Performance Testing of Yardney Li-ion Cells in Support of NASA's MSL and InSight Missions

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Outline

- *Objectives*
- *Introduction and Requirements*
- *Performance Testing of Yardney 20 Ah and 43 Ah Cells for MSL*
  - *Performance testing of Yardney 20 Ah cells*
    - *Discharge rate characterization*
    - *Mission simulation testing*
  - *Performance testing of Yardney 43 Ah cells*
    - *Discharge rate characterization*
    - *Mission simulation testing*
    - *Impedance comparisons (flight vs ground data)*
- *Performance Testing of Yardney 25 Ah Cells for InSight*
  - *Results of Group 1 Cell Testing*
    - *Effect of high temperature exposure; Mission relevant cycle life testing*
  - *Results of Group 2 Cell Testing*
    - *Discharge and charge rate characterization; Low temperature operation characterization*
  - *Results of Group 3 Cell Testing*
    - *Impact of accelerated cycling at high temperature*
  - *Results of Group 4 Cell Testing*
    - *NCA-based cells with different electrolytes (Heritage vs. LTE)*
- *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.**

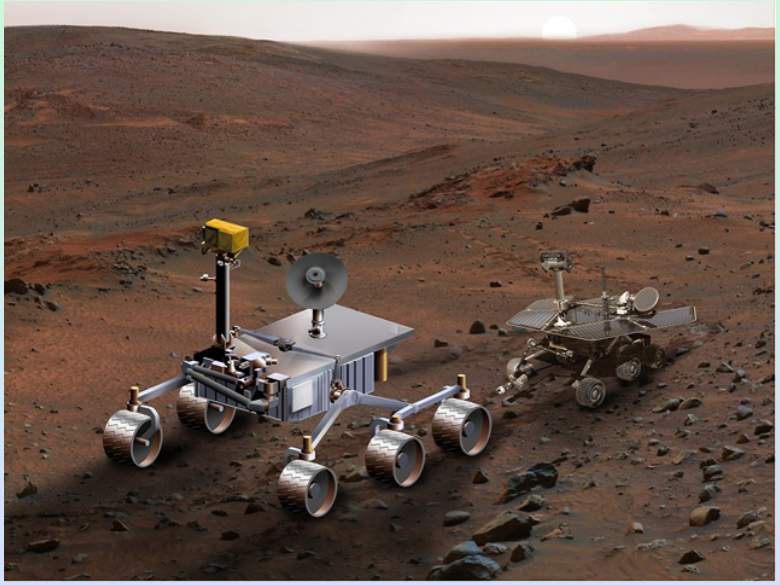
Approach:

- **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 for 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 power 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 for 800 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.
  - The second year has been devoted to driving toward long-term science destinations.



Battery Details

- Two 8-cell batteries in parallel (8s2p).
- 24-32.8 V, 86 Ah (MER, Grail, Juno Chemistry)
- Qualification Temperature range: -30 to +40°C.
- Operating Temperature Range: -20° to +30°C
- **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:
  - Shall support 670 sols of surface operations with two discharge cycles per sol, with one cycle being 1000Wh at 0 deg 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 shall provide a capacity of 59 Ah at 0C and C/5 end of life.
- Launch Capability:
  - The Rover Battery shall provide up to 1300 Wh during launch at 20 and 30°C at a 34 A max discharge current.
- EDL Capability:
  - Provide capability of supporting a 21 A load for 18 mSec (each battery).
  - Support 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

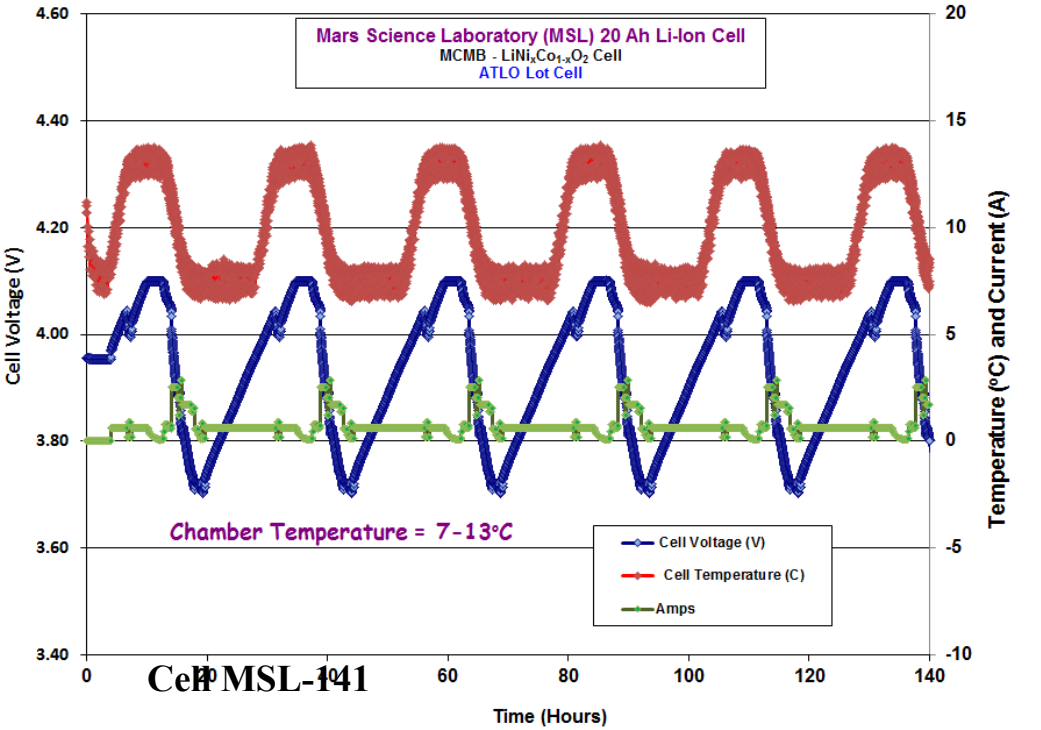
Performance Testing of Yardney MSL 20 Ah Li-Ion Cells
Mission Simulation Testing

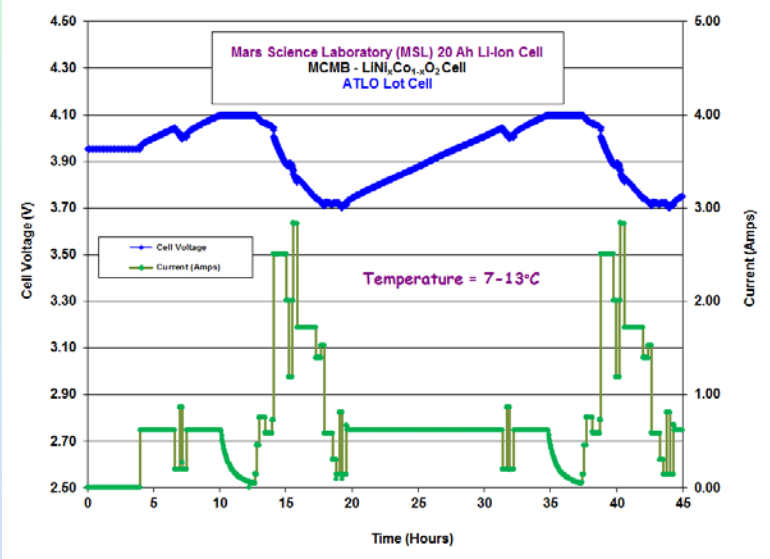
- **Cell Group 1 (Cells: MSL-147, MSL-150, MSL-153)**
  - Cells subjected to 30°C for only 10.5 days (removed and stored at ambient)
  - Cells in full SOC under OCV conditions
  - 360 Days at 25-30°C Cruise condition, 50% SOC bus storage
- **Cell Group 2 (Cells: MSL-141, MSL-142, MSL-143)**
  - Cells 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).

Yardney Li-ion MSL 20 Ah Li-Ion Performance Testing
Surface Operation Cycle Life Performance





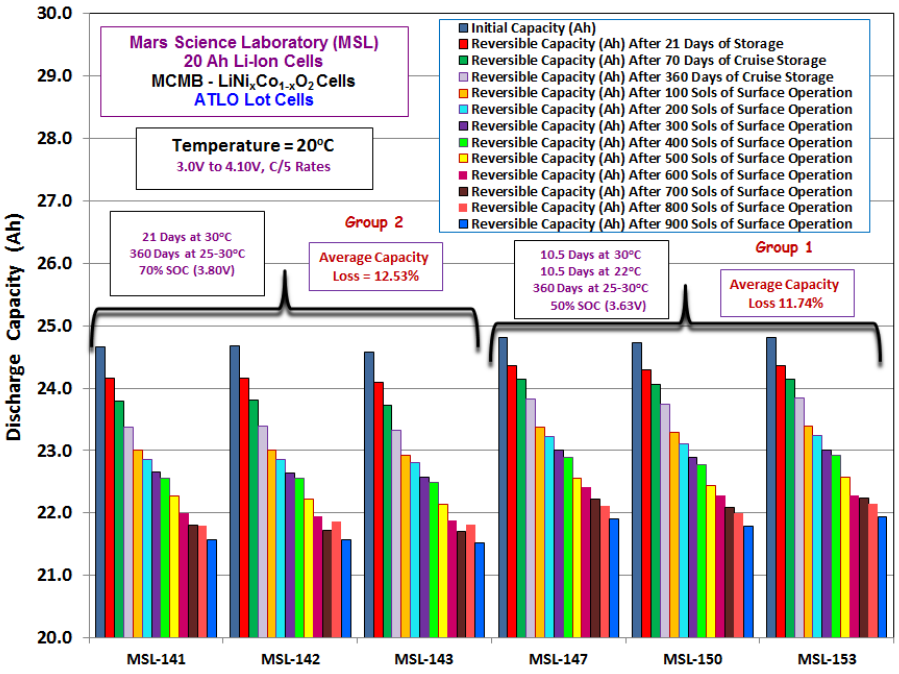
- Six cells were placed on a surface operation mission simulation testing after completing cruise period
- Temperature profile fluctuates between 7° and 13°C

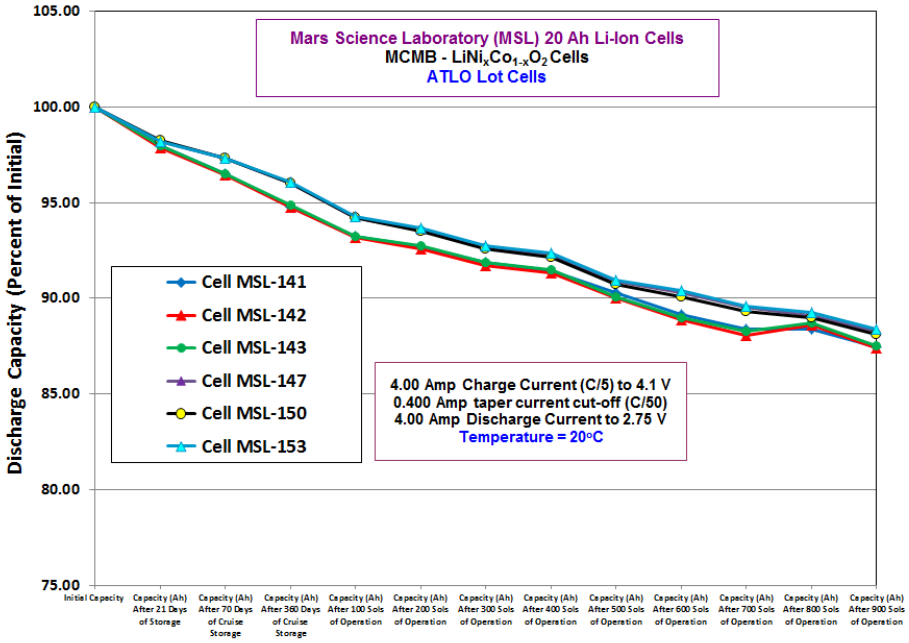
- ***Diagnostic health checks are performed every 100 sols***
- *Health checks consists of determining the capacity (C/5 rates over the voltage range of 2.75V to 4.10V) and performing current-interrupt impedance measurements at various states of charge.*

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



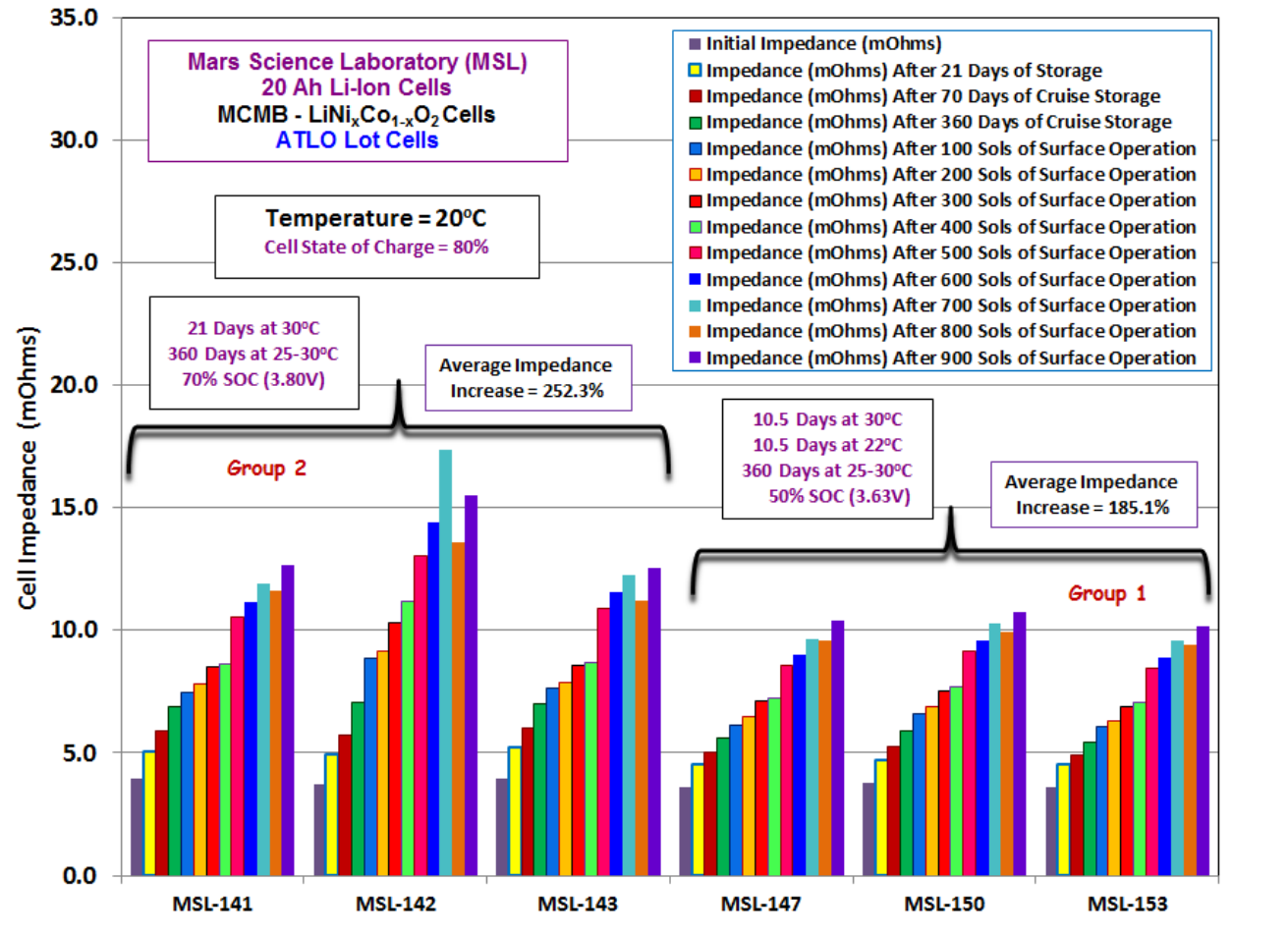


➢ *Approximately 11.6% capacity loss has been observed at +20°C (with the Group 1 cells) after completing pad storage + cruise + 900 sols of operation.*

Performance of Yardney MSL 20 Ah Li-Ion Cells

Characterization Testing at 20°C

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

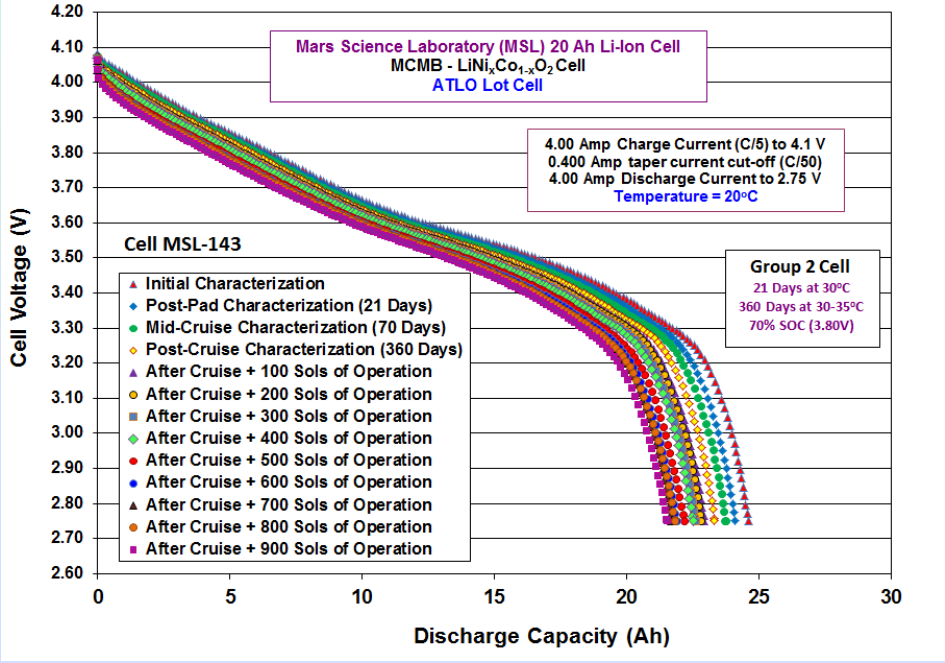


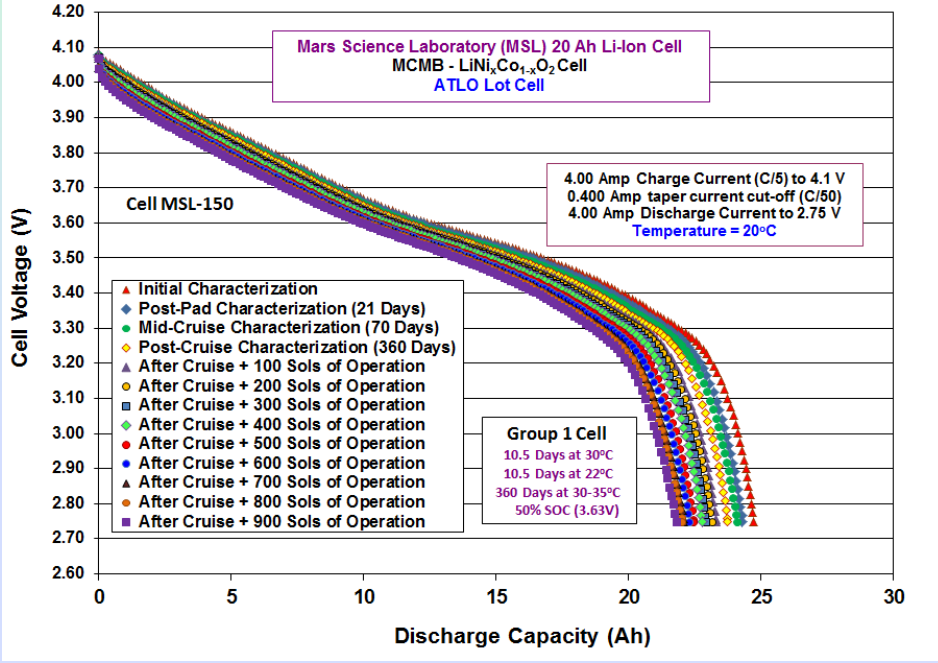
➢ *More impedance growth was observed for the Group 2 cells, which is attributed to high pad storage temperature and high SOC during cruise.*

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





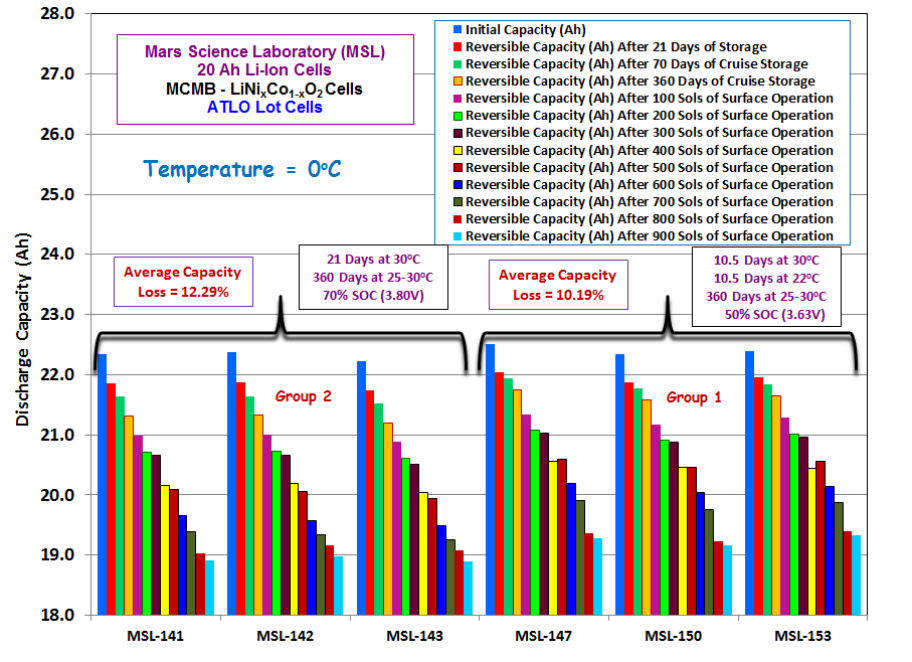
- *To date, cells from both Group 1 and Group 2 have displayed predicable degradation characteristics throughout their life.*

Performance of Yardney MSL 20 Ah Li-Ion Cells

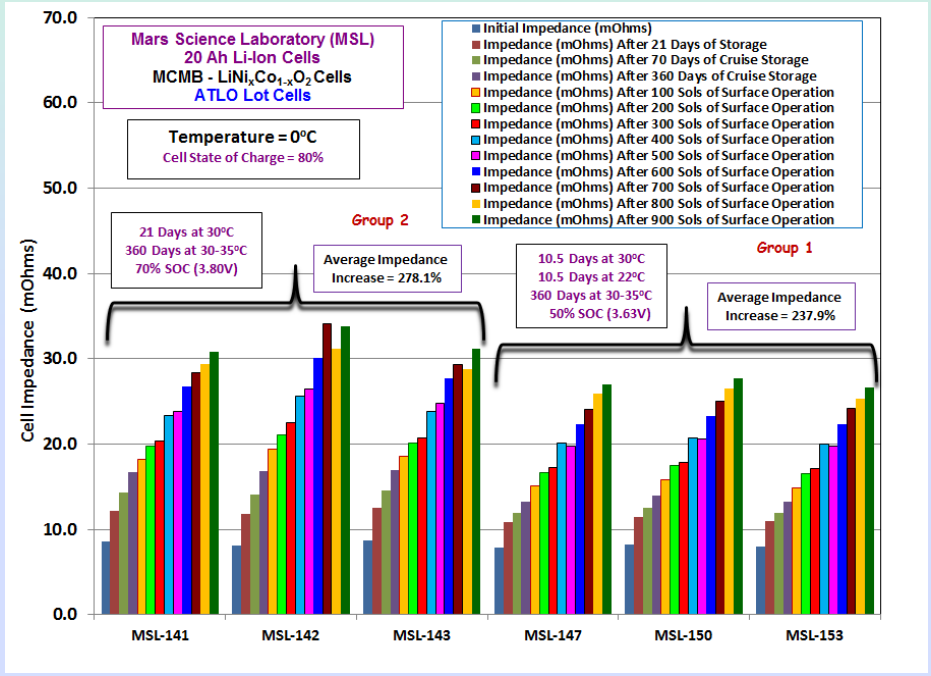
Characterization Testing at 0°C

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

Discharge Capacity (Ah) at 0°C



Cell Impedance (mΩ) at 0°C



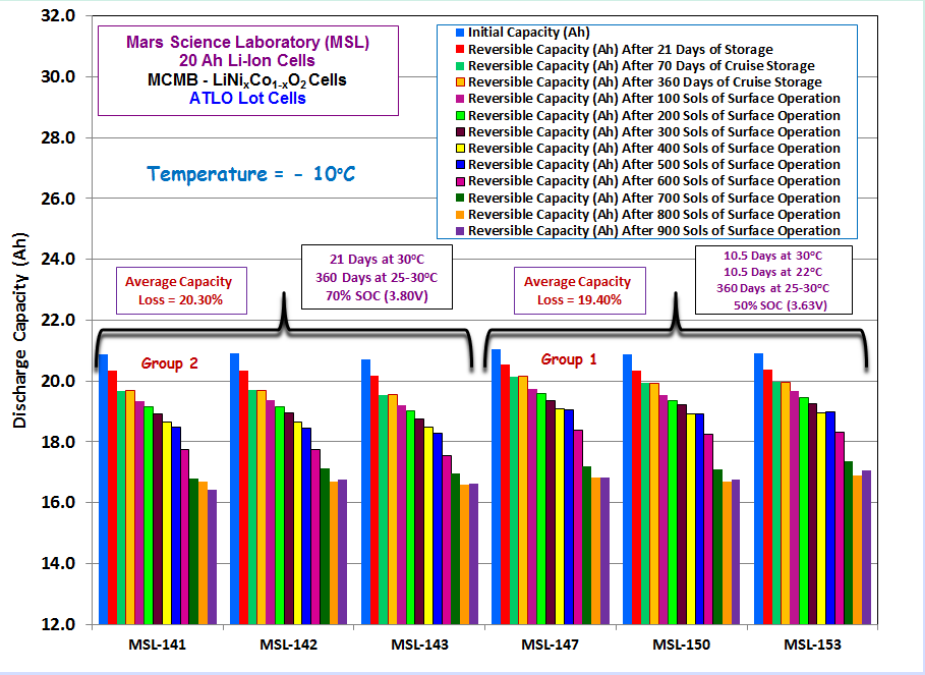
- *Similar trends in the capacity fade characteristics for Group 1 and Group 2 were observed at 0°C.*
- *Approximately 10.2% capacity loss has been observed at 0°C (with the Group 1 cells) after completing pad storage + cruise + 900 sols of operation.*

Performance of Yardney MSL 20 Ah Li-Ion Cells

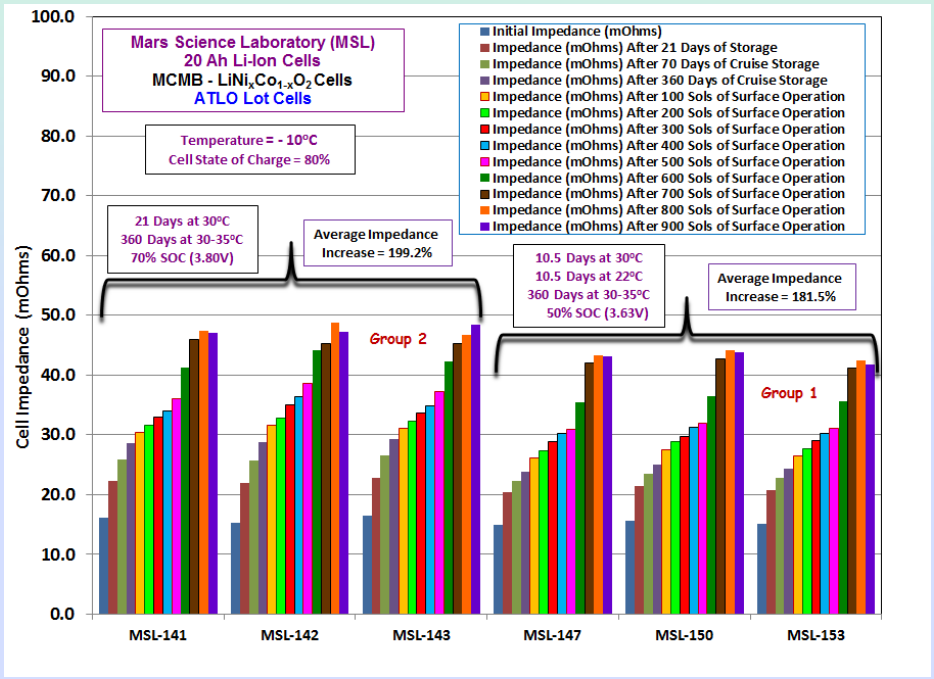
Characterization Testing at - 10°C

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

Discharge Capacity (Ah)



Cell Impedance (mΩ)



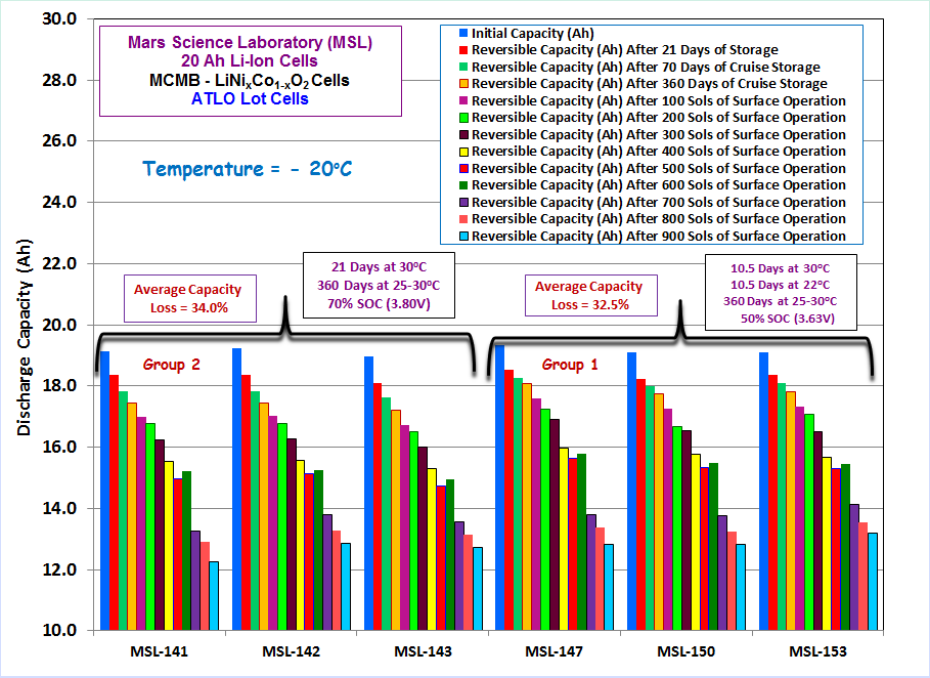
- *Somewhat larger capacity fade characteristics for Group 1 and Group 2 were observed at -10°C compared with the warmer temperatures.*
- *Approximately 19.4% capacity loss has been observed at - 10°C (with the Group 1 cells) after completing pad storage + cruise + 900 sols of operation.*

Performance of Yardney MSL 20 Ah Li-Ion Cells

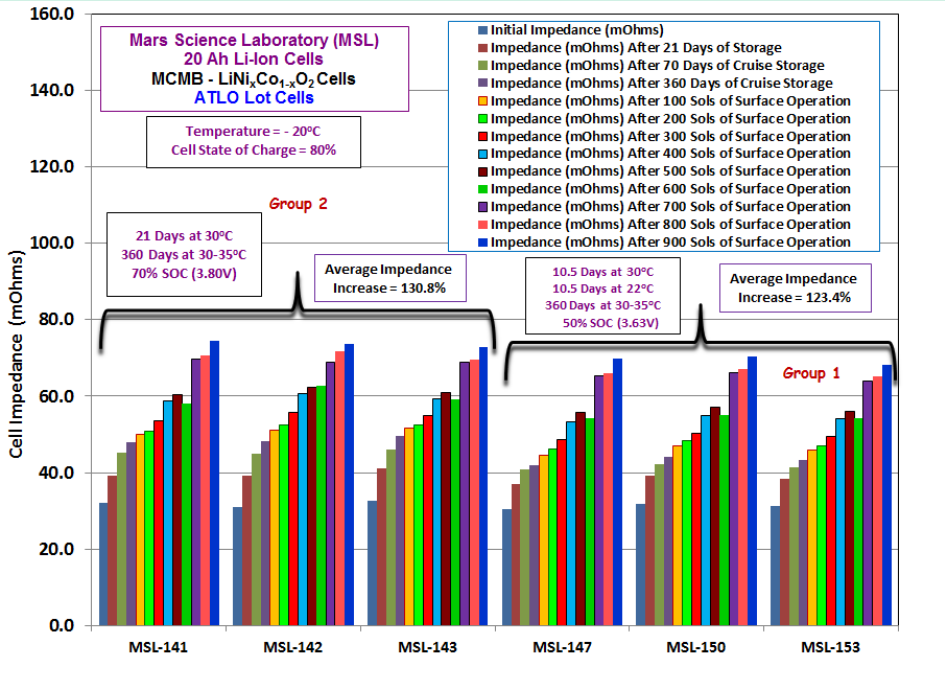
Characterization Testing at - 20°C

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

Discharge Capacity (Ah)



Cell Impedance (mΩ)

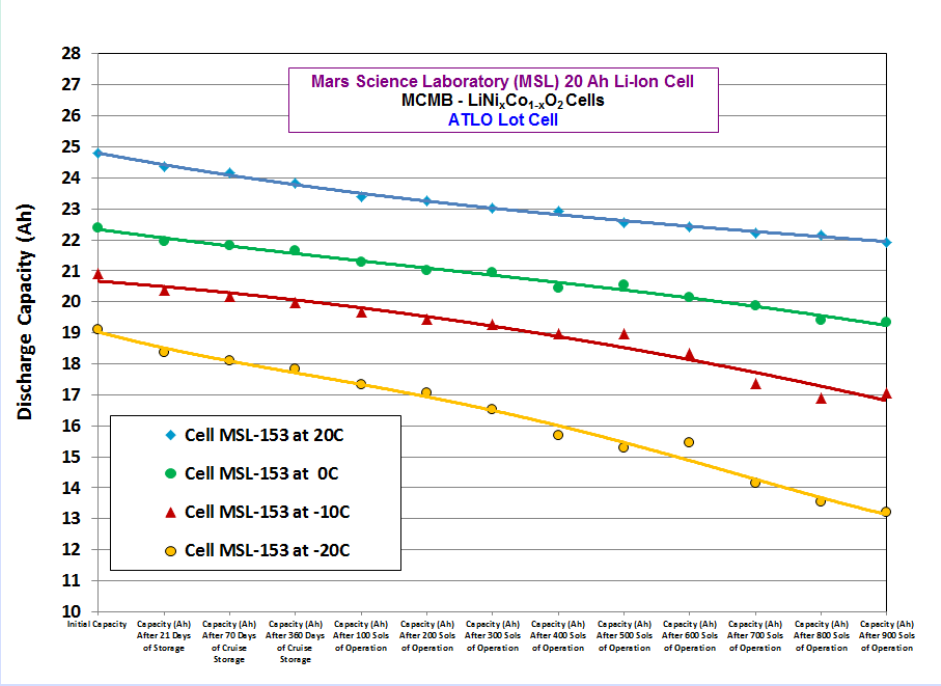


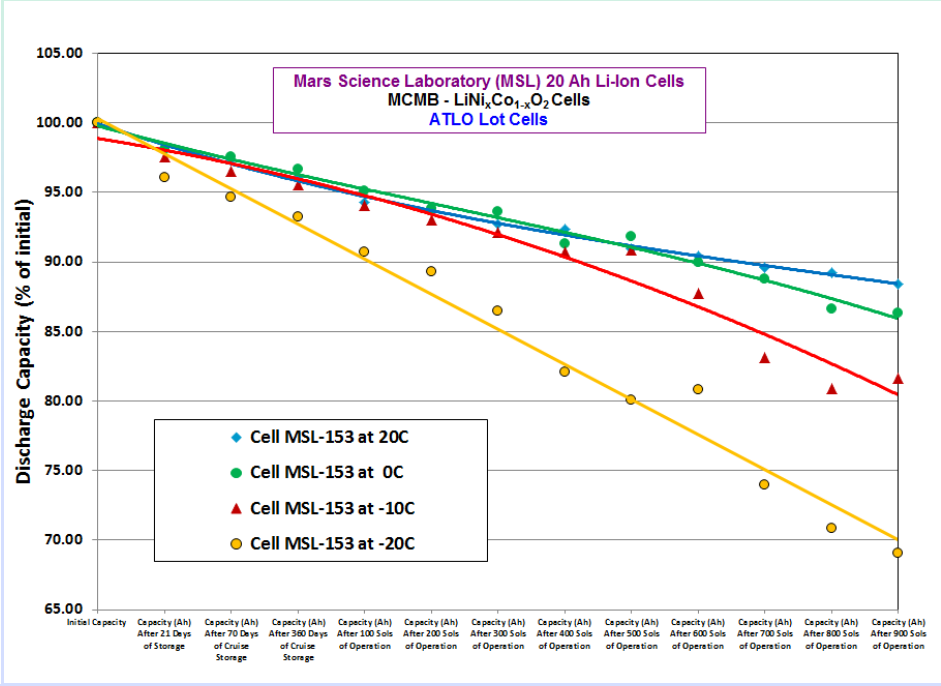
- *Larger capacity fade characteristics for Group 1 and Group 2 were observed at -20°C compared with the warmer temperatures.*
- *Approximately 32.5% capacity loss has been observed at - 20°C (with the Group 1 cells) after completing pad storage + cruise + 900 sols of operation.*

Performance of Yardney MSL 20 Ah Li-Ion Cells

Characterization Testing at Various Temperatures

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





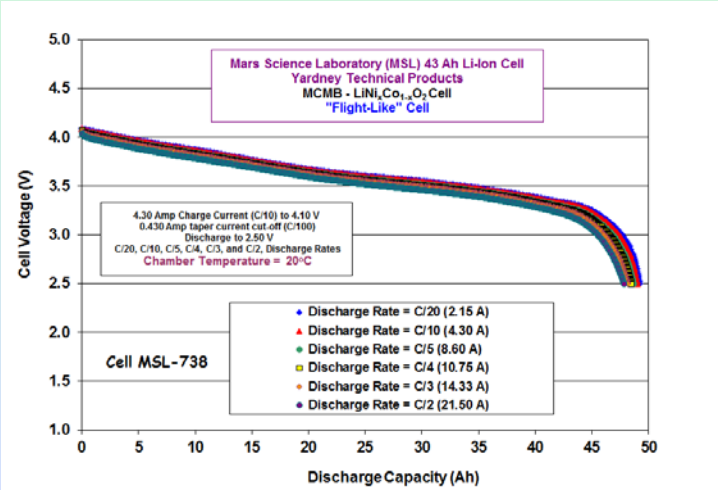
- *As previously noted, the capacity loss observed is more significant at low temperatures.*

Yardney Li-ion MSL 43 Ah Li-Ion Performance Testing

Summary of Discharge and Charge Rate Characterization Testing

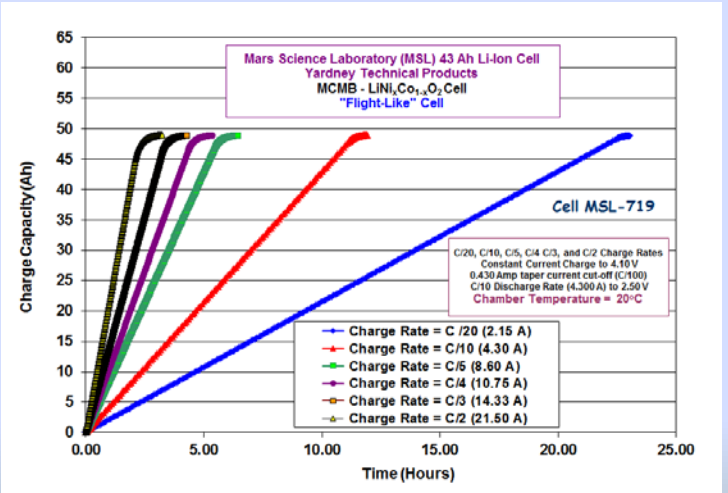
➢ *Discharge Rate Characterization Test Procedure*

- Six different charge rates evaluated (C20, C/10, C/5, C/4, C/3, and C/2 rate)
- All C rates based on 43 Ah nameplate capacity
- Five different temperatures will be evaluated (20°, 10°, 0°, -10°, and –20°C)
- Charge and discharge performed at prescribed temperature
- Two cycles performed for each rate (data plotted from second cycle)
- Cells charged at C/10 rate to 4.1 V (with C/100 taper current cut-off)
- Taper discharge step added to schedule for testing < 10°C
- Thermocouples present on cells (attached to side of cell can)
- Two cells tested (***Cells MSL-738 and MSL-757)***



➢ *Charge Rate Characterization Test Procedure*

- Six different charge rates evaluated (C20, C/10, C/5, C/4, C/3, and C/2 rate)
- All C rates based on 43 Ah nameplate capacity
- Five different temperatures will be evaluated (20°, 10°, 0°, -10°, and –20°C)
- Charge and discharge performed at prescribed temperature
- Two cycles performed for each rate (data plotted from second cycle)
- Cells charged at respective rate to 4.1 V (with C/100 taper current cut-off)
- Taper discharge step added to schedule for testing < 10°C
- Thermocouples present on cells (attached to side of cell can)
- Two cells tested (***Cells MSL-719 and MSL-723)***



Performance of Yardney MSL 43 Ah Li-Ion Cells
Mission Simulation Testing

- **Cells Evaluated (43 Ah)** (Cells: MSL-683, MSL-747, MSL-755)
- **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 (cells at 50% SOC, or 3.63 V bus storage)
  - 48 days at 25°C (cells at 50% SOC, or 3.63 V bus storage)
  - 196 days at 25°C (cells at 70% SOC, or 3.80V bus storage)
  - 18 days at 12.5°C (cells at 70% SOC, or 3.80V bus storage)

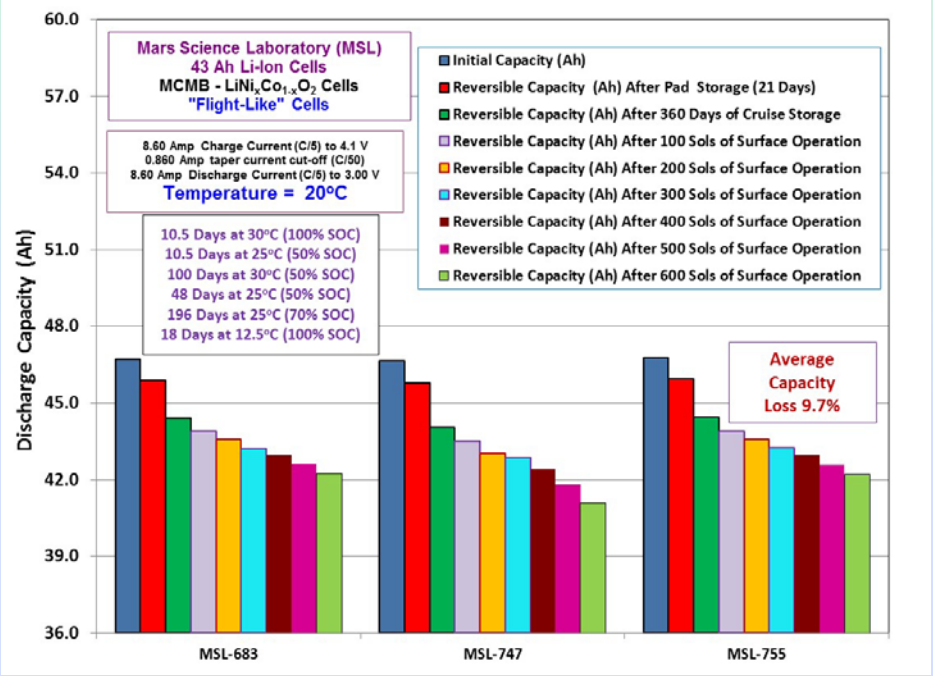
- Cells were subjected to capacity and impedance characterization at 20°C, 0°C, -10°C and -20°C after pad and cruise simulation.

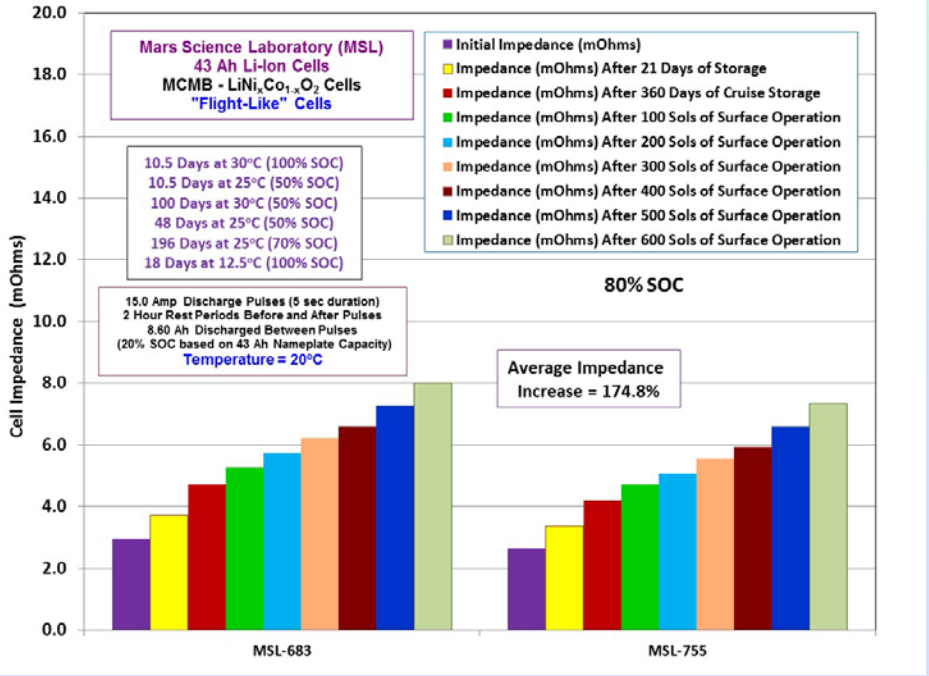
- After characterization, cells were subjected to surface operation mission simulation testing.

Performance of Yardney MSL 43 Ah Li-Ion Cells

Characterization Testing at 20°C

After Completing Pad Storage, Cruise Storage and 600 Sols on the Surface



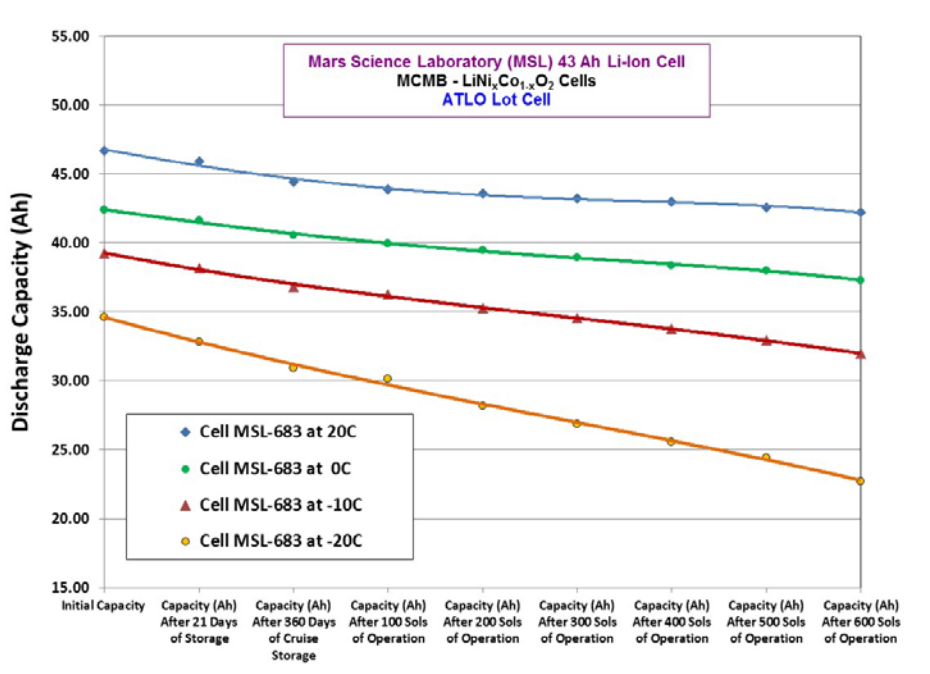


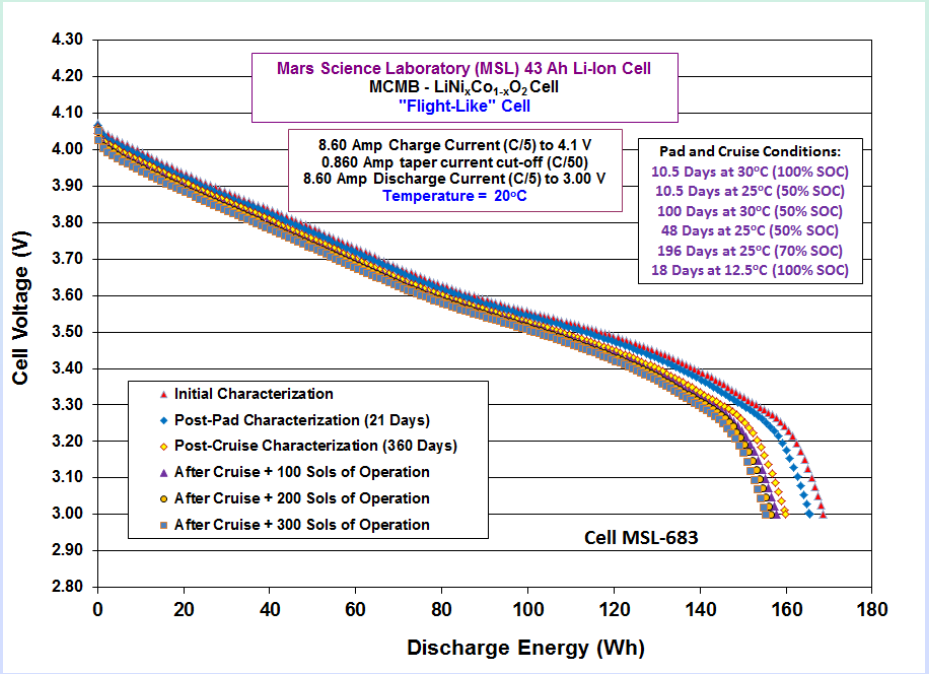
- **The capacity fade and impedance growth observed with the 43 Ah cells as a result of the cruise period was somewhat greater than seen with the 20 Ah. This is primarily attributed to the more realistic cruise simulation conditions (including temperature and cell SOC).**

Performance of Yardney MSL 43 Ah Li-Ion Cells

Characterization Testing at 20°C

After Completing Pad Storage, Cruise Storage and 600 Sols on the Surface

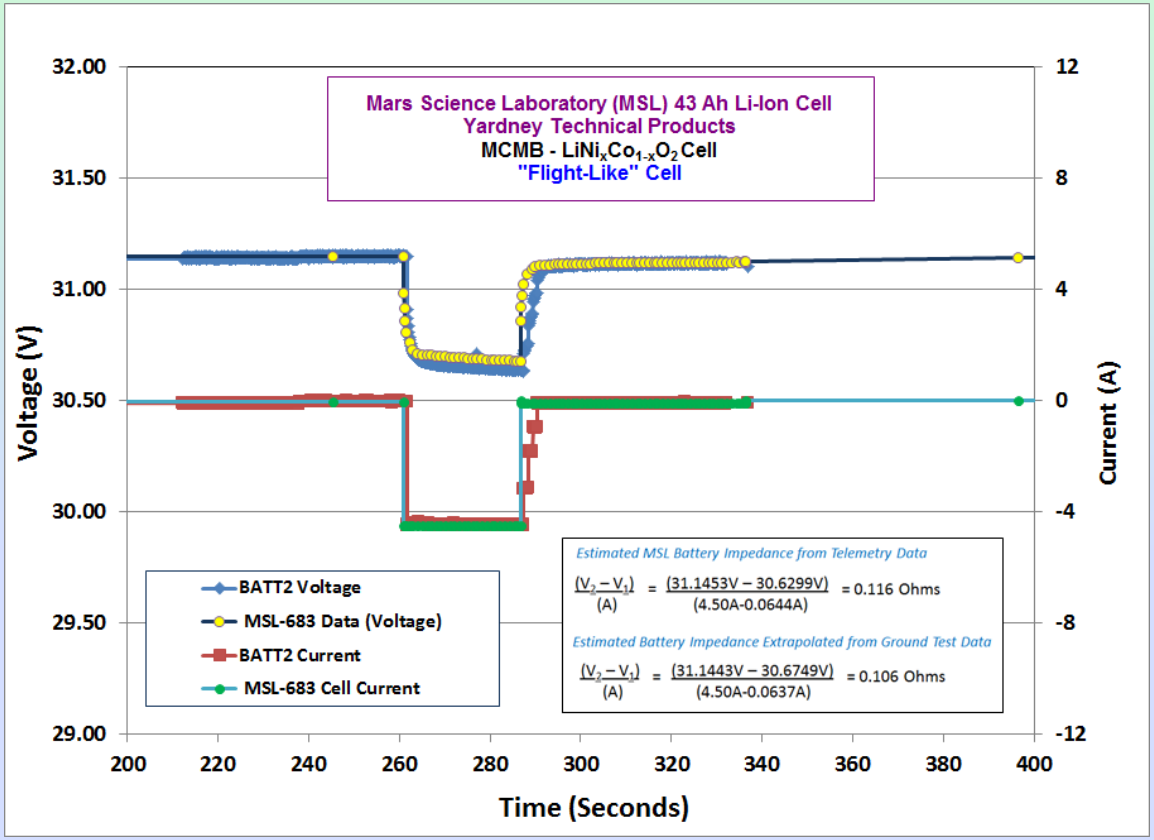




- **The capacity fade and impedance growth observed with the 43 Ah cells as a result of the cruise period was somewhat greater than seen with the 20 Ah. This is primarily attributed to the more realistic cruise simulation conditions (including temperature and cell SOC).**

Performance of Yardney MSL 43 Ah Li-Ion Cells

Comparison of Impedance Measurements (Flight Telemetry vs Ground Test Data)

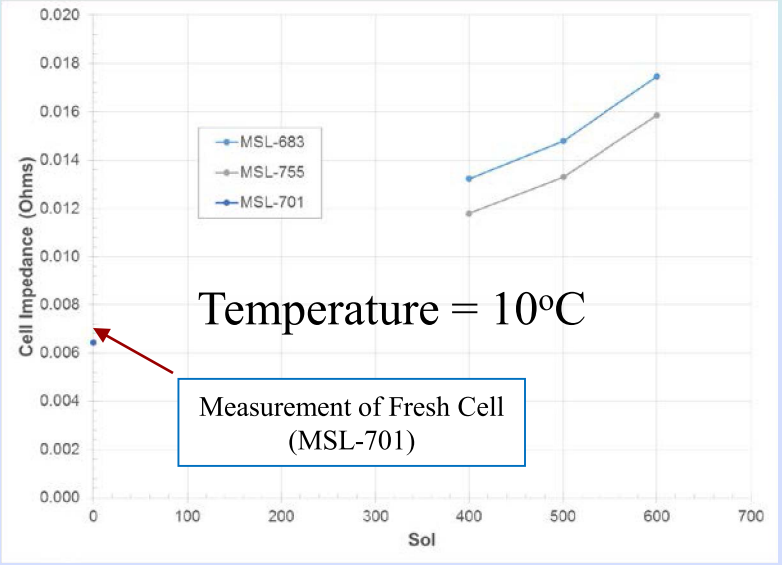


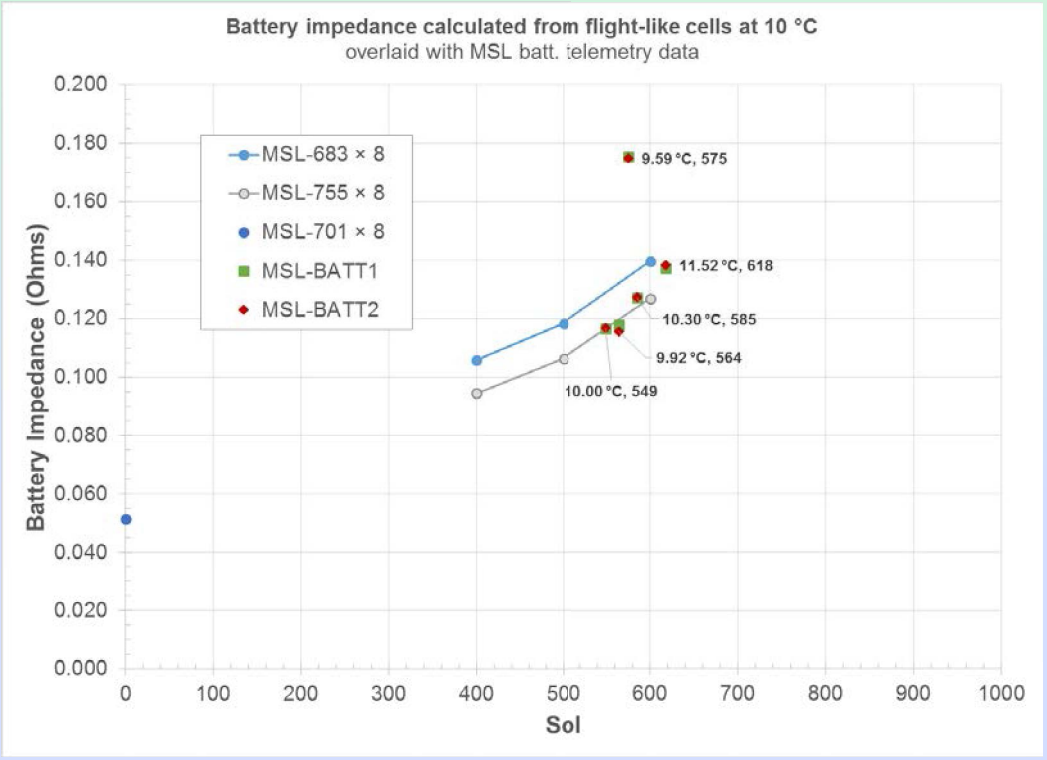
- Current efforts are focused on evaluating the impedance of the flight batteries determined from telemetry data and comparing it with comparable data generated on the ground test units subjected to mission simulation cycling.
- By briefly enabling the mobility heaters on the rover, we are able to estimate the internal resistance under controlled conditions (i.e., current injection/interruption measurements).
- These activities are useful in refining the output of the Multi-Mission Power Analysis Tool (MMPAT) that is being employed to model battery behavior.

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)

	MSL flight-like cell and projected battery impedance (Ohms)					
	Cell MSL-683	8s batt. Projection	Cell MSL-755	8s batt. Projection	Mean	8s batt. Projection
Sol #						
0	0.007	0.056	0.006	0.047	0.006	0.051
400	0.013	0.106	0.012	0.094	0.013	0.100
500	0.015	0.118	0.013	0.106	0.014	0.112
600	0.017	0.140	0.016	0.127	0.017	0.133



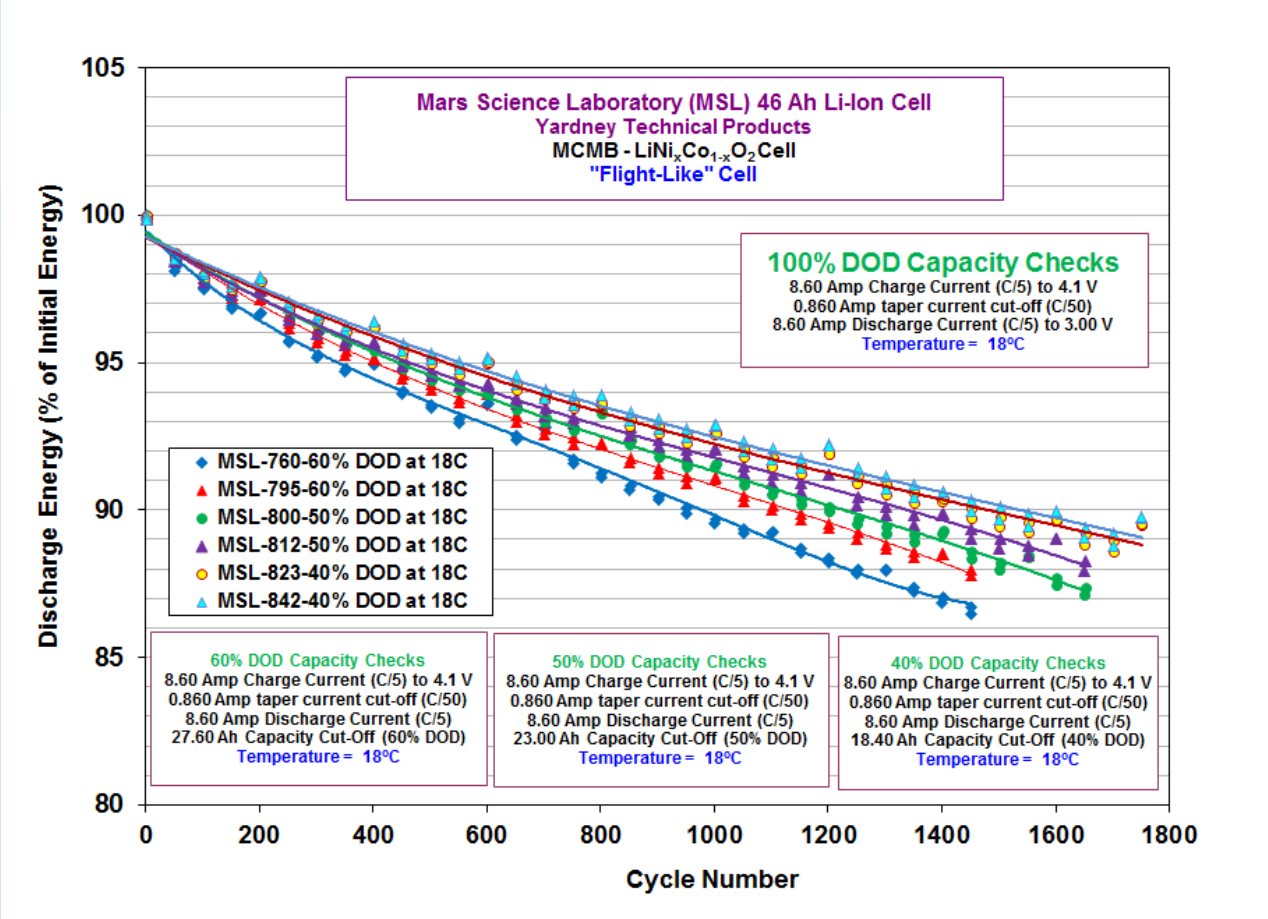


- **Simulated heater operation was performed on 43 Ah cells that have been subjected to mission simulation operation**
- **Generally, good agreement was observed when comparing comparable measurements at 10°C (i.e., ~ 125-140 mOhms was observed after completing 600 sols for both the flight batteries and ground test cells.**
- **Measurements help to validate relevance of ground testing data**

Performance of Yardney MSL 43 Ah Li-Ion Cells

Summary of Partial DOD Life Testing

100% DOD Capacity Determination Throughout Life (Percent of Initial Wh)



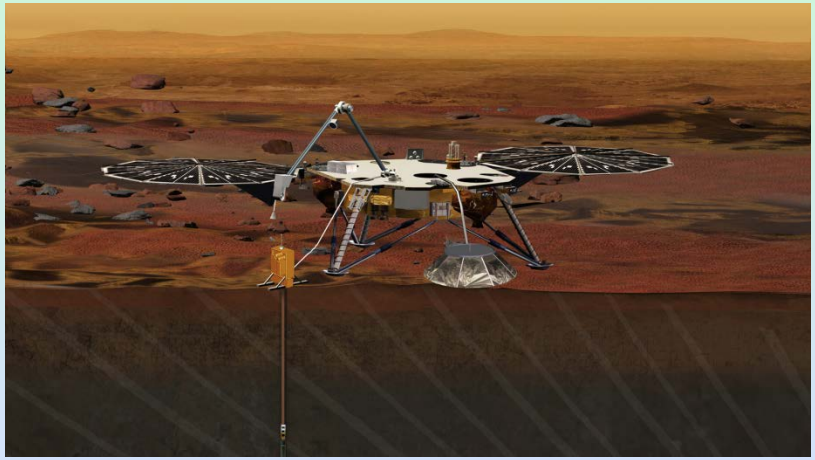
- As anticipated, the capacity fade is less dramatic with lower depth of discharge (DOD).
- Capacity fade also anticipated to be lower at lower temperatures, which has been substantiated with other data.

Summary and Conclusions

- **Due to dramatic differences predicted for the cruise temperatures for MSL compared with MER, effort is on-going to establish a comprehensive data base to enable quantification of capacity loss and impedance growth implications.**
  - **The following results have been obtained on the 24 Ah cells thus far:**
    - **Best Case Scenario: Group # 1 Cells**
      (10.5 Days at 30°C, 10.5 Days at 22°C, 360 Days at 25-30°C, 50% SOC)
      - **After Cruise:**
        Permanent Capacity Loss = 4.0%, Impedance Growth = 54%
      - **After 900 Sols of Surface Operation:**
        Permanent Capacity Loss = 11.6%, Impedance Growth = 185%
  - **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).**
  - **However, the capacity loss under the surface operation simulation was less pronounced with the 43 Ah compared to the 20 Ah cells. This is likely due to the fact that the cells were subjected to a more extensive "burn in" period as a result of the cruise conditions.**
  - **In general, the performance is consistent with that obtained with the smaller prototype cells, demonstrating that the technology scales properly.**
  - **Partial DOD cycling of the 43 Ah cells confirms the expectation that improved life is obtained with shallower DOD (i.e., from 60% to 40% DOD).**
  - **It should be noted that the MSL Curiosity Rover battery has been subjected to relatively benign DOD's and moderate temperatures, to date, suggesting that the health of the flight batteries will exceed expectations based on ground testing.**

NASA's Mars InSight Lander

- Anticipated Launch Date: March 2016
- **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



Battery Details

- Two 8-cell batteries (connected in parallel)
- Manufactured by Yardney Technical Products
- 24-32.8 V (Phoenix Battery Design)
- Qualification Temperature range: -40 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)

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

Summary of Test Plan for InSight

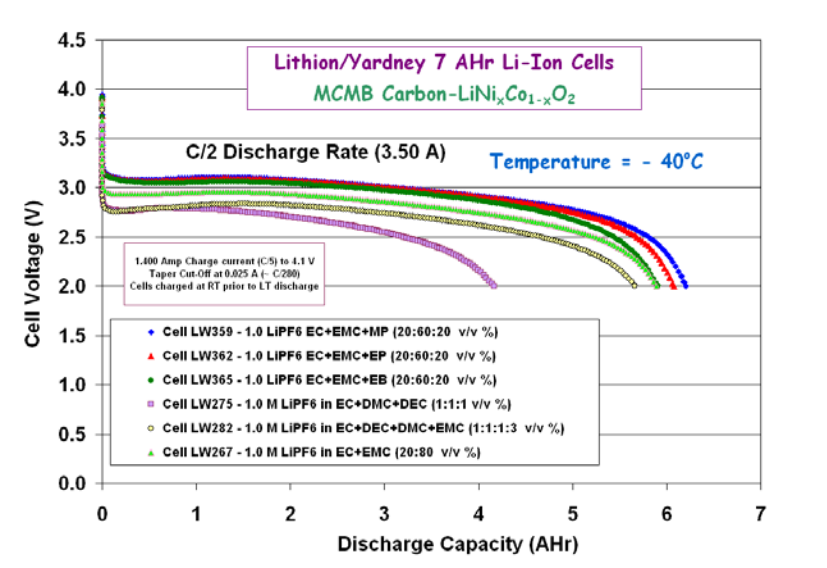
- Next Generation Yardney NCP-25x Li-Ion Cells
  - **18 Cells are currently on test possessing four chemistry variations**
  - **Cell are 25 Ah Nameplate capacity (based on Yardney NCP-25-1 design)**
  - **Cells are being subjected to performance testing to determine applicability to InSight**

Cell Group (Quantity)	Cell Definition	Cathode	Anode	Material Loading	Electrolyte
Group 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)
Group 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)
Group 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)**
Group 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)

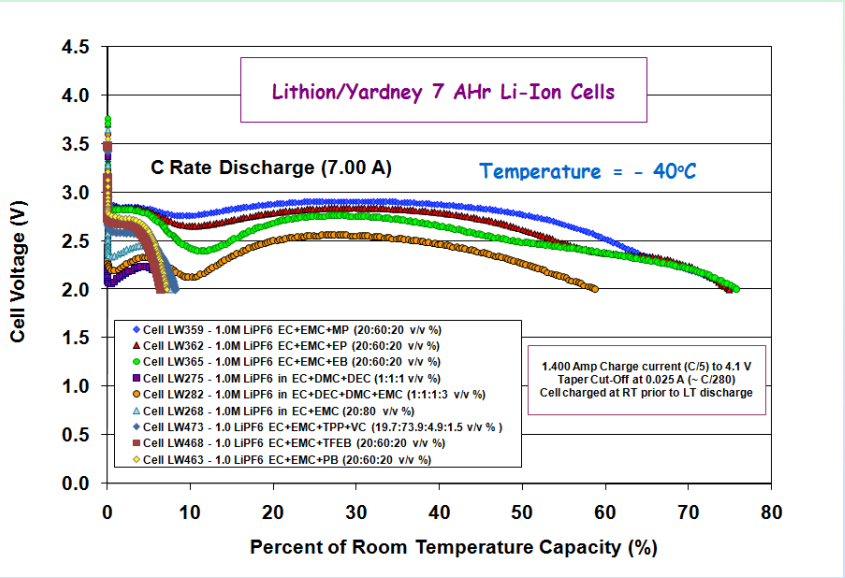
Development of Advanced Low Temperature Electrolytes

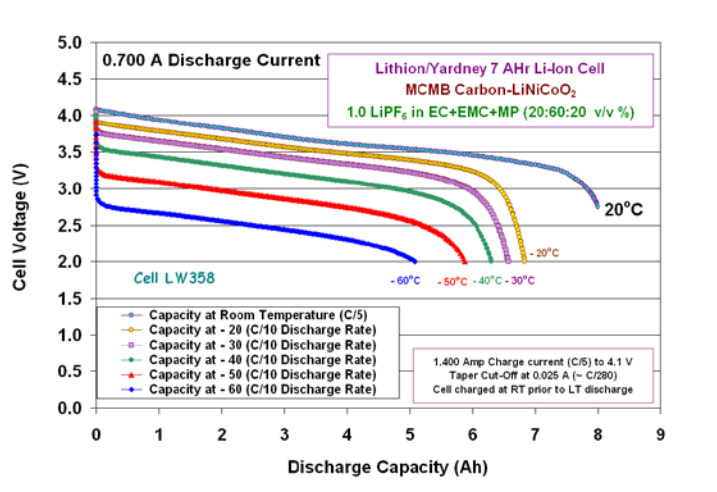
Demonstration of Ester-Based Electrolytes in Yardney Prototype Cells

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).

Overview of Test Plan

- Three different chemistries are distributed amongst three different testing groups.
- Fourth group of cells consist of one chemistry (NCA + Heritage Electrolyte)

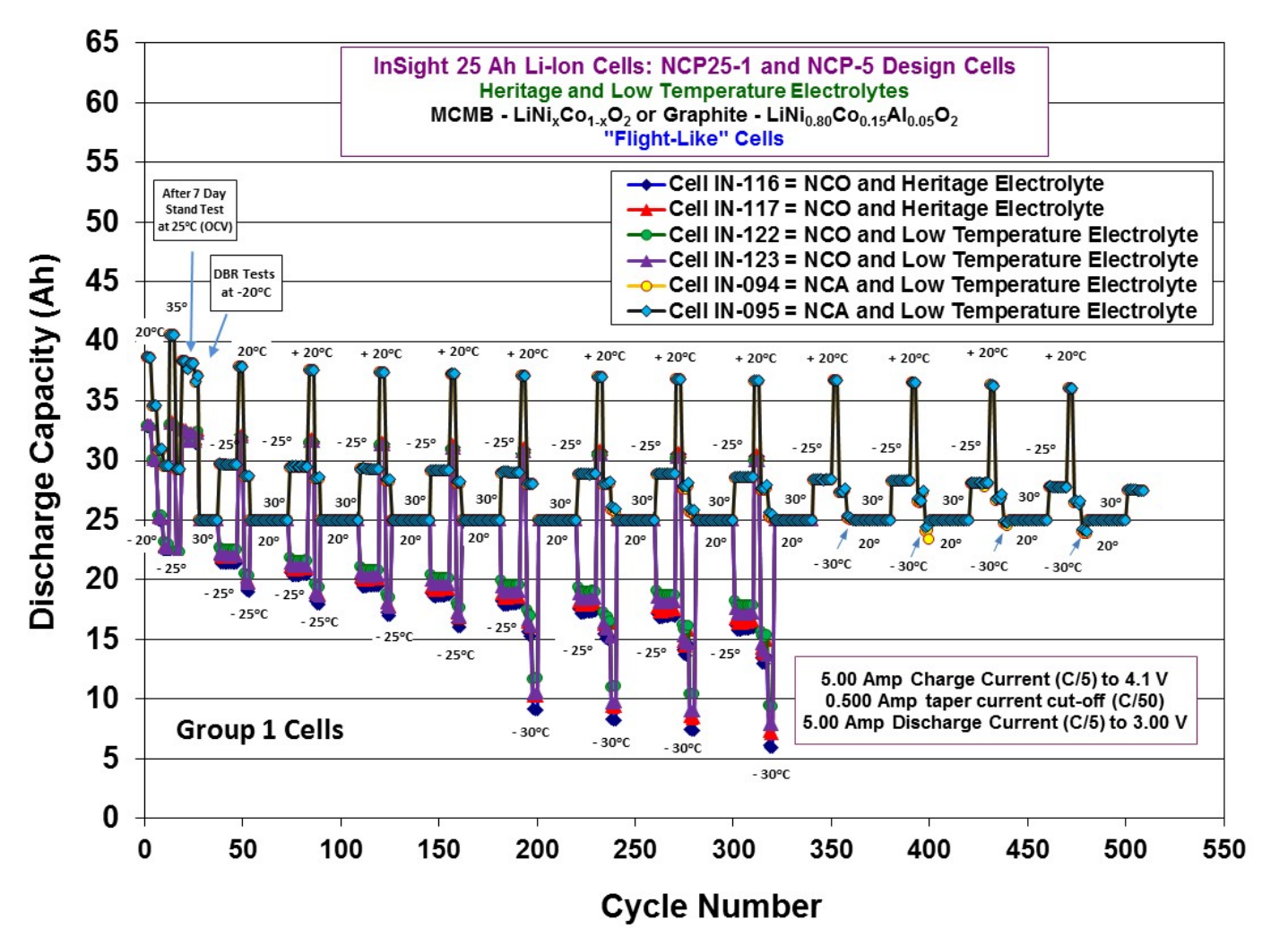
Group 1 (Six Cells, Two of Each Type)	*Group 2 (Six Cells, Two of Each Type)*	*Group 3 (Three Cells, One of Each Type)*	*Group 4 (Three Cells, All One Type) (NCA+Heritage)*
High Temperature Exposure Characterization Group, mission relevant cycling conditions	Low Temperature Discharge and Charge Rate Characterization Group	**Accelerated Mission Relevant Life Testing**	High Temperature Exposure Characterization Group (Same as Group 1)
Initial Characterization at 20°, 0°, -20° and -25°C	Initial Characterization at 20°, 0°, -20° and -25°C	Initial Characterization at Only +20° and -25°C	Initial Characterization at 20°, 0°, -20° and -25°C
Characterization at +35° and -25°C	Discharge Rate Testing Performing in the following order: -20°C, -25°C, -30°C, -40°C, -10°C, 0°C, 20°C	(A) 60 % DOD Life Test Over (i) 20 to +35°C, 3 Cycles Each Day C/5 Charge and Discharge Rates (60 Cycles Total)	Characterization at +35° and -25°C
Pad Storage Characterization (7 Days at 25°C)	Charge Rate Testing (20 to -40°C)	Repeat Characterization at +20° and -25°C	Pad Storage Characterization (7 Days at 25°C)
Cycling Between +30°, +20° and -25°C (10 Cycles Each Temp)	Repeat Characterization at +20° and -25°C	(A) 60 % DOD Life Test at (i) +33°C, 3 Cycles Each Day C/5 Charge and Discharge Rates (60 Cycles Total)	Cycling Between +30°, +20° and -25°C (10 Cycles Each Temp)
Continue cycling at temperature extremes with periodic diagnostic characterization at +20°C -25°C, and -30°C.	Continuous cycling at -30°C under flight like conditions, with periodic diagnostic checks at different temperatures.	Repeat Characterization at +20°, -25°, and -30°C	Continue cycling at temperature extremes with periodic diagnostic characterization at +20°C -25°C, and -30°C.

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)**
  - Subjected to +35°C cycling, 7 day stand test at +25°C, and DBR characterization
  - NCA cells completed over **506 cycles;** NCO cells discontinued after completing 340 cycles
  - To date, the flight like cells have completed the following:
    - 130 cycles at +30°C using low rate (capacity = 25 Ah)
    - 120 cycles at +20°C using low rate (capacity = 25 Ah)
    - 130 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 = 45
    - Temperature = - 25°C; Total number of cycles = 45
    - Temperature = - 30°C; Total number of cycles = 28

Results of Group 1 Cell Testing

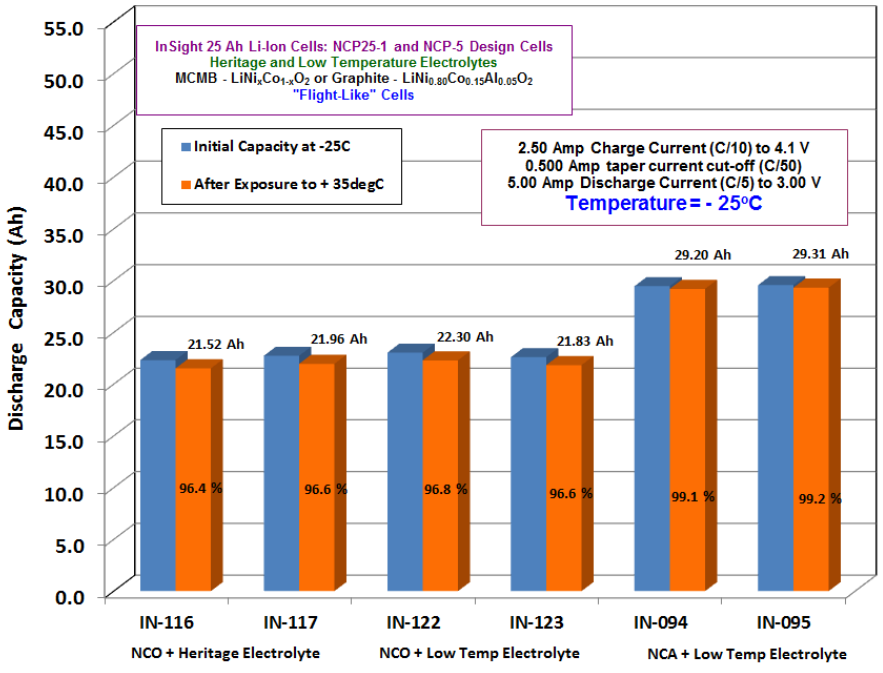
Summary of Results (Discharge Capacity, Ah)

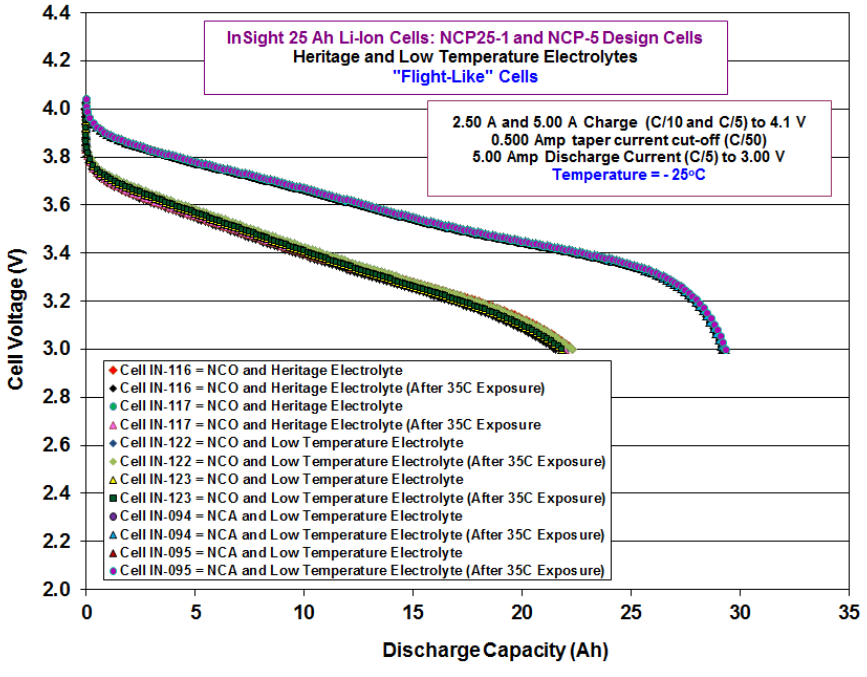


Results of Group 1 Cell Testing

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

Comparison of Different Chemistries



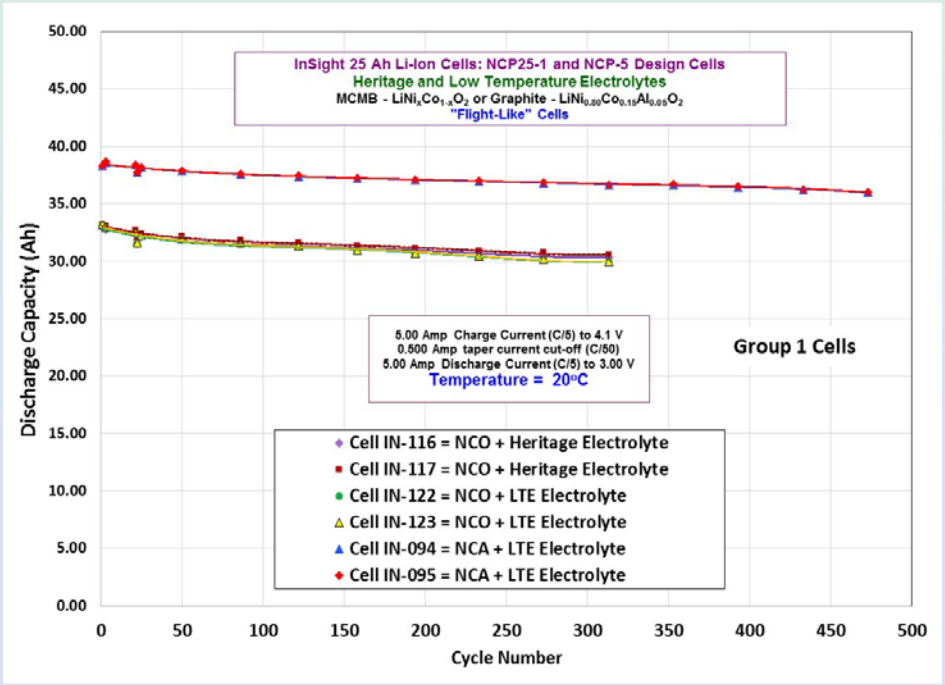


- Cells with NCA and Low Temperature Electrolyte deliver 31% more capacity at -25°C compared with heritage chemistry and display much higher operating voltage throughout the discharge.
- The NCA-based cells display enhanced resilience to high temperatures.

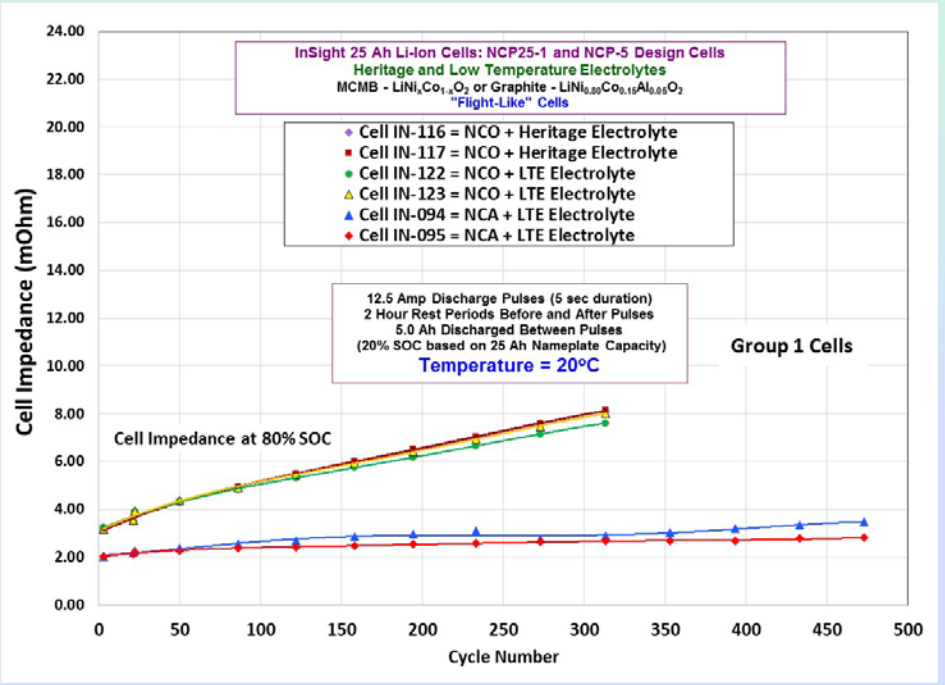
Results of Group 1 Cell Testing

Summary of Results (Discharge Capacity at 20°C)

Discharge Capacity (Ah) at 20°C



Cell Impedance (mΩ) at 20°C

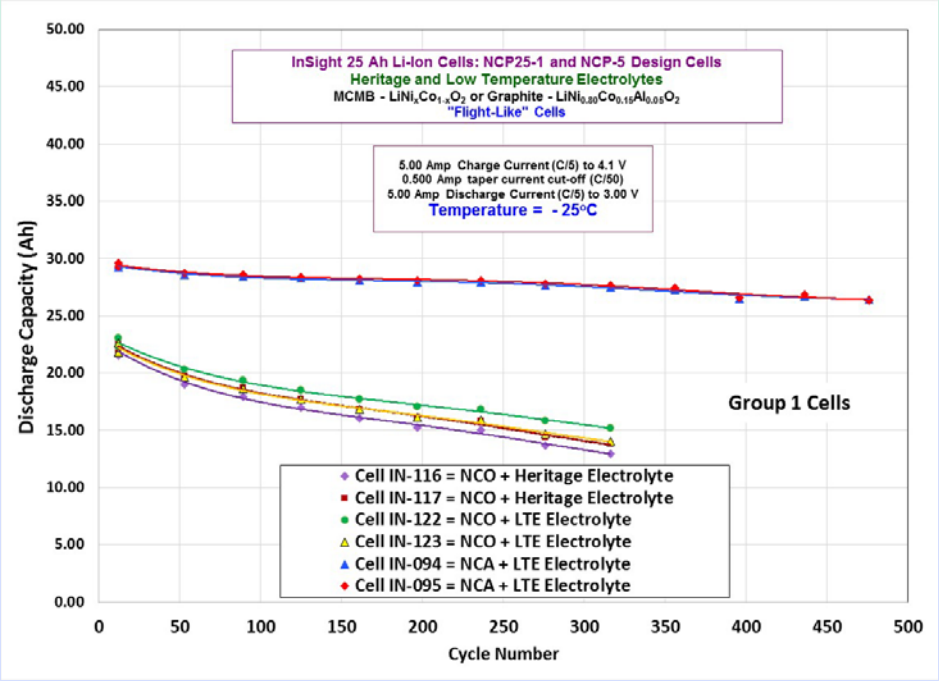


- Good capacity retention and low impedance growth was observed with the NCA+LTE cells
  - NCA+LTE cells delivered 94% of the initial capacity after completing 473 cycles (> 1.75 years)
  - NCA+LTE cells displayed less than half the impedance of the NCO systems, and the impedance growth is much lower

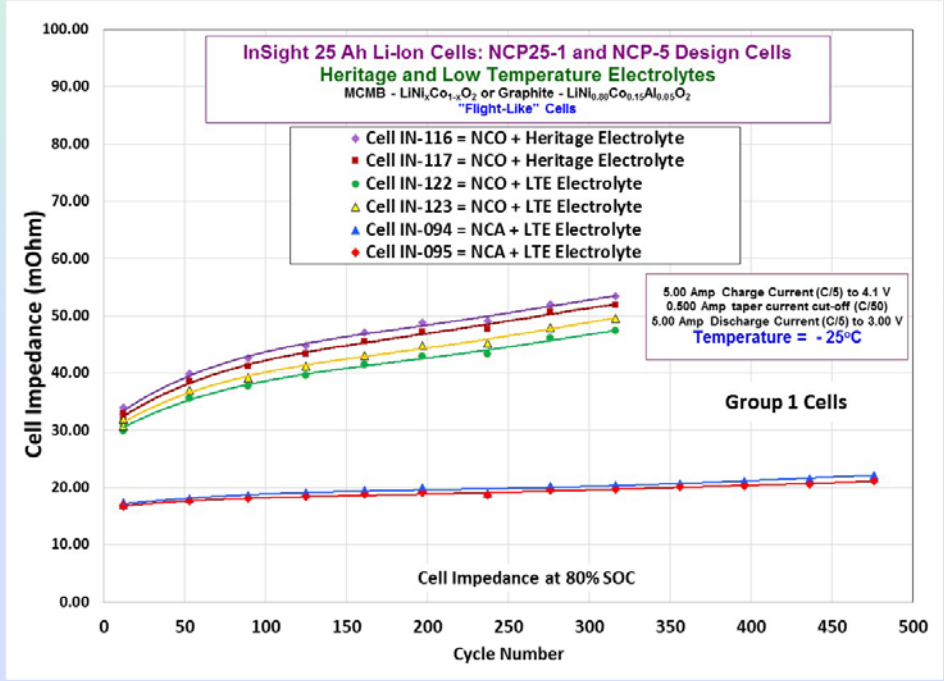
Results of Group 1 Cell Testing

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

Discharge Capacity (Ah) at -25°C



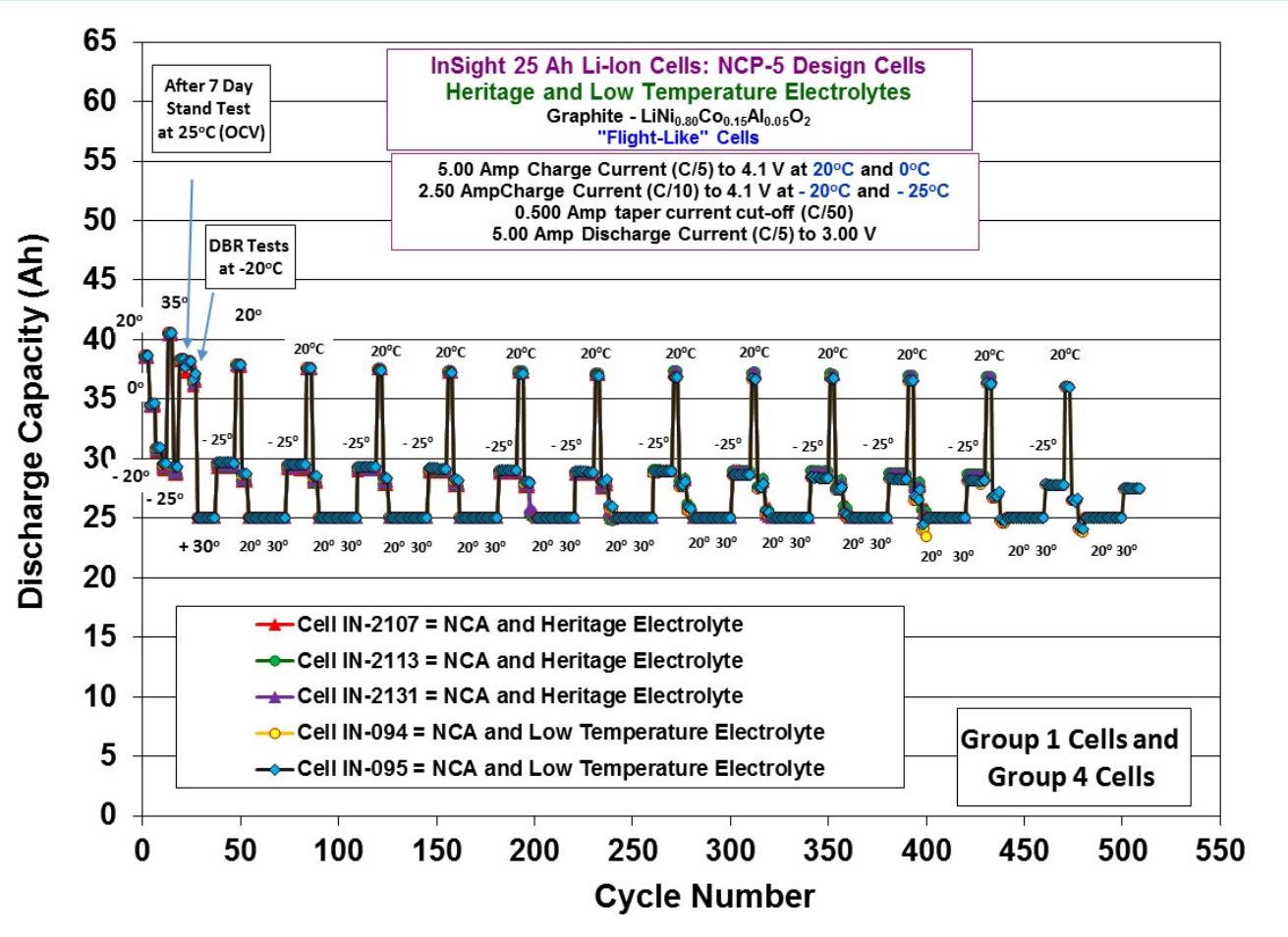
Cell Impedance (mΩ) at -25°C



- *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)



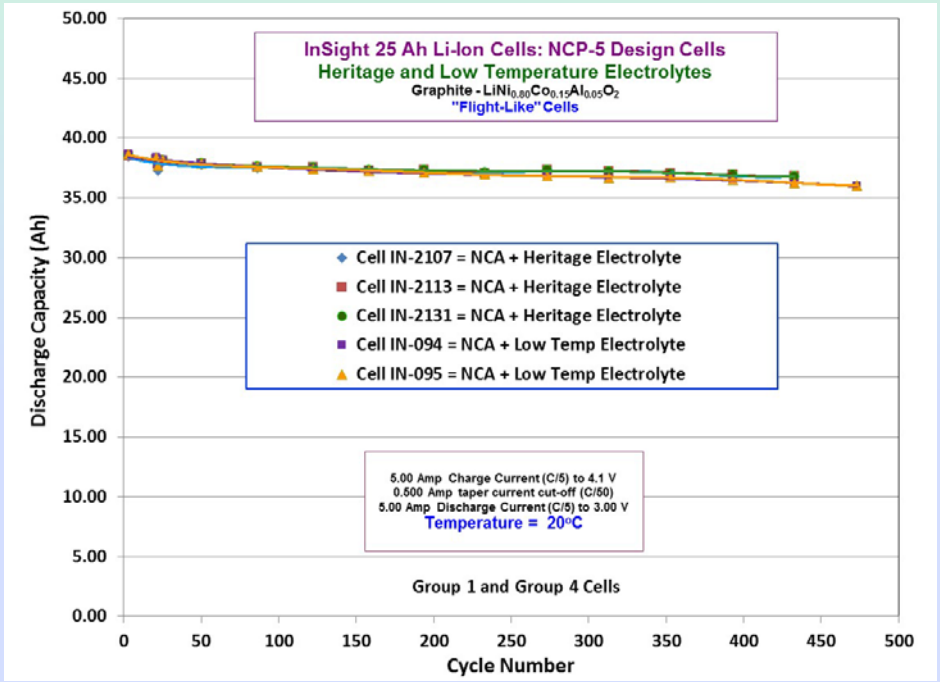
- *NCA-based cells that contain the low temperature MP-based electrolyte and the heritage all carbonate-based electrolyte performed very comparably throughout the testing.*

Results of Group 4 Cell Testing

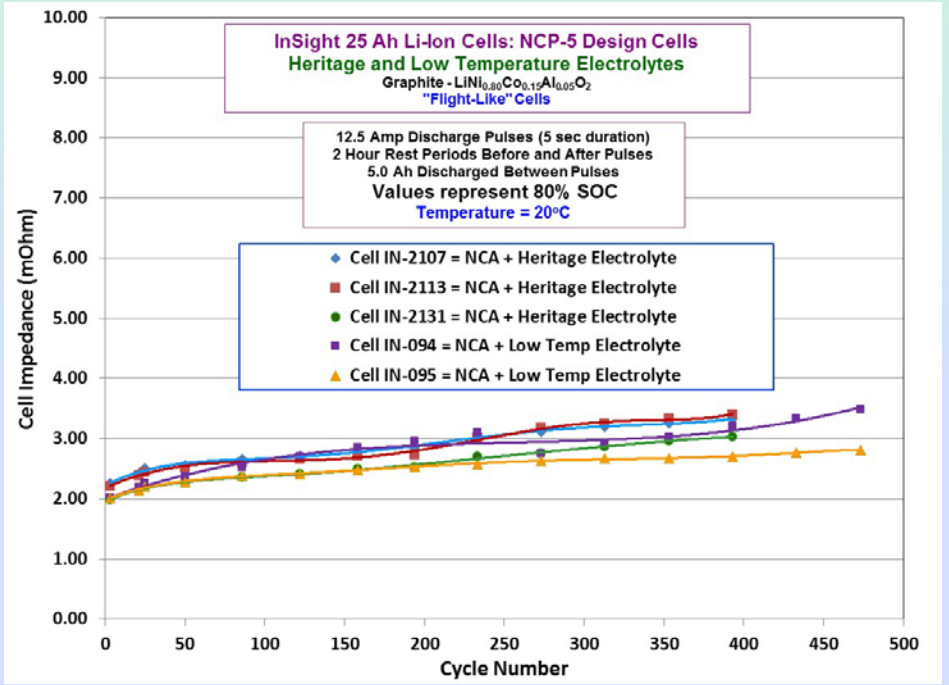
Summary of Results (Capacity and Impedance at 20°C)

Comparison with Group 1 Cell Testing

Discharge Capacity (Ah) at +20°C



Cell Impedance at +20°C



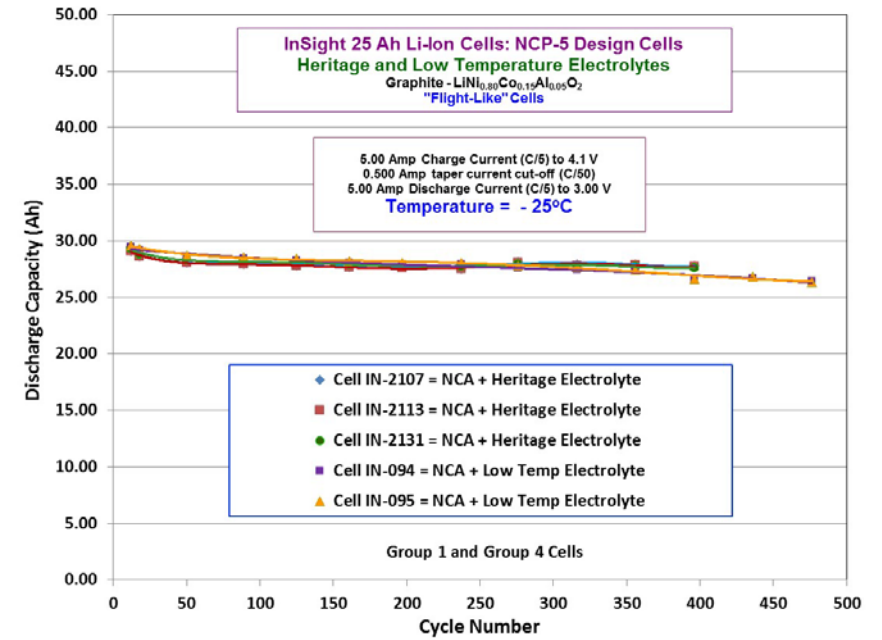
- *The NCA+LTE cells displayed modestly higher capacity fade rate with cycling compared with the NCA+heritage cells.*
- *However, somewhat lower impedance growth was observed with the NCA+LTE cells.*
- *Cells were subjected to +35°C testing, a 7 day stand test, and cycling over a wide temperature range (+30° to -25°C)*

Results of Group 4 Cell Testing

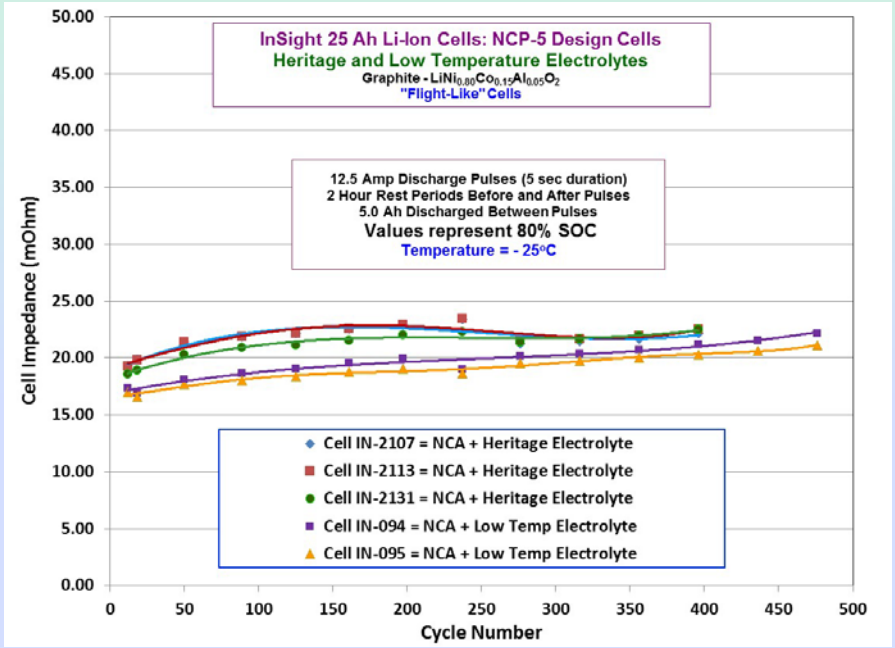
Summary of Results (Capacity and Impedance at -25°C)

Comparison with Group 1 Cell Testing

Discharge Capacity (Ah) at -25°C



Cell Impedance at -25°C



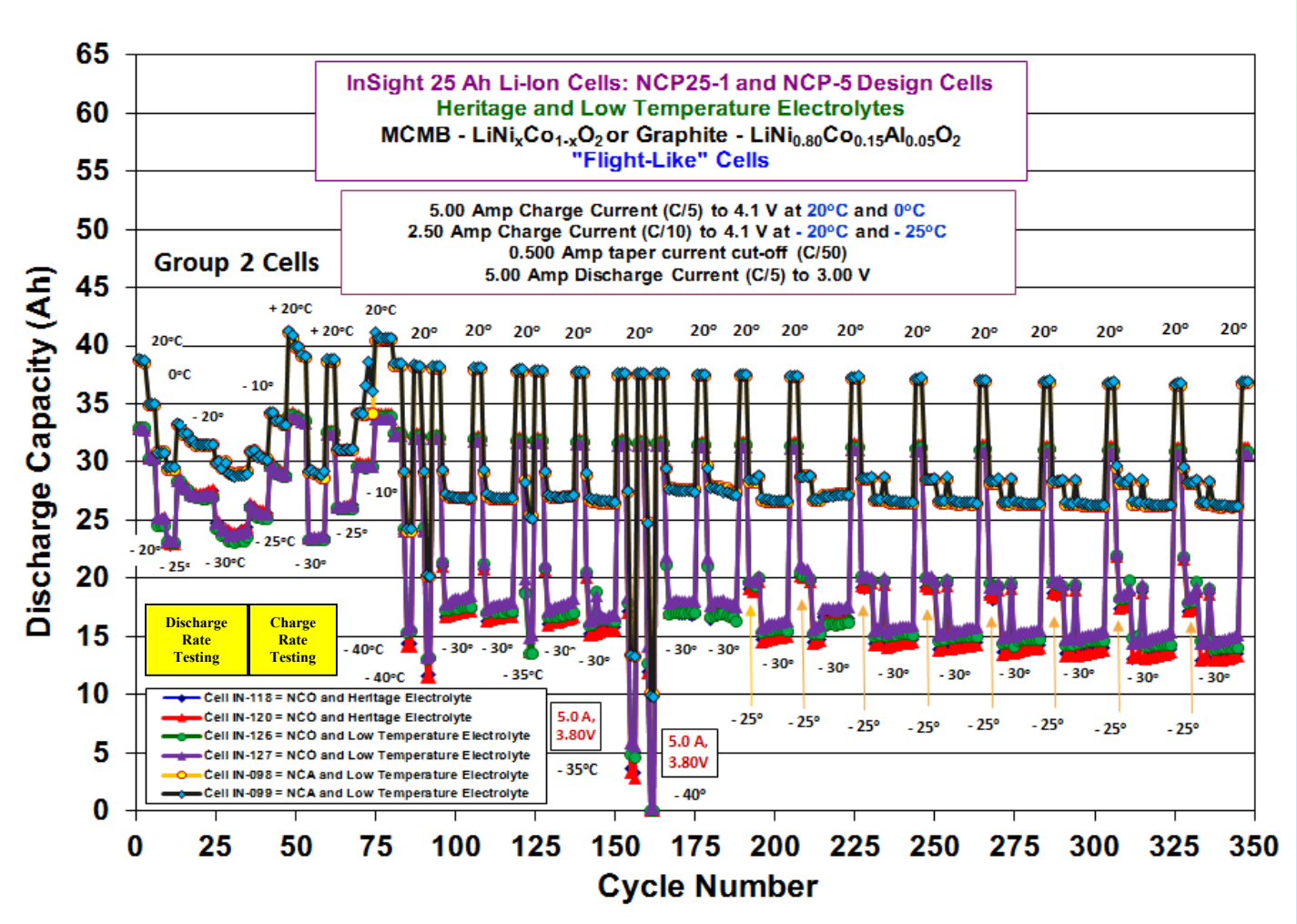
- *The NCA+LTE cells displayed modestly higher capacity fade rate with cycling at -25°C compared with the NCA+heritage cells.*
- *However, somewhat lower impedance growth was observed with the NCA+LTE cells.*
- *Cells were subjected to +35°C testing, a 7 day stand test, and cycling over a wide temperature range (+30° to -25°C)*

Performance Testing of InSight Yardney NCP-25-6 Li-Ion Cells
Status of Group 2 Cell Testing

- **Status of Group 2 Cells (6 Cells):**
- **Subjected continuous cycling at -30°C using flight relevant conditions (> 120 cycles)**
  - Subjected to rate characterization (~60 cycles, +20°C to -30°C)
  - Subjected to very low temperature characterization (-35°C and - 40°C)
  - Cells still display > 95% of original capacity at +20°C
  - Completed over **345 cycles and displayed excellent resilience to cycling at -30°C**
  - ***Testing discontinued to accommodate other tests***

Results of Group 2 Cell Testing

Summary of Results (Discharge Capacity, Ah)

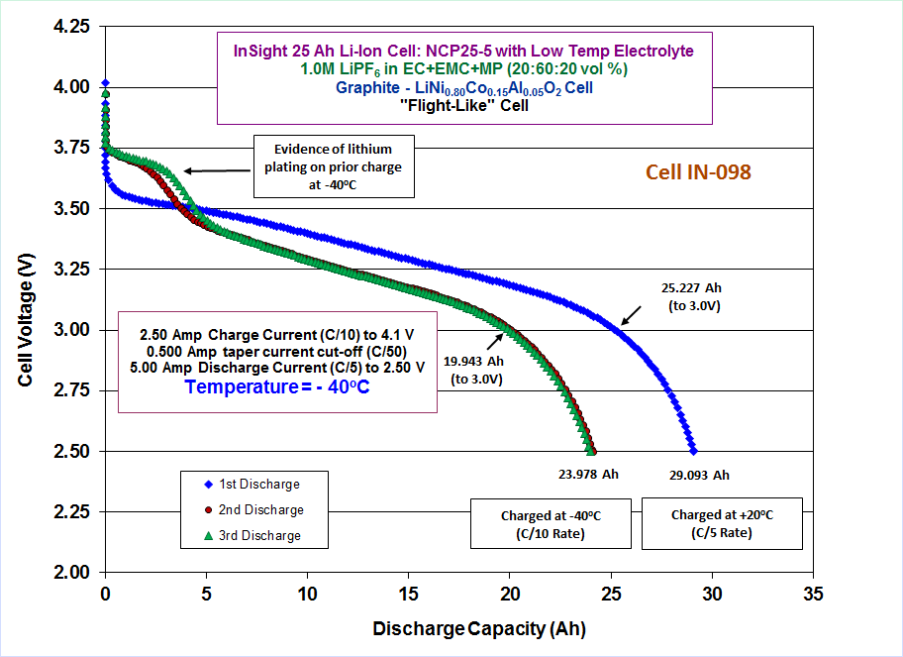


- *After (a) initial characterization at different temperatures (20, 0, -20, and -25°C), (b) discharge rate characterization (down to -30°C), (c) charge rate characterization (down to -30°C), and (d) diagnostic testing at -40°C, the cells have been subjected to (e) continuous cycling at -30°C to assess robustness.* ***Over 140 cycles completed at flight-like conditions at -30°C***

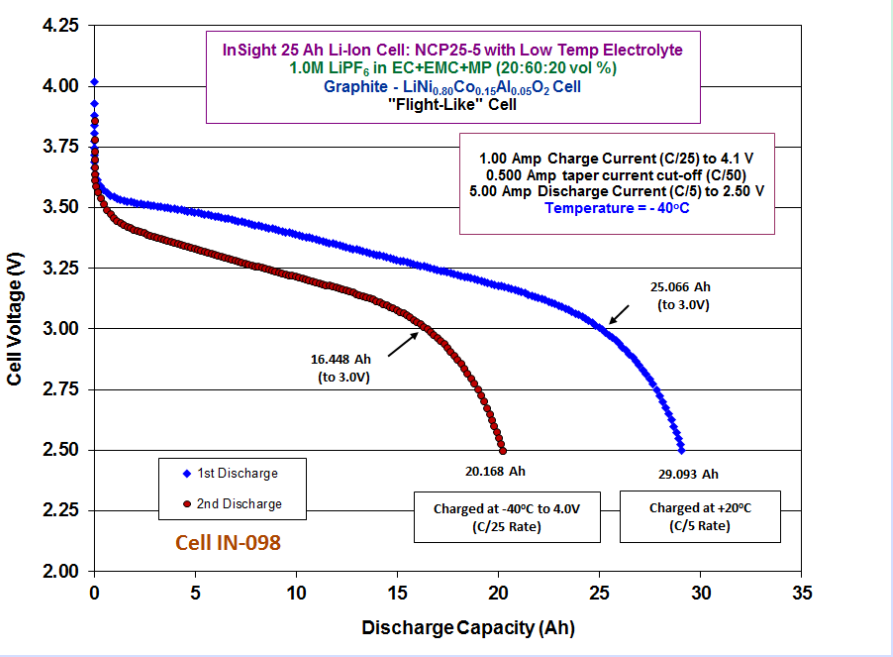
Results of Group 2 Cell Testing

Summary of Results (Performance of IN-098 at -40°C)

C/10 (2.5A) to 4.10V at -40°C



C/25 (1.0A) to 4.00V at -40°C



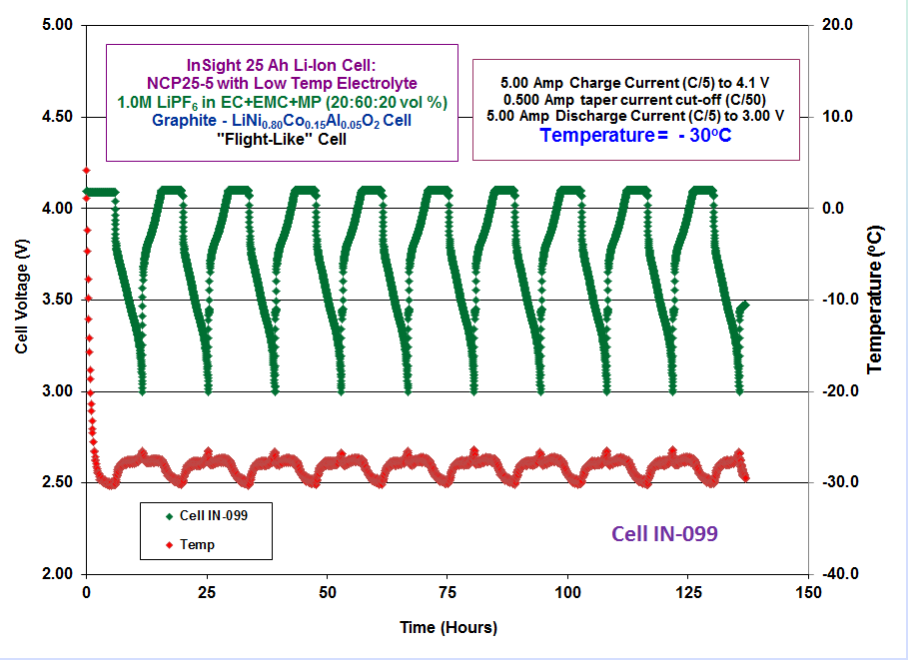
- When NCA/LTE cells were cycled at -40°C using C/10 charge rate, **Li plating was observed on the anode**
- This is indirectly observed by the higher voltage plateau on the subsequent discharge (i.e., the lower overpotential of lithium stripping compared to Li^+ de-intercalation from graphite).
- Results led to the evaluation of lower charge rates and charge voltage test at -40°C (i.e., C/25
- charge rate to 4.00V), where no evidence was observed.
- **Subsequent testing established only modest plating at -35°C (C/5 rates to 4.10V) and no plating evident at -30°C (using C/5 charge rates to 4.10V)**

Results of Group 2 Cell Testing

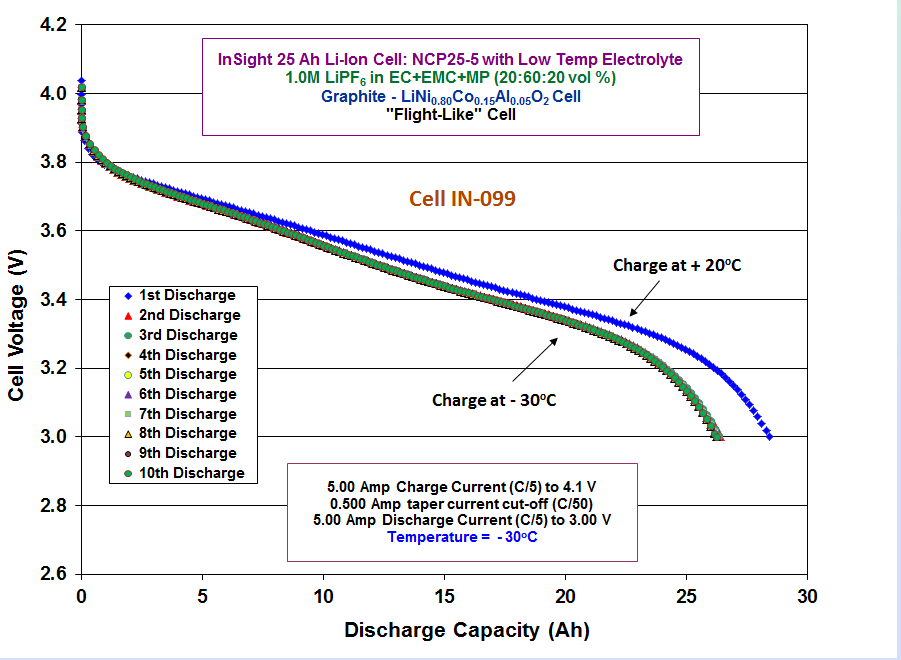
Summary of Results (Performance at -30°C)

Cycles 336-345 (14th set of 10 cycles performed at -30°C)

Cell IN-099



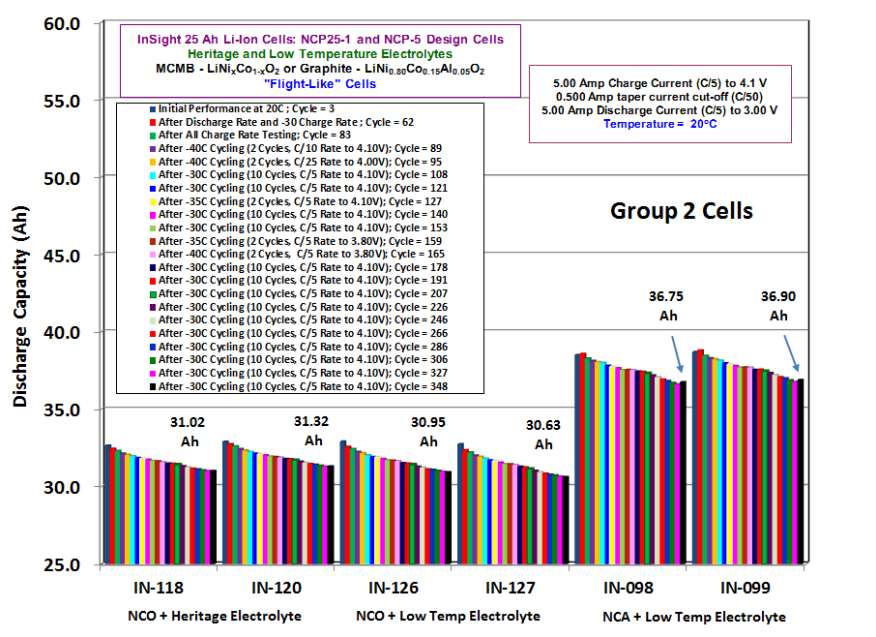
Cell IN-099

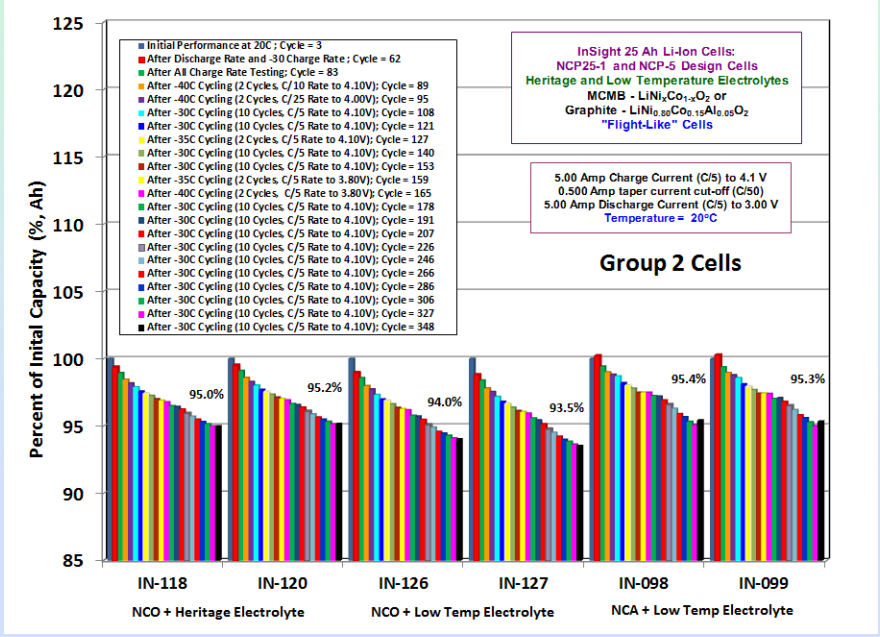


- The Group 2 Cells were recently subjected to cycling continuously at -30°C (14th group of cycles)
- The charging represents flight relevant conditions (5.00A charge current to 4.10V)
- Cells have completed ~ 140 cycles under these conditions
- Stable performance was observed
- Cells have completed over 160 cycles at temperatures of -30°C or below (different conditions)

Results of Group 2 Cell Testing

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





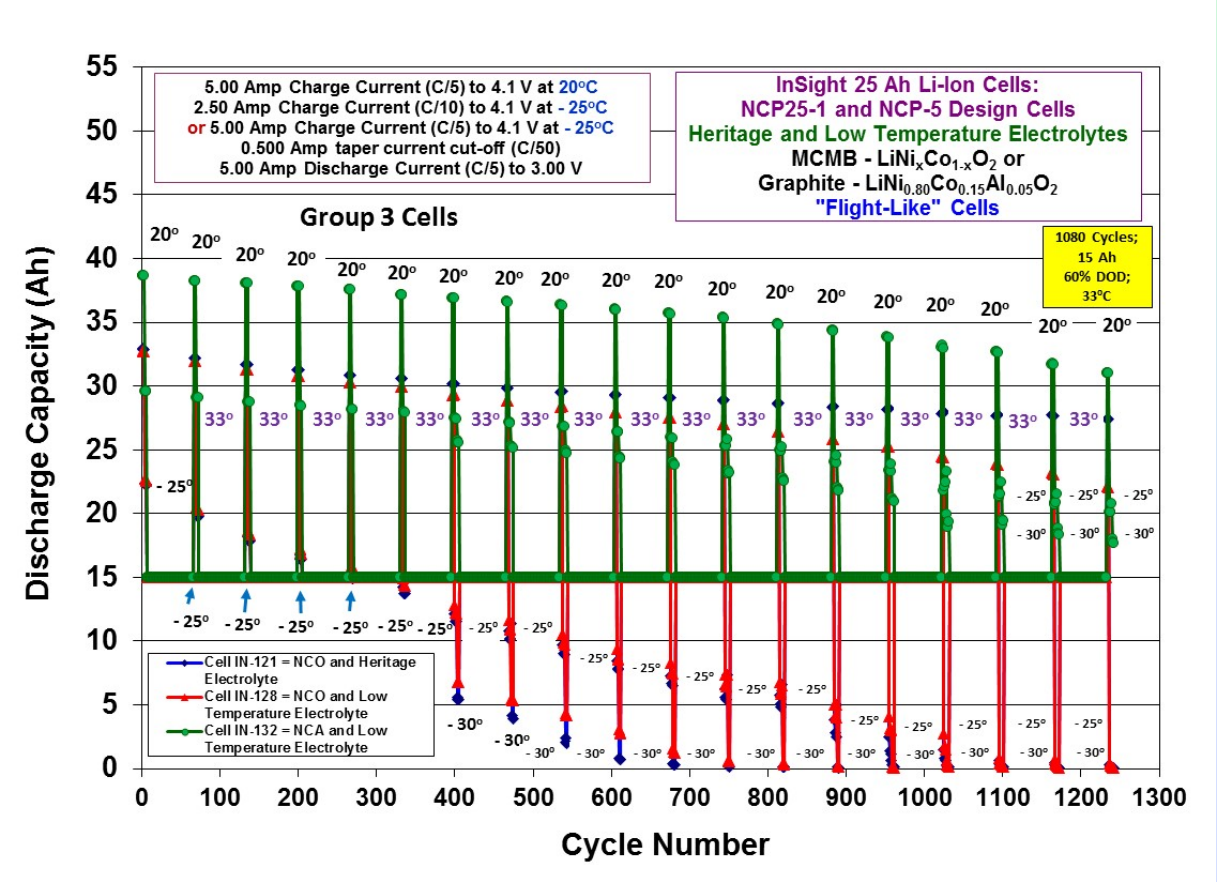
- *The NCA+ LTE chemistry has not displayed any deleterious effects as a result of cycling continuously at -30°C. Good retention of capacity is observed with a low capacity fade rate.*
- *The NCA+ LTE chemistry also displays very low impedance growth as a result of cycling over a wide temperature range. This result is significant, since the harmful effects of lithium plating often manifests itself in terms of increased impedance growth.*
- *In addition to a lower impedance growth rate, the absolute value of the impedance is less than half that of the NCO systems.*
- *It should be noted that even though lithium plating was observed on a few cycles of the NCA cells under aggressive conditions, no long-term negative impact upon performance was observed.*

Performance Testing of InSight Yardney NCP-25-6 Li-Ion Cells
Status of Group 3 Cell Testing

- **Status of Group 3 Cells (3 Cells):** ***Testing is on-going***
  - **Accelerated partial DOD (60%) cycling at high temperature (+33°C)**
  - Completed over **1,235 cycles** (1,080 cycles at 60% DOD at +33°C)
  - Accelerated cycled 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)

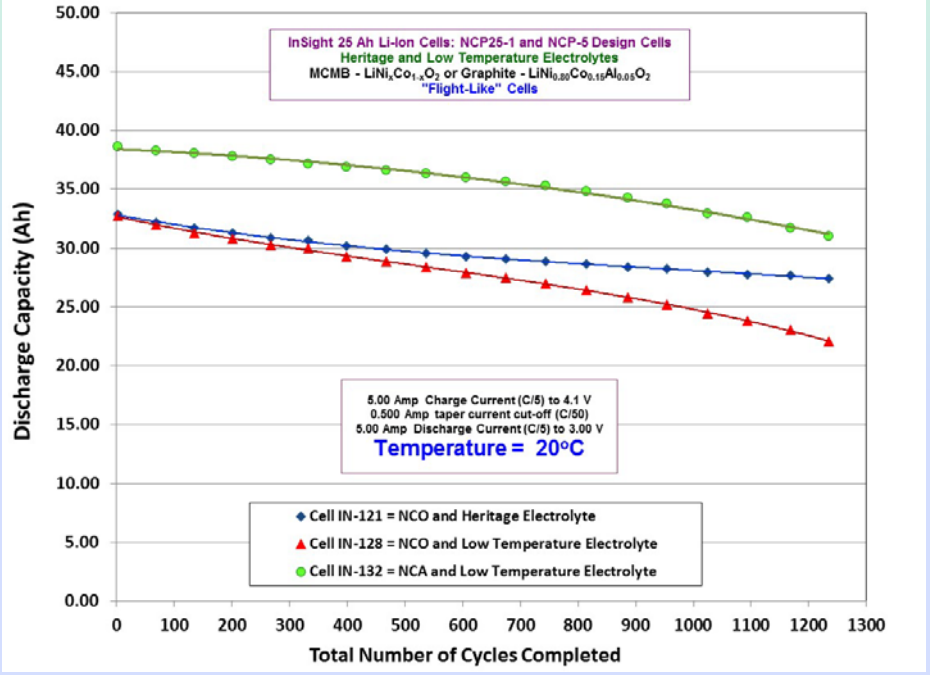


- *The Group 3 cells were cycled at high temperature +33°C and periodically characterized at +20°, -25°, and-30°C*
- *The NCA+LTE cell IN-132 delivered 20.11 Ah at -25°C (cycle 1,238) and 17.70 Ah at -30oC (cycle 1,241) In contrast, the NCO+Heritage only delivered 0.176 Ah and the NCO+LTE delivered 1.503Ah at -25°C*
- *Cell cycled under flight-like conditions (i.e., C/5 charge rate to 4.10V)*
- *Cells have completed 1,080 accelerated cycles at high temperature (i.e., 33°C)*

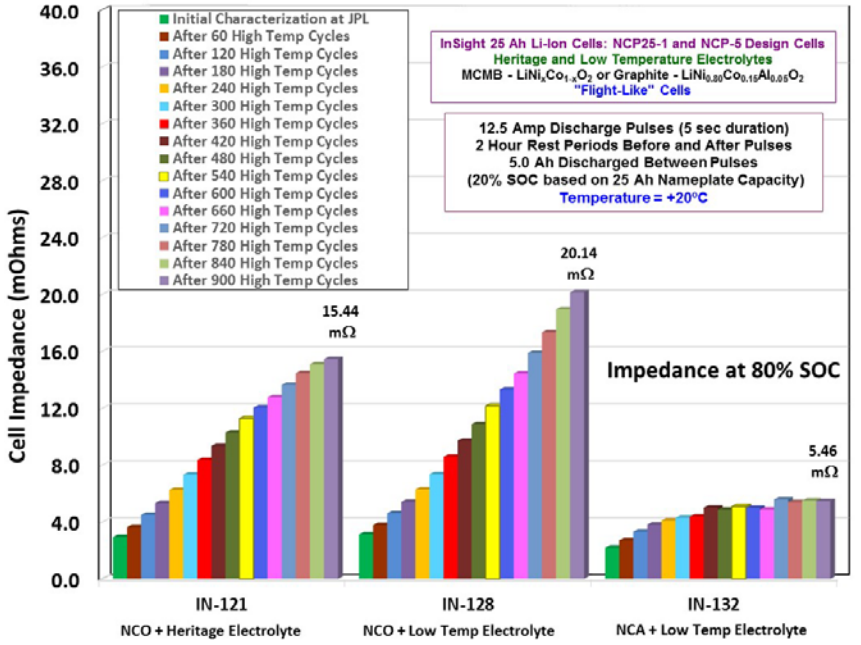
Results of Group 3 Cell Testing

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

Discharge Capacity (Ah) at +20°C



Cell Impedance at +20°C

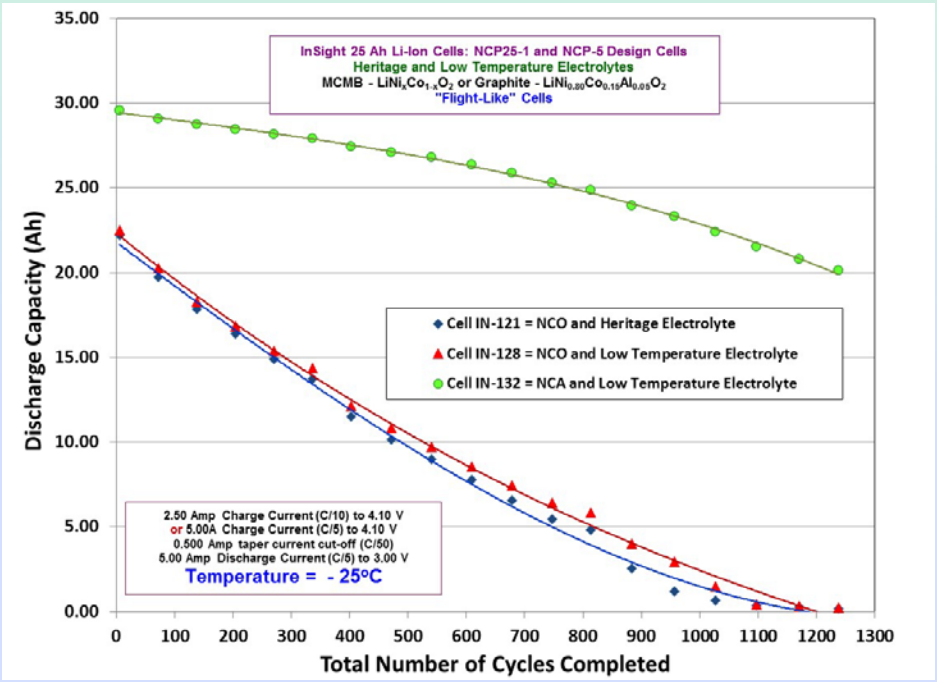


- *The NCA +LTE cell displays good tolerance to high temperatures (i.e., 33°C) and lower impedance growth compared to the NCO heritage cell.*
- *The trend in the capacity retained as a result of the high temperature cycling is the following:*
  - *NCO+Heritage (27.43 Ah, 83.4%) > NCA+LTE (31.0 Ah, 80.2%)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

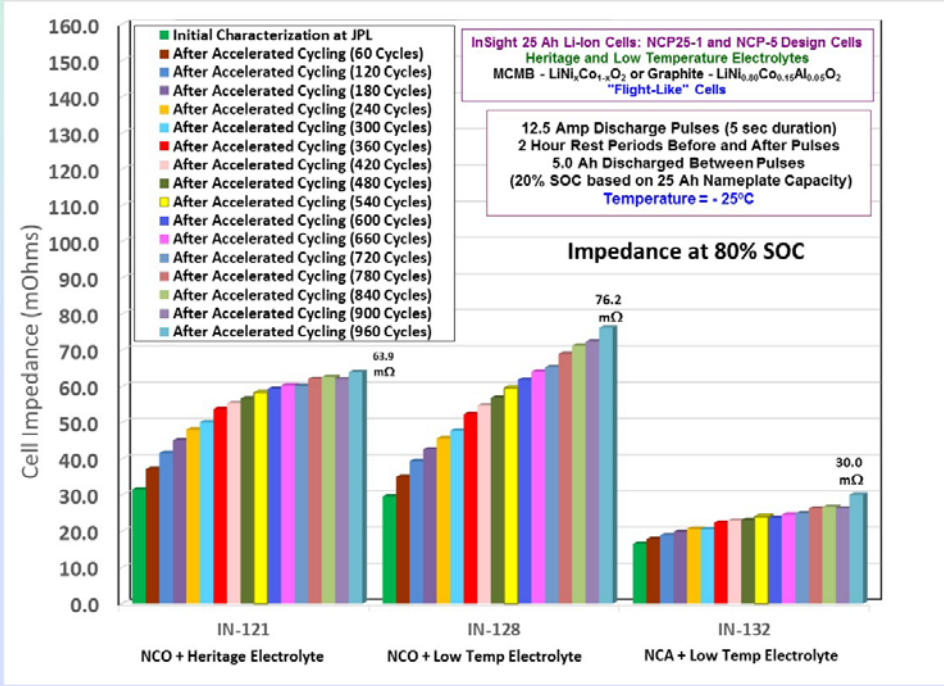
Results of Group 3 Cell Testing

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

Discharge Capacity (Ah) at -25°C



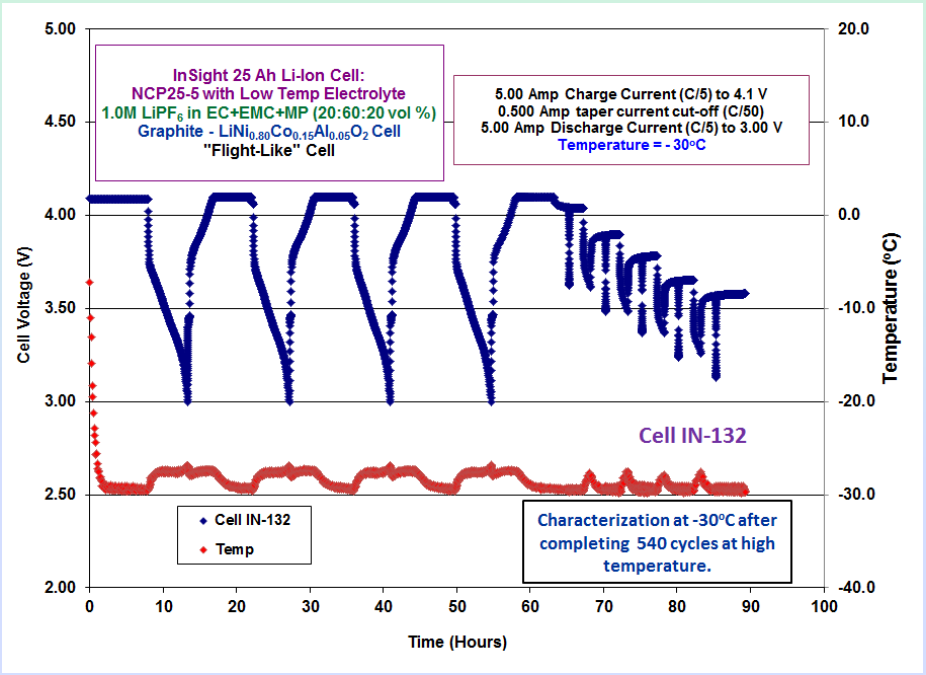
Cell Impedance at -25°C

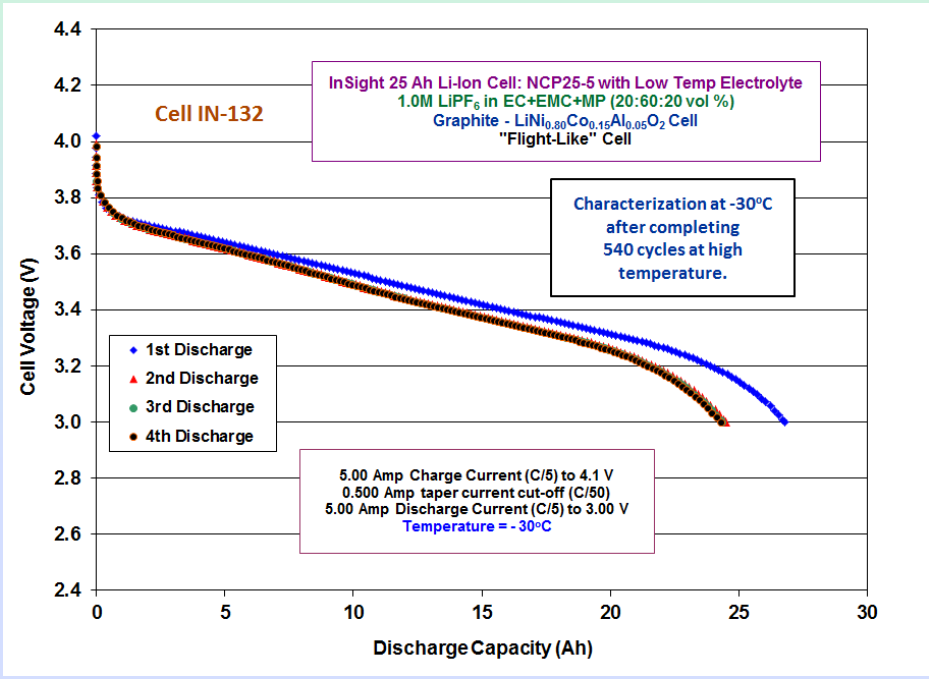


- *The low temperature performance of the NCA +LTE cell was superior to that of the NCO-based cells, and that capability was preserved much better after being subjected to high temperature cycling.*
- *After completing over 1,200 total cycles, the NCA +LTE cell delivered over 3 times the capacity of 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 (Discharge Capacity at -30°C)

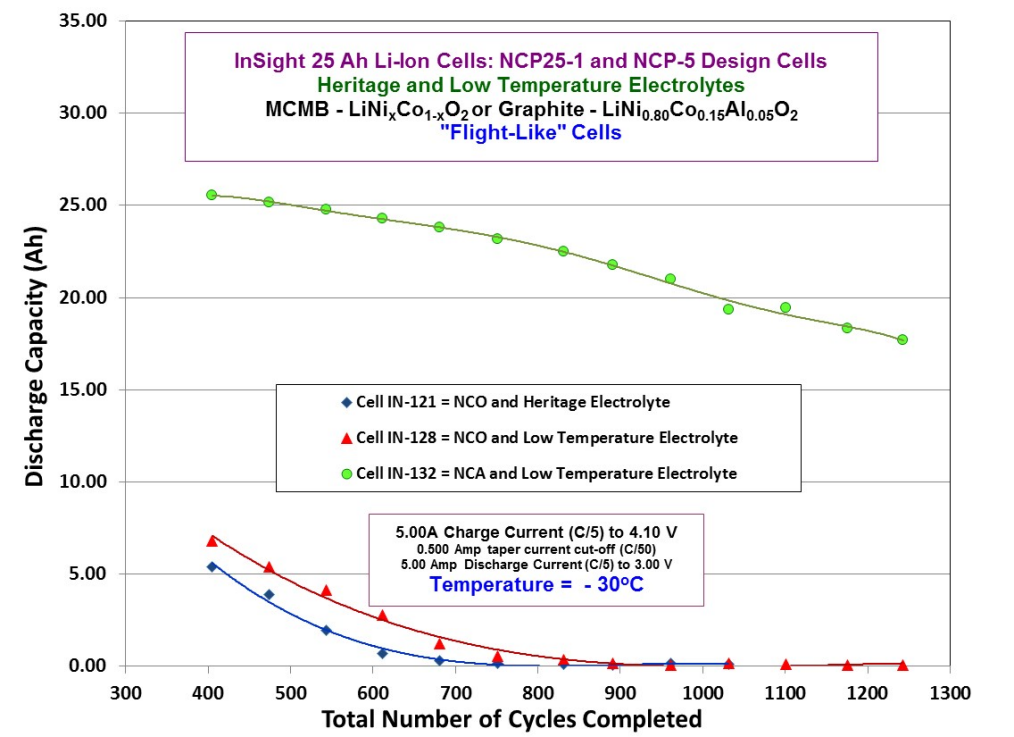


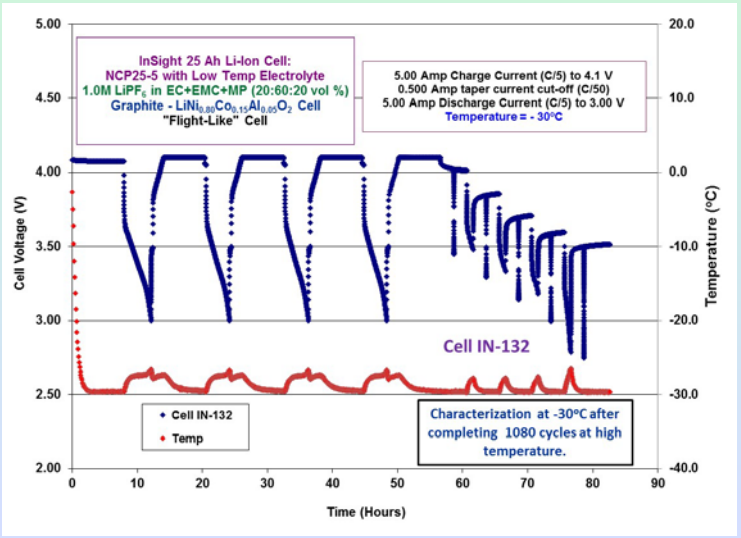


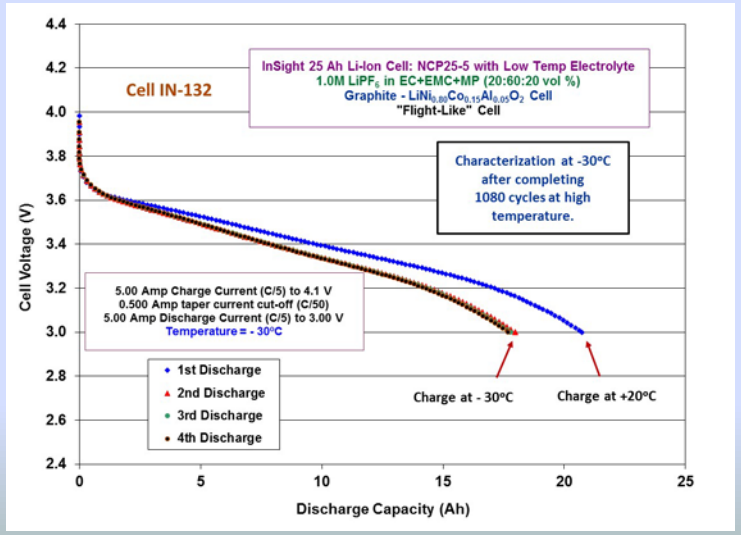
- No evidence of Li plating was observed with the cells using a C/5 charge rate (5.0A) at -30°C.
- Cells have completed 540 cycles at high temperature.
- Over 24 Ah delivered at -30°C under flight relevant conditions (24.29 Ah) (Cycles 610-612)
- Cell charged at +20°C prior to test (i.e., first discharge is with room temperature charge). Subsequent discharge steps are all preceded by a charge at -30oC under flight relevant conditions.

Results of Group 3 Cell Testing

Summary of Results (Performance at -30°C)







- After completing 1080 high temperature cycles (and over 1240 total cycles), the NCA+LTE dramatically outperforms the heritage chemistry at -30°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°C.

Summary and Conclusions

- **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 baselined 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 compared to the NCO-based chemistries.**
  - **BOL, Cells with NCA +LTE deliver 31% more capacity at -25°C compared with heritage chemistry and display much higher operating voltage throughout the discharge.**
  - ***Group 1 Cell Testing:** The NCA+ Low Temperature Electrolyte chemistry delivers improved capacity at -25°C compared with the NCO heritage (> 78% improvement) and displays dramatically better low temperature capacity retention throughout the life of the cells.*
  - ***The NCA+ LTE chemistry displays much lower impedance at -25°C compared with the NCO chemistry (less than half the value) and displays a lower growth rate as a result of cycling***
  - ***Group 2 Cell Testing:** NCA+ LTE chemistry did not display any deleterious effects as a result of cycling continuously at -30°C. Good retention of capacity is observed with a low capacity fade rate.*
  - ***Group 3 Cell Testing:** 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 (i.e., 1,080 cycles at +33oC, representing a mission bounding scenario).*
  - ***After completing over 1,300 total cycles, the NCA +LTE cell displayed good performance at -25°C and -30°C , whereas both NCO cells delivered negligible capacity.***
  - **In summary, the NCA+LTE based system displays good life characteristics and preservation of the low temperature capability throughout the life of the cell compared with the heritage NCO-based system, and is anticipated to more successfully meet mission requirements.**

Acknowledgments

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