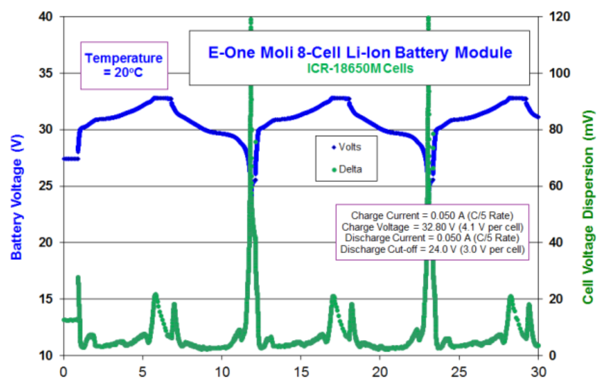
- ***Summary of String Level, Long Term Storage Life and Cycling Testing:***
  - **Three different module designs: (i) NCR-A, (ii) NCR-B, (iii) Moli ICR-M (Supplied by ABSL)**
  - **Validate cell dispersion characteristics; Modules do not contained pre-matched cells**
  - **Strings characterized for capacity and impedance (at 20º and 0ºC) periodically**

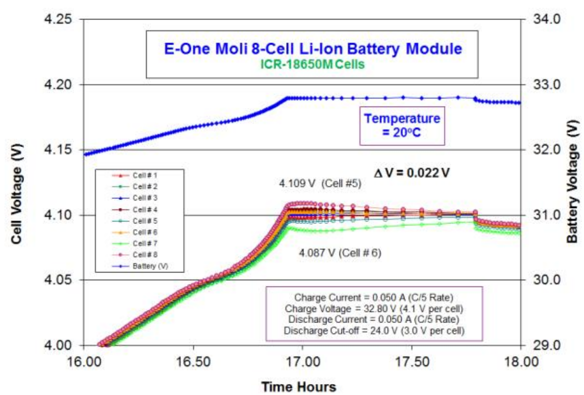
Panasonic NCR-A Module





Moli ICR-M Module





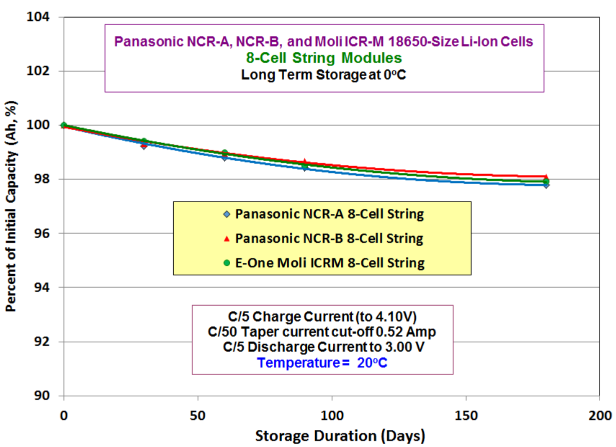
- All five modules display little increase in voltage dispersion with storage and cycling.
- Maximum voltage dispersion is observed at the end of discharge.
- The E-One Moli string displays greater voltage dispersion on discharge due to the presence of one weak cell (i.e., presumably lower capacity compared to the rest).
- Voltage dispersion will be tracked throughout the testing of all 5 modules (both cycle life and storage life testing).

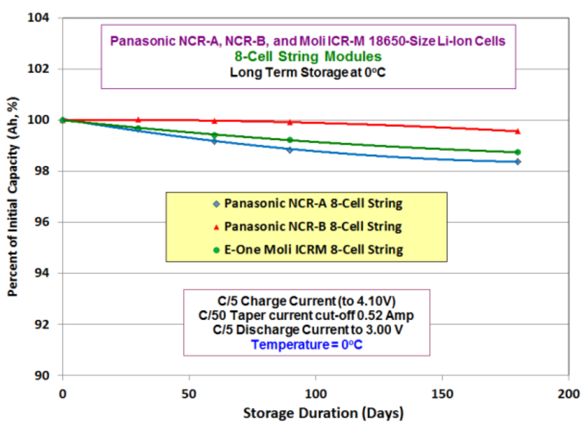
NASA's Planned Europa Mission:
Lithium-Ion 18650 Cell Chemistry Assessment

❑ Summary of String Level, Long Term Storage Life at 0°C:

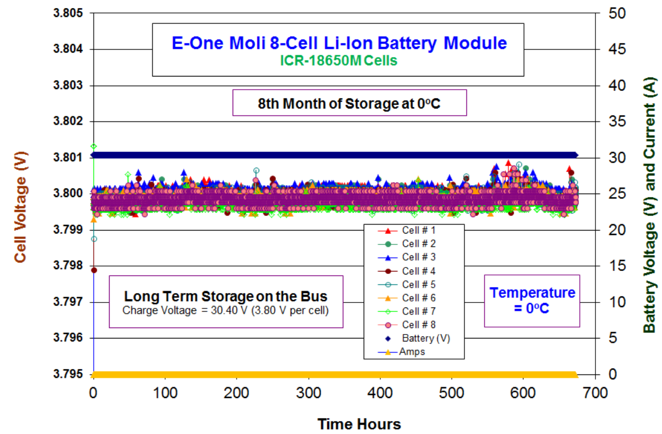
Bus Storage at +0°C (Module Data)

Capacity Delivered at +20°C

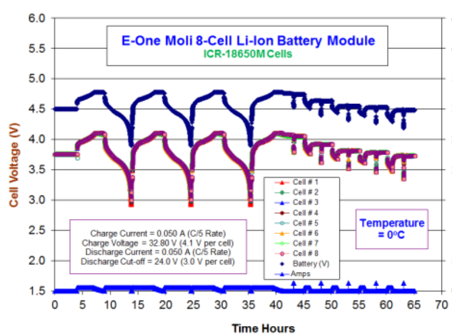


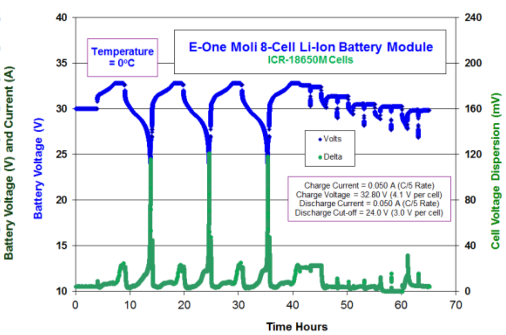


Bus Storage at +0°C (Module Data)



Moli ICR-M 8-Cell Module displays minimal cell dispersion during storage

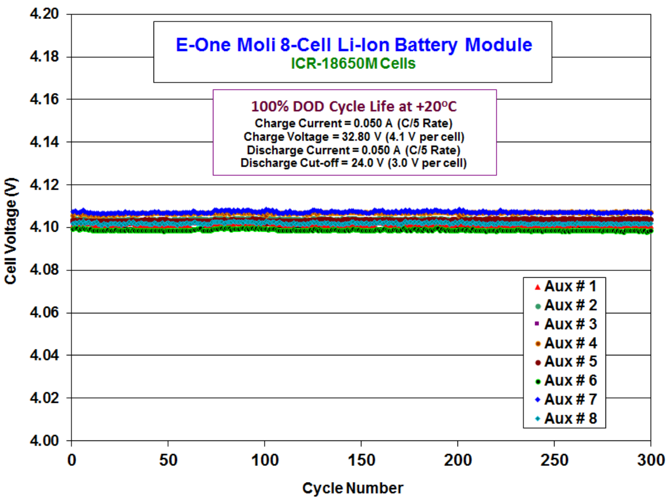


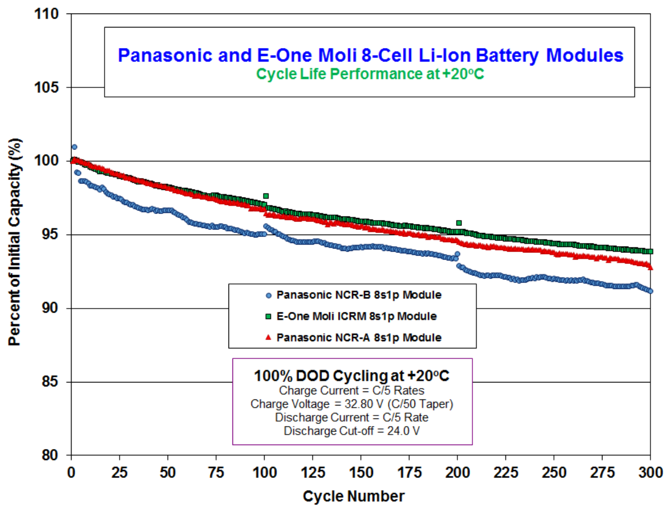


Cell dispersion characteristics after 6 months are very comparable to beginning of life behavior

NASA's Planned Europa Mission:
Lithium-Ion 18650 Cell Chemistry Assessment

- **Summary of String Level Cycle Life Testing :**
  - Two different cell designs: (i) NCR-A, and (ii) Moli ICR-M (*NCR-B is completed*)
  - Modules fabricated by ABSL (8s1p modules)
  - Validate cell dispersion characteristics (up to 300 cycles)
  - Cycling performed at +20°C (100 % DOD, 24V to 32.80V)
    - A total of 300 cycles should be completed to establish dispersion characteristics
  - Strings characterized for capacity and impedance
    - At 20° and 0°C every 100 cycles
  - This testing has been completed on Panasonic NCR-B strings





Minimal cell voltage dispersion observed on charge (EOCV) after completing 300 cycles (< 15 mV)

Summary and Conclusions

- **MSL Curiosity:**
  - Good consistency has been observed with the on-going mission simulation testing of the 24Ah and 43Ah Li-ion cells.
  - To-date, approximately 12% capacity loss has been observed with the 43 Ah cells after being subjected to pad conditions, cruise, and 900 sols of simulated surface operation.
  - Ground testing impedance measurements have correlated well with telemetry data obtained from the rover after enabling mobility heaters.
  - A number of tailored charge and discharge characterization tests have been performed in support of MMPAT development.
- **InSight Mission:**
  - Due to the need for good low temperature capability throughout the mission, and the favorable results obtained with this testing program, the InSight project has adopted the NCA+LTE chemistry for the flight battery.
  - Beginning of life (BOL), the NCA-based cells delivered >15% improvement in the capacity and energy delivered at ambient temperature and 31% more capacity at -25°C compared to the NCO-based chemistries.
  - Real-time mission simulation testing has demonstrated minimal capacity loss (< 1.8%) after being subjected to flight-like acceptance testing, pad simulation, cruise simulation, and 3 month of prolonged storage.
- **Planned Europa Mission :**
  - String level module testing has demonstrated minimal voltage dispersion with life, when subjected to 100% DOD life testing and long term storage testing at 0°C.

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