# Lithium-ion Batteries for Mars Missions

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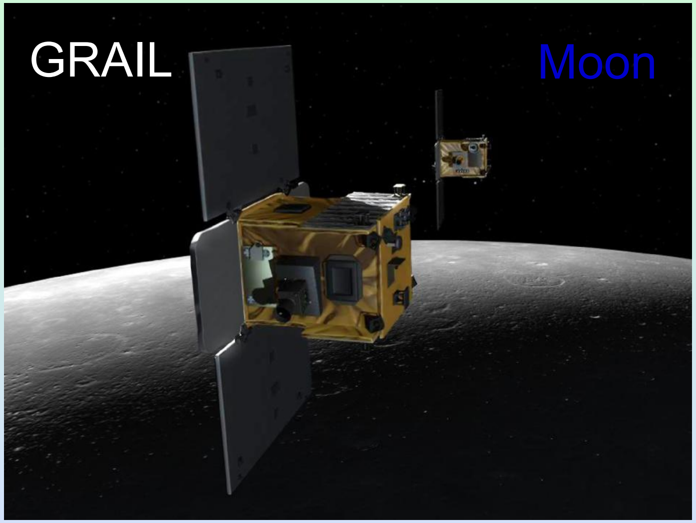
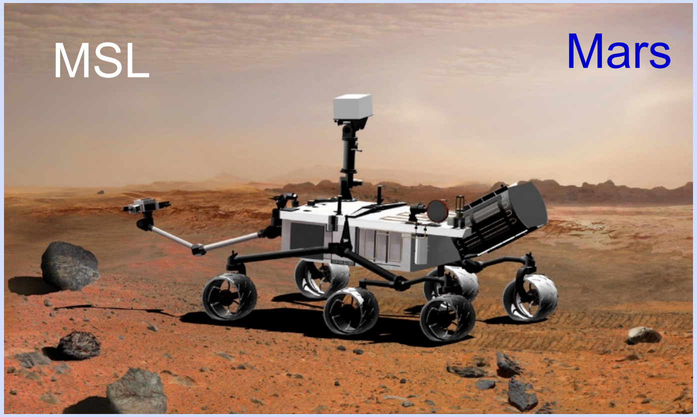
# Outline

- **Overview of Li-ion Batteries for Solar System Exploration**
- **Overview of State-of-Practice (SOP) Rechargeable Batteries**
- **Use of Li-ion Batteries in Mars Lander and Rover Missions**
  - **2003 Mars Exploration Rovers (MER) Spirit and Opportunity**
  - **2007 Mars Phoenix Lander**
  - **2011 Mars Science Laboratory (MSL) Rover Curiosity**
  - **2018 Mars InSight Lander**
  - **2021 Mars 2020 Perseverance Rover**
- **Use of COTS Small Cells for Mars Missions**
  - **Mars Express**
  - **MarCO CubeSat**
  - **Mars Helicopter Ingenuity**
- **Conclusions**

# Li-Ion Battery Applications for Solar System Exploration

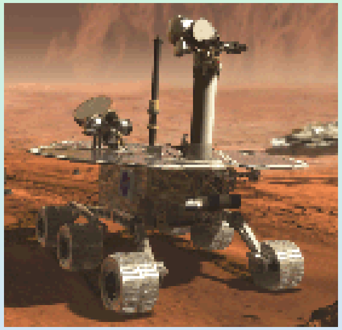





Rechargeable batteries provide power during launch, and power during eclipses and night time operations with solar arrays, and for load-levelling with both solar arrays and radioisotope thermoelectric generator power sources

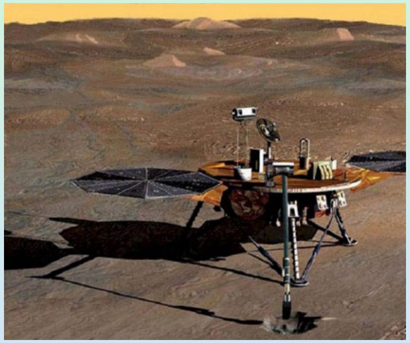
# NASA Mars Landers and Rovers Using Large Cell Batteries

## Mars Exploration Rovers (2003)



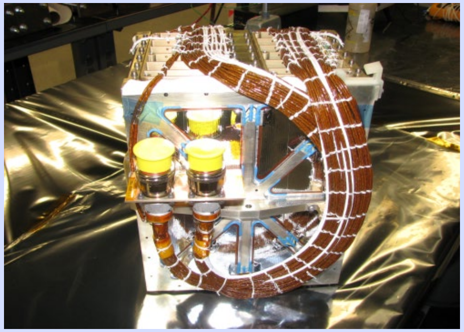
- Battery specific energy: 90 Wh/kg
- Operated on Mars 2004 – 2018

## Mars Phoenix Lander (2007)



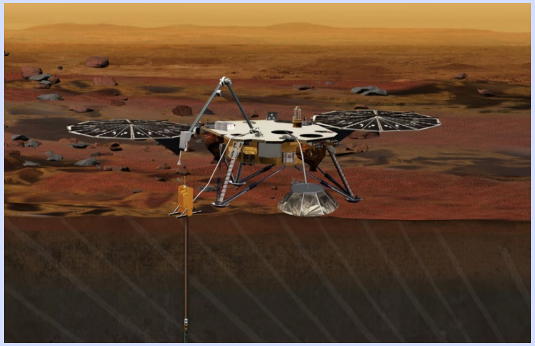
- Battery specific energy: 105 Wh/kg
- Successfully supported mission (90 days)

## Mars Science Laboratory (2011)



- Battery specific energy: 104 Wh/kg
- Operating on Mars since Aug. 2012

## Mars InSight Mission (2011)



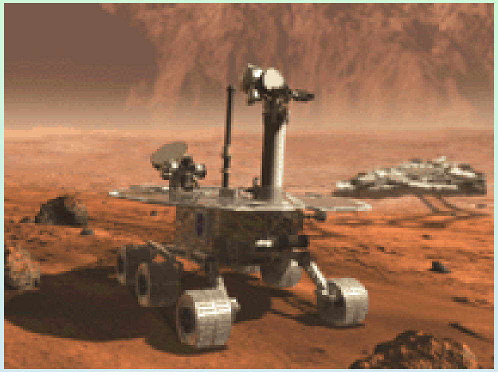
- Battery specific energy: 115 Wh/kg
- Operating on Mars since Nov. 2018

# Characteristics of State-of-Practice (SOP) Rechargeable Batteries

| Technology | Cell Type | Mission | Battery Specific Energy at +20°C (Wh/kg) | Battery Energy Density at +20°C (Wh/L) | Operating Temperature Range (°C) | Design Life (Years) | Cycle Life (Partial DOD) (Design) | Cycle Life (Partial DOD) (Actual) | Chemistry |
|---|---|---|---|---|---|---|---|---|---|
| Li-Ion | Large Cell (NCO Based) | MER | 90 | 225 | -20°C to +30°C | 2 | > 90 (Design) | > 5,000 (Actual) | MCMB-$LiNiCoO_2$ (NCO) |
| Li-Ion | Large Cell (NCO Based) | MSL | 104 | 250 | -20°C to +30°C | 3 | > 686 (Design) | > 3,000 (Operational) | MCMB-$LiNiCoO_2$ (NCO) |
| Li-Ion | Large Cell (NCO Based) | Phoenix | 112 | Not Optimized | -20°C to +30°C | 2 | > 90 (Design) | > 150 (Actual) | MCMB-$LiNiCoO_2$ (NCO) |
| Li-Ion | Large Cell (NCA Based) | InSight | 125 | Not Optimized | -30°C to +35°C | 3 | > 686 (Design) | > 832 (Operational) | Graphite-$LiNiCoAlO_2$ (NCA) Low Temp Electrolyte |
| Li-Ion | Large Cell (NCA Based) | Mars 2020 | 115 | 275 | -20°C to +30°C | 4 | > 1,003 (Design) | > 39 (Operational) | Graphite-$LiNiCoAlO_2$ (NCA) Heritage Electrolyte |

- **Secondary batteries are required that can survive over wider temperature range.**
- **High specific energy is desired over the range of temperatures.**

# 2003 Mars Exploration Rover- Rover Batteries

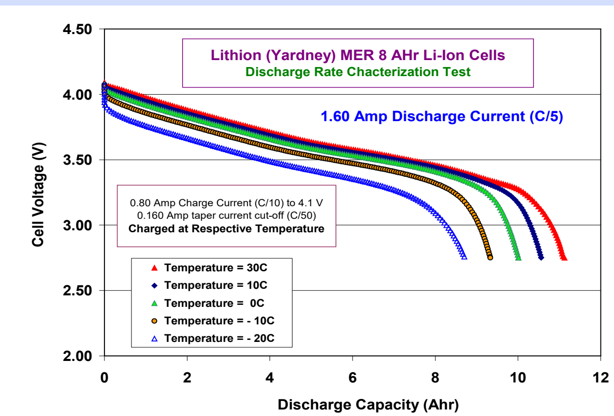


- **Lithium-ion technology was used for '03 MER Rovers**
- **Heritage chemistry, including electrolyte, adopted from MSP'01**
- **Opportunity operated for 14 years after landing on Mars in 2004**

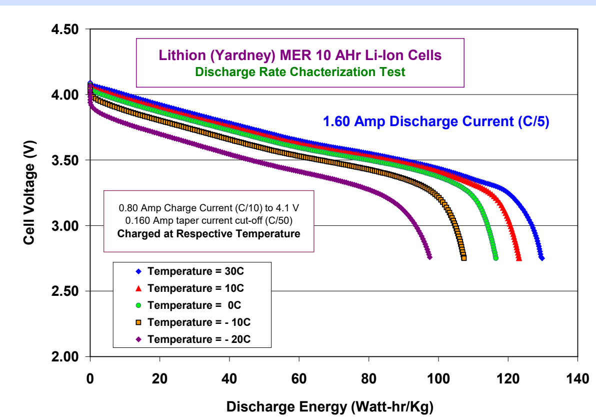
## Rover Battery Requirements

- Voltage : 32-24 V (8s2p Configuration)
- Capacity: 16 Ah (BOL) at RT and 10 Ah at –20$^{o}$C (BOL)
- Load : C/2 max at RT; Typical C/5
- Temperature : Charge at 0-25$^{o}$C and discharge >-20$^{o}$C
- Light weight and compact
- Long cycle life of over 300 cycles
- Long storage life of over 2 years

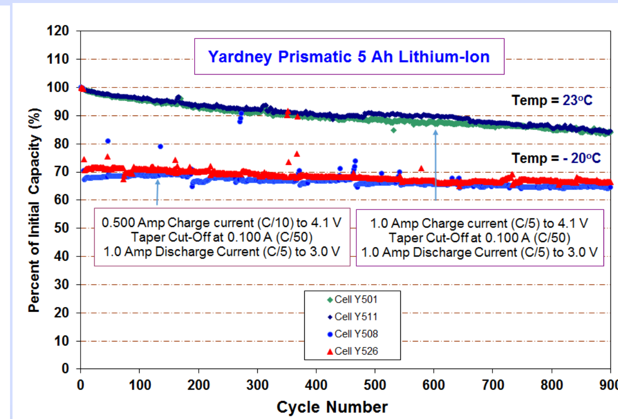
### Discharge Capacity (Ah)




### Discharge Energy (Wh/kg)




### 100% DOD Cycling Life

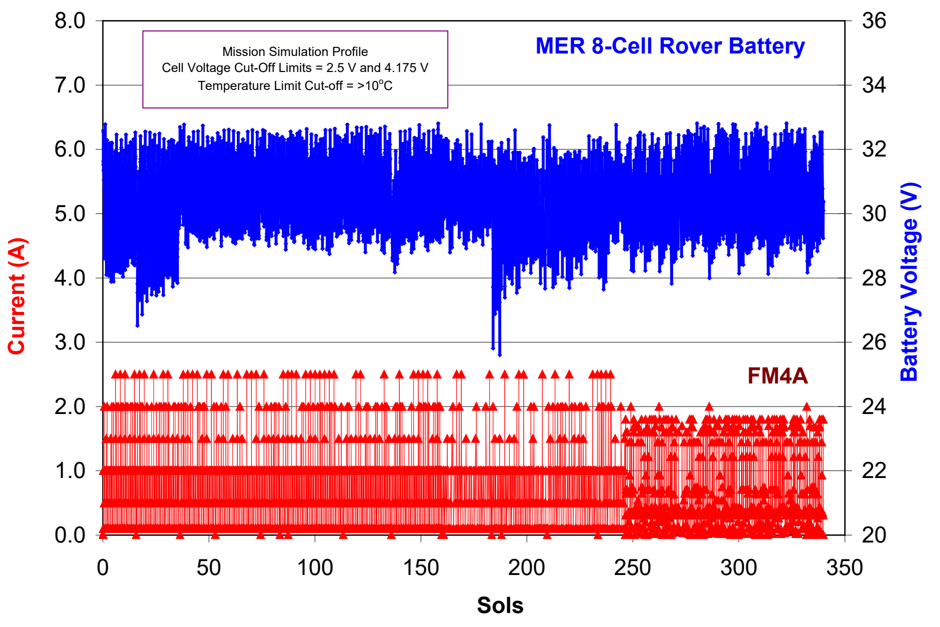


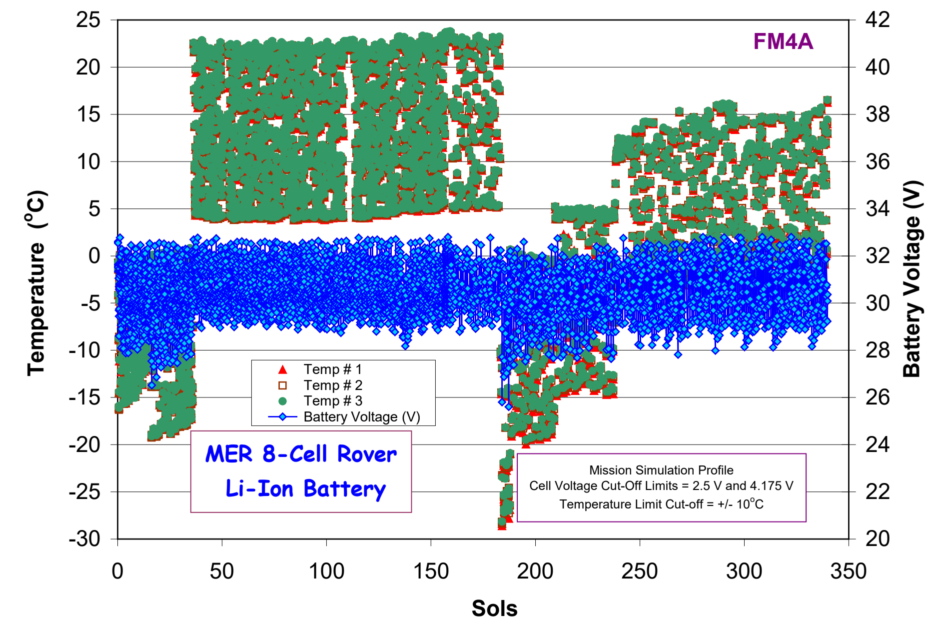

***Cells contain 1.0M $LiPF_6$ EC+DMC+DEC (1:1:1) (Range of operation –30 to +40$^{o}$C)***

# MER 10 Ah Rover Lithium-Ion Battery (FM4A)

## Mission Simulation Surface Operation Testing After Cruise

### Mission Simulation Test - (Battery Voltage, Current, and Temperature)



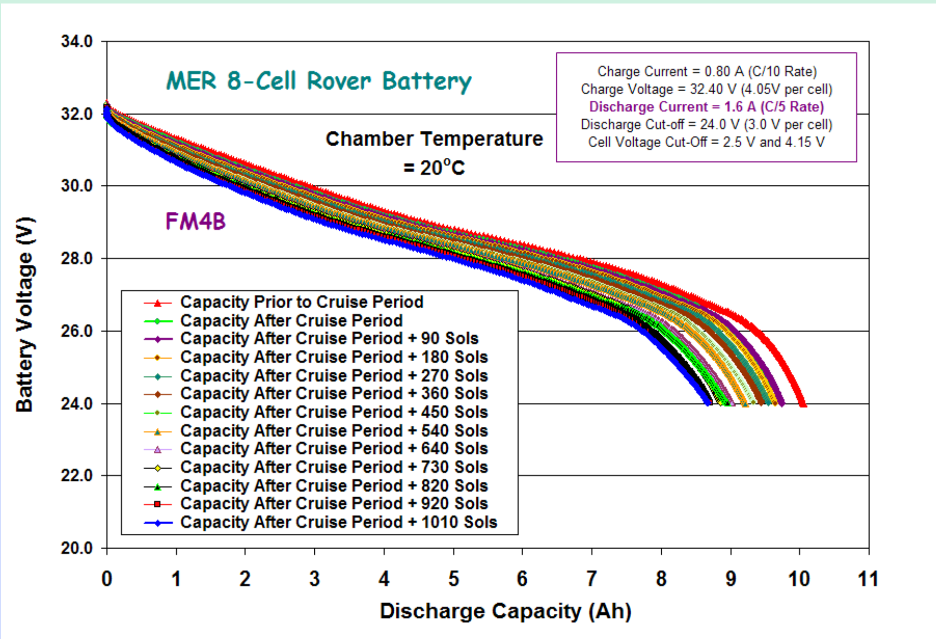

- To support the mission, a ground test battery was subjected to real-time mission simulation testing, including the long cruise period.
- The ground test battery was also subjected to dynamic thermal and electrical load profiles that mimicked the performance observed with the flight Rover batteries.

# MER 8 Ah Rover Lithium-Ion Battery (FM4B)

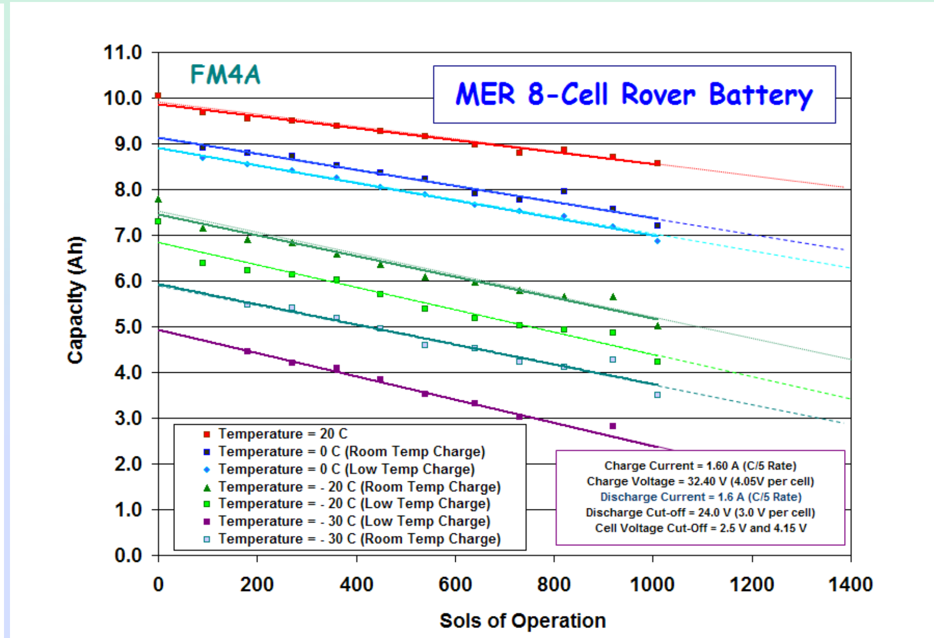
## Characterization After Cruise Period + 1010 Sols (Mission Simulation Battery)

### Observed Capacity Loss After Completing Cruise + 1010 Sols

**Capacity Determination at 20°C**




**Capacity Fade Trends**

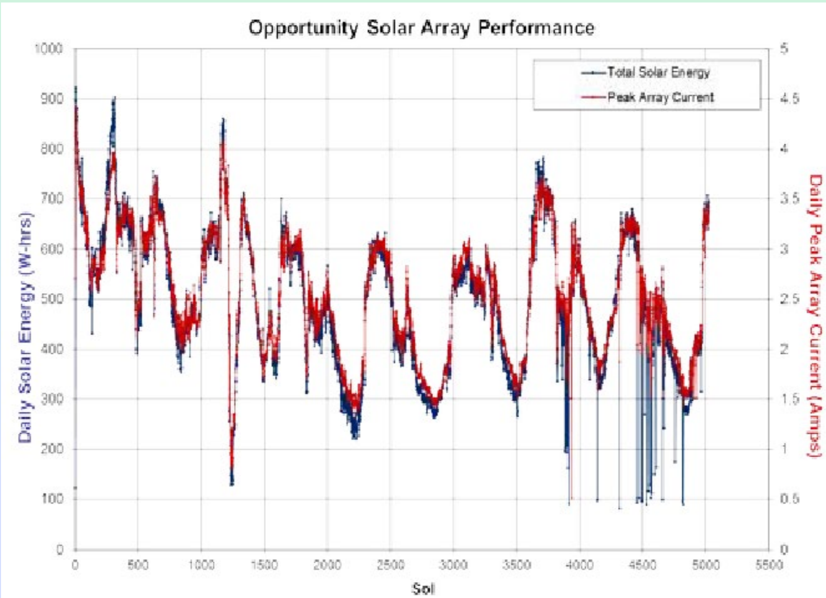



- Periodically (every 100 Sols), capacity and impedance diagnostic health checks were performed to gauge the performance degradation.
- Information was useful in assessing likelihood of supporting extended mission.
- **Approximately 14% capacity loss observed at 20°C after > 5.00 years of testing.**
- The batteries on the Rovers were determined to display less dramatic degradation, due to milder depth of discharge (DOD) and the moderate temperature environments. In addition, the diagnostic checks themselves add some additional degradation.

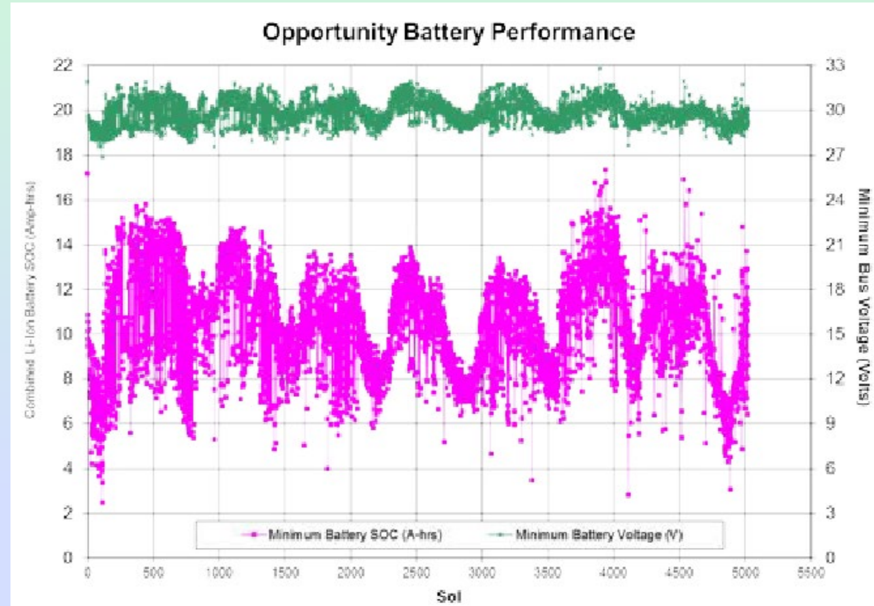
# Mars Exploration Rover- Opportunity

## Mission Telemetry Data

### Solar Array Performance




### Battery Performance




- Opportunity operated on the surface of Mars for over fourteen years until it stopped communicating on June 10, 2018.
- By this time, the rover had been operational for 5,111 sols, representing 57 times longer than the design requirement of 90 sols of operation.
- During its mission, the Opportunity Rover supported a similar cycle life profile compared to Spirit, with approximately a 44-50% DOD duty cycle.
- In total, from the initial acceptance testing to the mission ending in 2018, the wet life of the battery exceeded 16 years and completed over 5,000 cycles over a wide temperature range setting a record for the longest operation on the surface of Mars.

# NASA's Mars Phoenix Lander

- **After the success of the Mars Pathfinder mission, NASA launched the Phoenix Mars Mission on August 04, 2007, which landed on the planet in May 2008 in the Martian north polar region**
- **The Phoenix Mars Mission was the first in NASA's "Scout Program" which were relatively low-cost (i.e., < $500M) innovative missions that relied on legacy hardware.**
- **Toward this end, the Phoenix Mission utilized the Mars Surveyor 2001 Lander built in 2000 by Lockheed Martin that included the Li-ion battery designed and qualified by Yardney Technical Products, Inc.**
- **The goal of this mission was to study the history of water in the Martian arctic's ice rich soil and the potential of the habitability of life.**
- **The Phoenix Lander completed its three-month mission and met the primary objectives and operated for an additional two months prior to becoming inoperable due the reduced sunlight associated the winter leading to insufficient energy to power the spacecraft.**

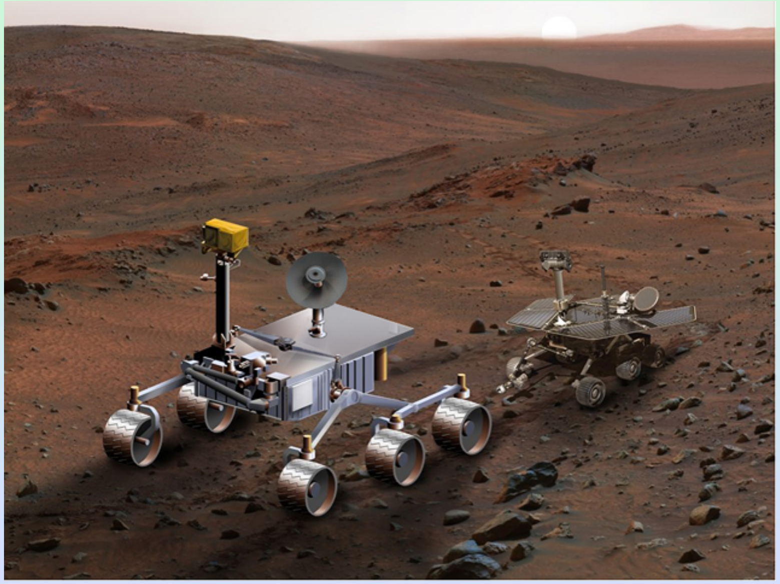
- Two 8-cell batteries (connected in parallel)
- Large capacity prismatic cells (25 Ah nameplate)
- 24-32.8 V (MSP'01 Battery Design)
- Qualification Temperature range: - 30$^{o}$C to +40$^{o}$C.
- **Operating Temperature Range: -20$^{o}$ to +30$^{o}$C**
- **Required Life: ~ 2 years**
- **Surface Life: Three months of operation.**
- **Fabricated by Yardney Technical Products, Inc.**

# 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 3013 Sols to-date**
  - After 8 years and almost 24 km of driving, Curiosity had reached the base of Mount Sharp and beyond.
  - 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 3000, Curiosity had driven 15 miles (or 24 kilometers).**



## Battery Details

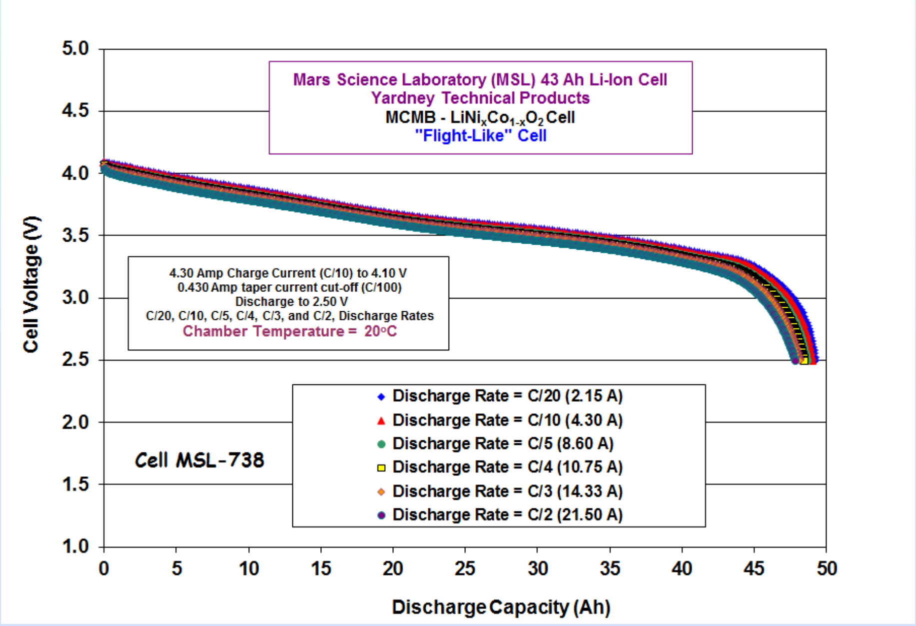
- Two 8-cell batteries in parallel (8s2p).
- 24-32.8 V, 86 Ah (MER, Grail, Juno Chemistry)
- Qualification Temperature range: -30$^{o}$ to +40$^{o}$C.
- Operating Temperature Range: -20$^{o}$ to +30$^{o}$C
- **Required Life: ~ 4 years**
- **Surface Design Life: 670 Sols of operation.**
- Battery temperature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

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

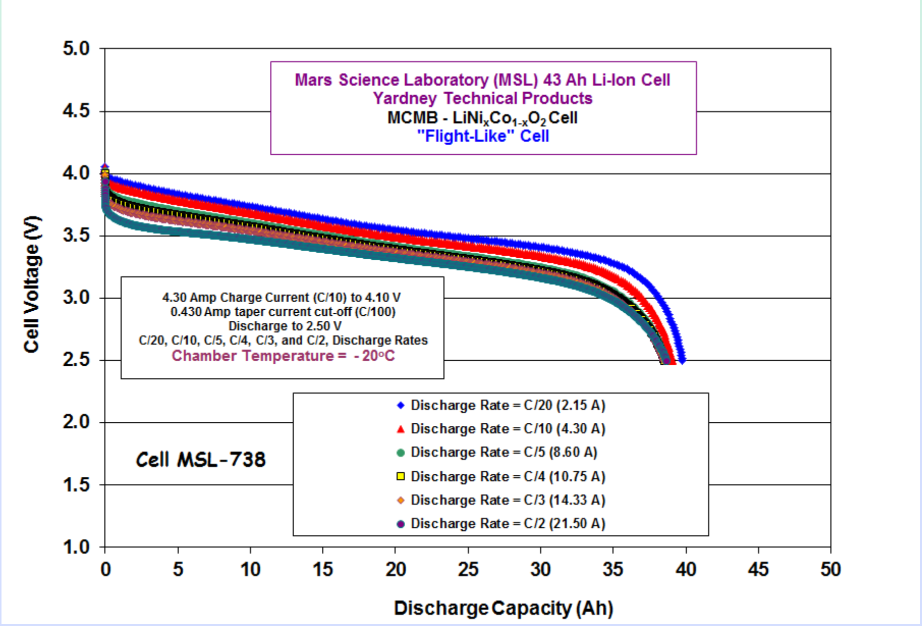
## Discharge Rate Characterization Testing at 20°C and -20°C

### Cell MSL-738– Discharge Capacity (Ah)

**Temperature = +20°C**




**Temperature = - 20°C**




| | | | Cell MSL- 738 | | | | | Cell MSL- 757 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | Discharge Rate | Discharge Current (A) | Discharge Capacity (Ah) | Percent C/20 Capacity | Percent C/20 Capacity at 20°C | Discharge Watt-Hr (Wh) | Discharge Energy (Wh/Kg) | Discharge Capacity (Ah) | Percent C/20 Capacity | Percent C/20 Capacity at 20°C | Discharge Watt-Hr (Wh) | Discharge Energy (Wh/Kg) |
| 20°C | C/20 | 2.150 | 49.2061 | 100.00 | 100.00 | 177.756 | 148.97 | 48.9692 | 100.00 | 100.00 | 176.858 | 148.02 |
| | C/10 | 4.300 | 48.9989 | 99.58 | 99.58 | 176.543 | 147.96 | 48.7904 | 99.63 | 99.63 | 175.742 | 147.09 |
| | C/5 | 8.600 | 48.6170 | 98.80 | 98.80 | 174.244 | 146.03 | 48.3960 | 98.83 | 98.83 | 173.357 | 145.09 |
| | C/4 | 10.75 | 48.4333 | 98.43 | 98.43 | 173.141 | 145.11 | 48.2208 | 98.47 | 98.47 | 172.275 | 144.19 |
| | C/3 | 14.33 | 48.1604 | 97.87 | 97.87 | 171.458 | 143.70 | 47.9510 | 97.92 | 97.92 | 170.588 | 142.78 |
| | C/2 | 21.50 | 47.7824 | 97.11 | 97.11 | 168.820 | 141.49 | 47.5403 | 97.08 | 97.08 | 167.806 | 140.45 |

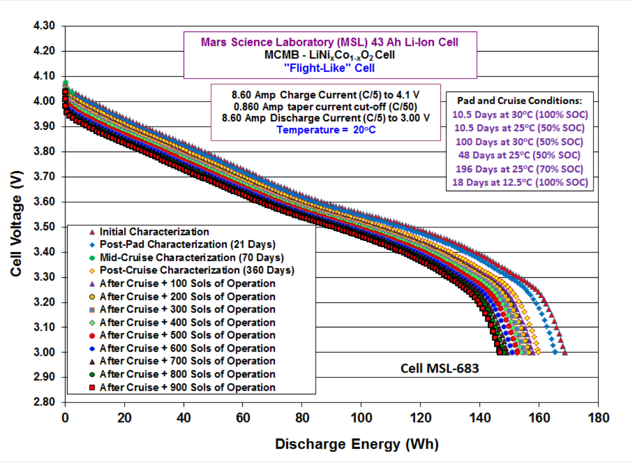
| | | | Cell MSL- 738 | | | | | Cell MSL- 757 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | Discharge Rate | Discharge Current (A) | Discharge Capacity (Ah) | Percent C/20 Capacity | Percent C/20 Capacity at 20°C | Discharge Watt-Hr (Wh) | Discharge Energy (Wh/Kg) | Discharge Capacity (Ah) | Percent C/20 Capacity | Percent C/20 Capacity at 20°C | Discharge Watt-Hr (Wh) | Discharge Energy (Wh/Kg) |
| - 20°C | C/20 | 2.150 | 39.7706 | 100.00 | 80.82 | 140.857 | 118.05 | 39.8947 | 100.00 | 81.47 | 141.401 | 118.35 |
| | C/10 | 4.300 | 39.0600 | 98.21 | 79.38 | 136.220 | 114.16 | 39.2206 | 98.31 | 80.09 | 136.951 | 114.62 |
| | C/5 | 8.600 | 38.5709 | 96.98 | 78.39 | 131.578 | 110.27 | 38.7713 | 97.18 | 79.17 | 132.541 | 110.93 |
| | C/4 | 10.75 | 38.5001 | 96.81 | 78.24 | 130.386 | 109.27 | 38.7282 | 97.08 | 79.09 | 131.468 | 110.03 |
| | C/3 | 14.33 | 38.4872 | 96.77 | 78.22 | 129.076 | 108.18 | 38.7479 | 97.13 | 79.13 | 130.282 | 109.04 |
| | C/2 | 21.50 | 38.6546 | 97.19 | 78.56 | 127.644 | 106.98 | 38.9490 | 97.63 | 79.54 | 128.972 | 107.94 |

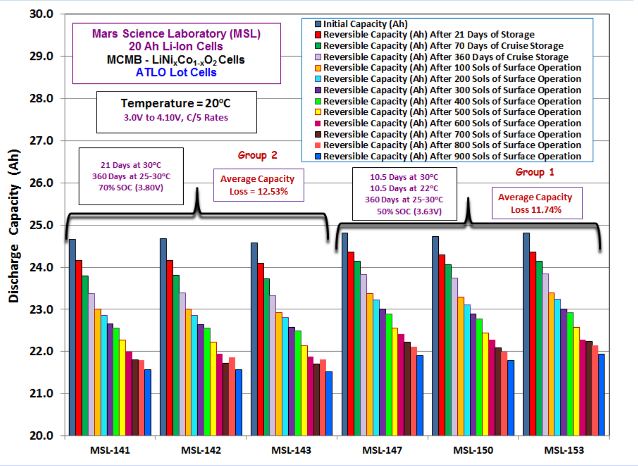
# Performance Testing of Yardney MSL 20 Ah Li-Ion Cells

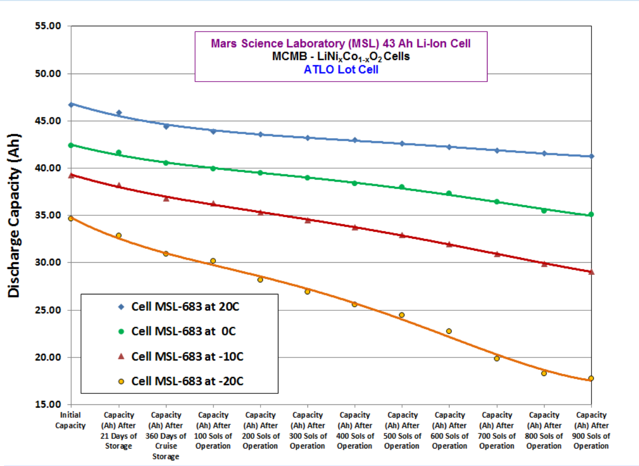
## Mission Simulation Testing

- After completing the cruise simulation and characterization, a number of cells were subjected to surface operation mission simulation testing. Cells were subjected to varying pad storage and cruise storage to quantify degradation.

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



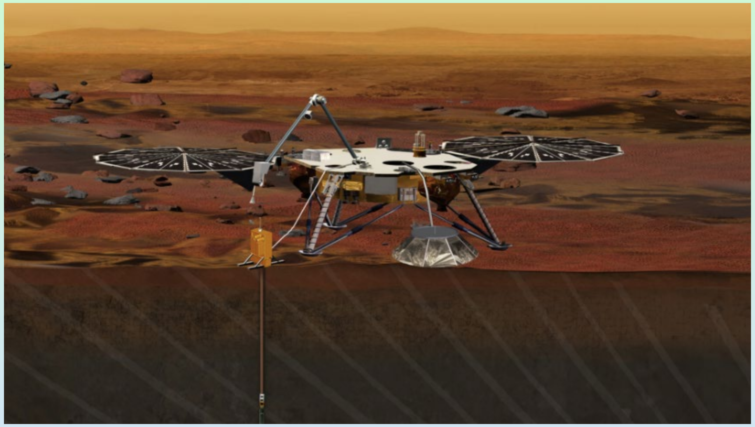




M. C. Smart, B. V. Ratnakumar, F. C. Krause, L. D. Whitcanack, E. A. Dewell, S. F. Dawson, R. B. Shaw, S. Santee, F. J. Puglia, A. Buonanno, C. Deroy, and R. Gitzendanner, "Performance Testing of Yardney Li-ion Cells in Support of NASA's MSL and InSight Missions", NASA Aerospace Battery Workshop, Huntsville, Alabama, November 17-19, 2015.

# NASA's Mars InSight Lander

- **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 investigates the processes that shaped the rocky planets of the inner solar system more than four billion years ago
  - InSight will attempt to probe beneath the surface of Mars, detecting the fingerprints of the processes of terrestrial planet formation
- **The mission was initially delayed ~ 2 years to allow the repair of a leak in a section of the prime instrument in the science payload.**
- **The InSight mission was launched successfully on May 5, 2018 and it landed on November 26, 2018 on Elysium Planitia, Mars**
- **On April 23, 2019, InSight detected the first likely Quake on Mars.**
- **InSight has been successfully operating for over 260 Sols to date.**



## Battery Details

- Two 8-cell batteries (connected in parallel)
- Large capacity prismatic cells (25 Ah nameplate)
- 24-32.8 V (Phoenix Battery Design)
- Qualification Temperature range: - 40$^{o}$C to +50$^{o}$C.
- **Operating Temperature Range: -30$^{o}$ to +35$^{o}$C**
- **Required Life: ~ 4 years**
- **Surface Life: 709 Sols of operation.**
- **Fabricated by Yardney Technical Products, Inc**

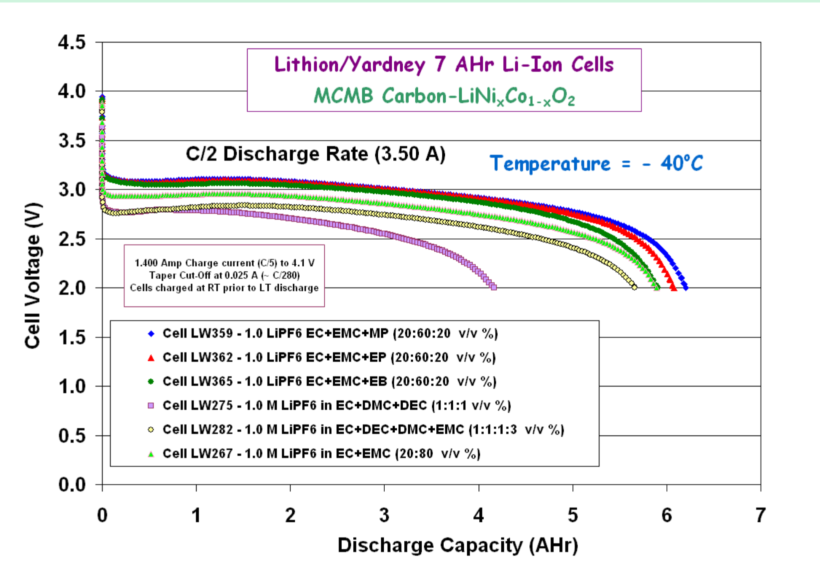
***Battery Contains the Next Generation JPL Low Temperature Electrolyte:***

***1.0M $LiPF_6$ EC+EMC+MP (20:60:20 v/v %) (Range of operation –30 to +35$^{o}$C)***

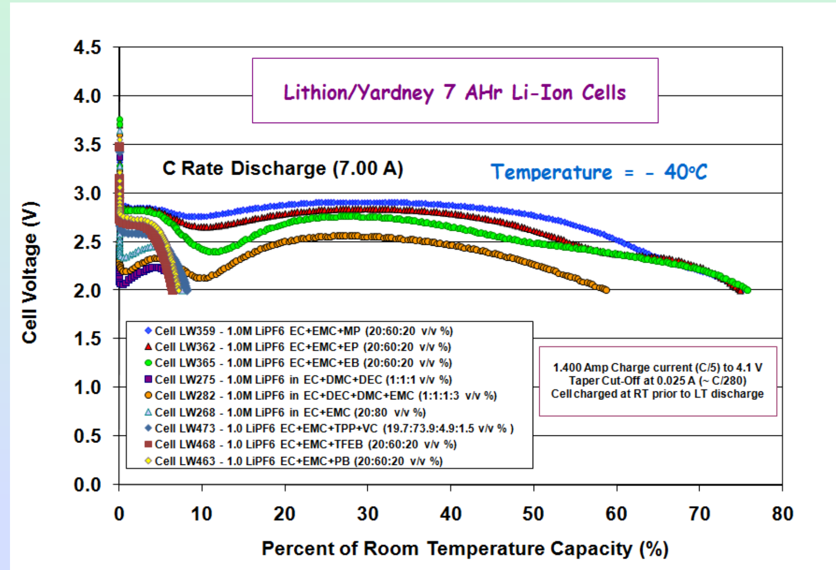
# Development of Advanced Low Temperature Electrolytes

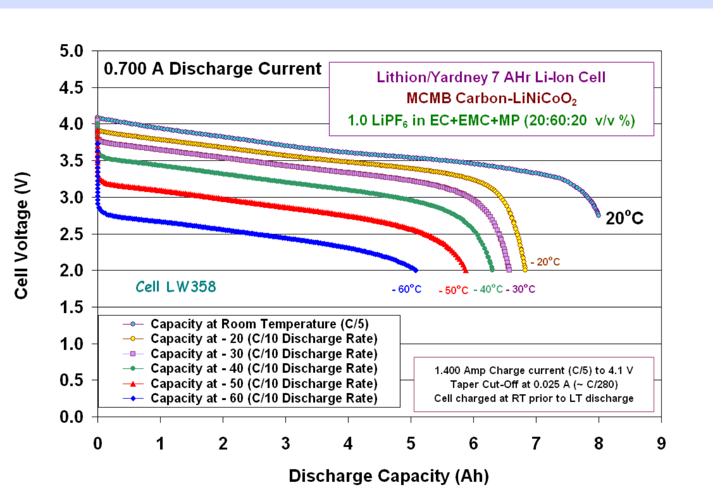
# Demonstration of Ester-Based Electrolytes in Yardney Prototype Cells

### Performance at -40°C (C/2 Rate)




### Performance at -40°C (C Rate)



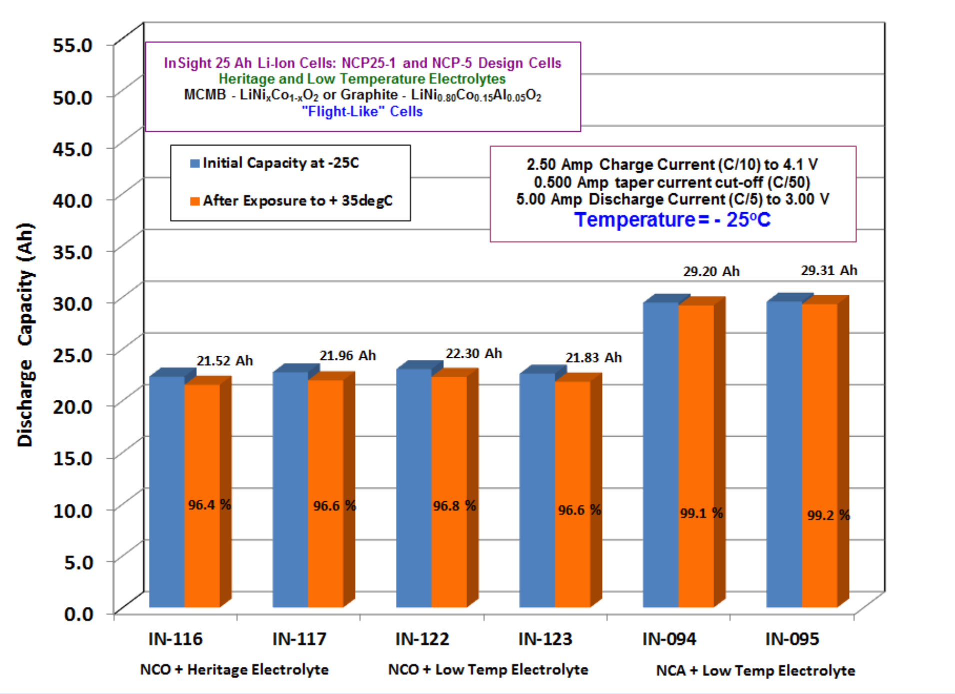

***An electrolyte formulation containing methyl propionate, 1.0M LiPF$_6$ EC+EMC+MP (20:60:20 v/v %) was demonstrated to provide improved low temperature performance over baseline all carbonate-based electrolytes (including the heritage blend), while still providing reasonable high temperature resilience.***

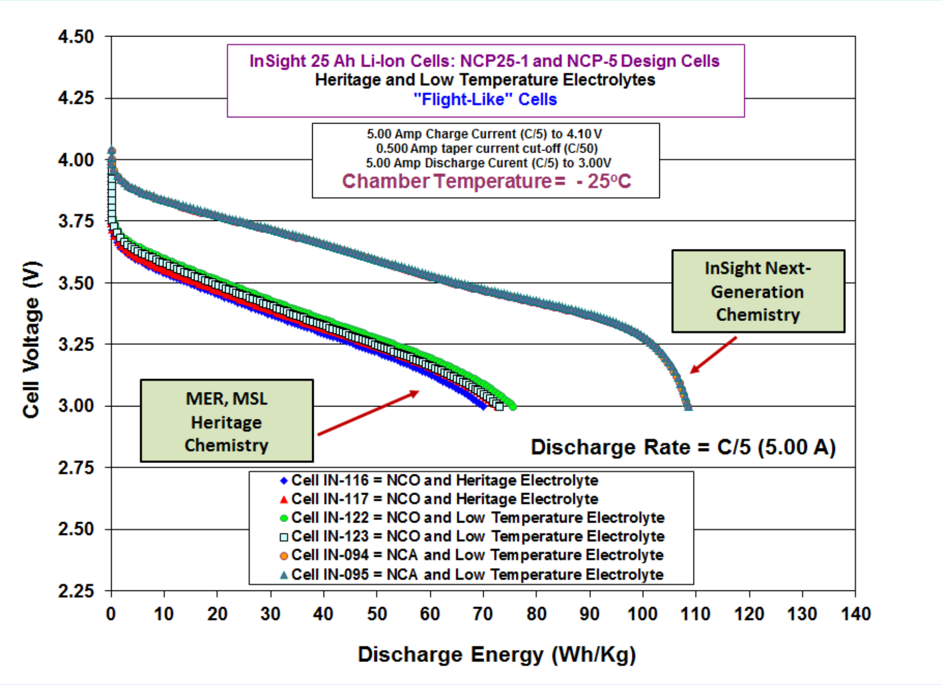

- M.C. Smart, and B.V. Ratnakumar, L.D. Whitcanack, K.A. Smith, S. Santee, R. Gitzendanner, V. Yevoli, "Li-Ion Electrolytes Containing Ester Co-Solvents for Wide Operating Temperature Range", *ECS Trans.* **11**, (29) 99 (2008).
- M. C. Smart, B. V. Ratnakumar, K. B. Chin, and L. D. Whitcanack, "Lithium-Ion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

# Results of InSight Cell Testing

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

### Comparison of Different Chemistries



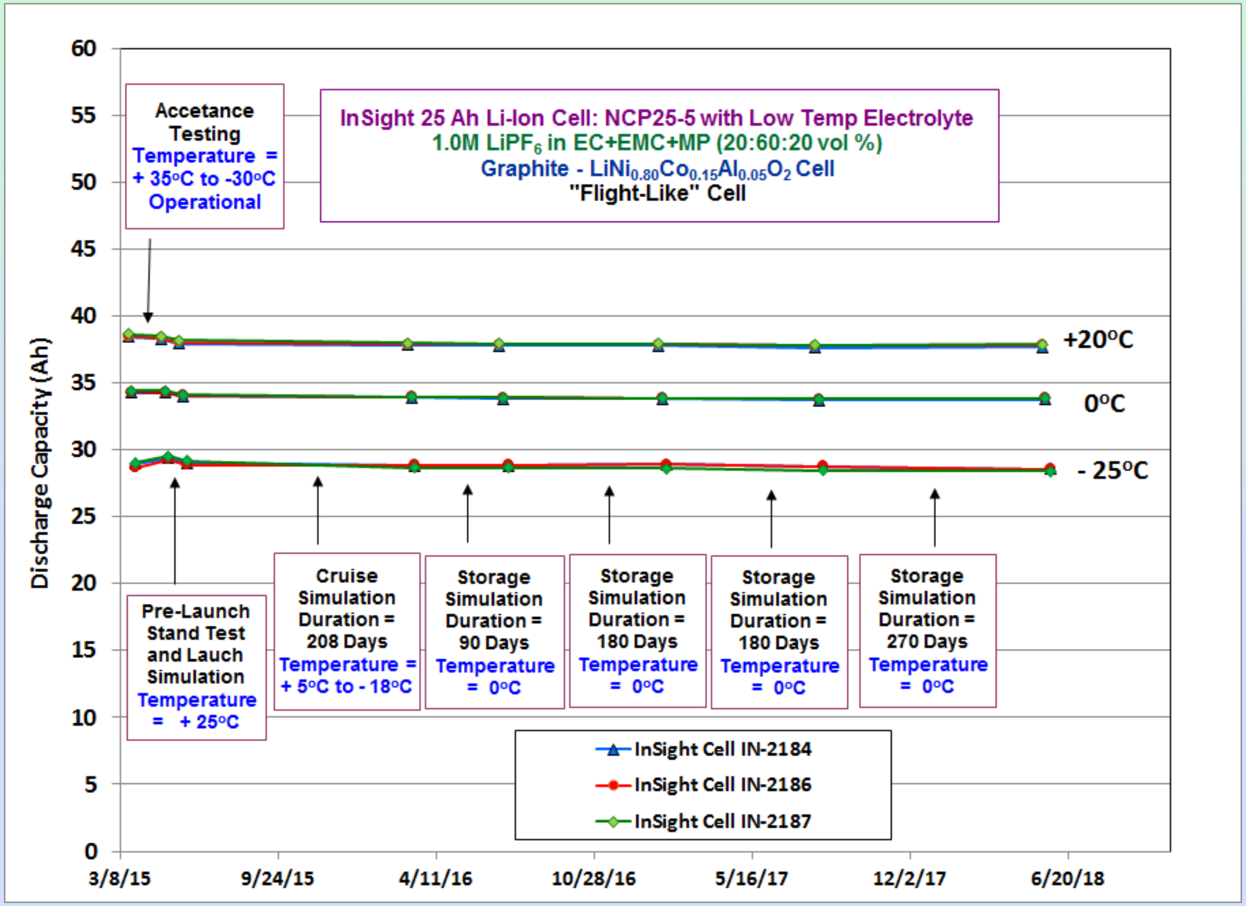




- Cells with NCA and Low Temperature Electrolyte deliver 31% more capacity at -25°C compared with heritage chemistry and display much higher operating voltage throughout the discharge.
- The NCA-based cells display enhanced resilience to high temperatures.


M.C. Smart, D. Muthulingam, M. E. Lisano, S. F. Dawson, R. B Shaw, B. T. White, A. Buonanno, C. Deroy and R. Gitzendanner ,
"The Use of Low Temperature Lithium-ion Batteries to Enable the NASA InSight Mission on Mars",
*236th Meeting of the Electrochemical Society, Atlanta, Georgia, October 15, 2019*

# Performance Testing of InSight Yardney Li-Ion Cells

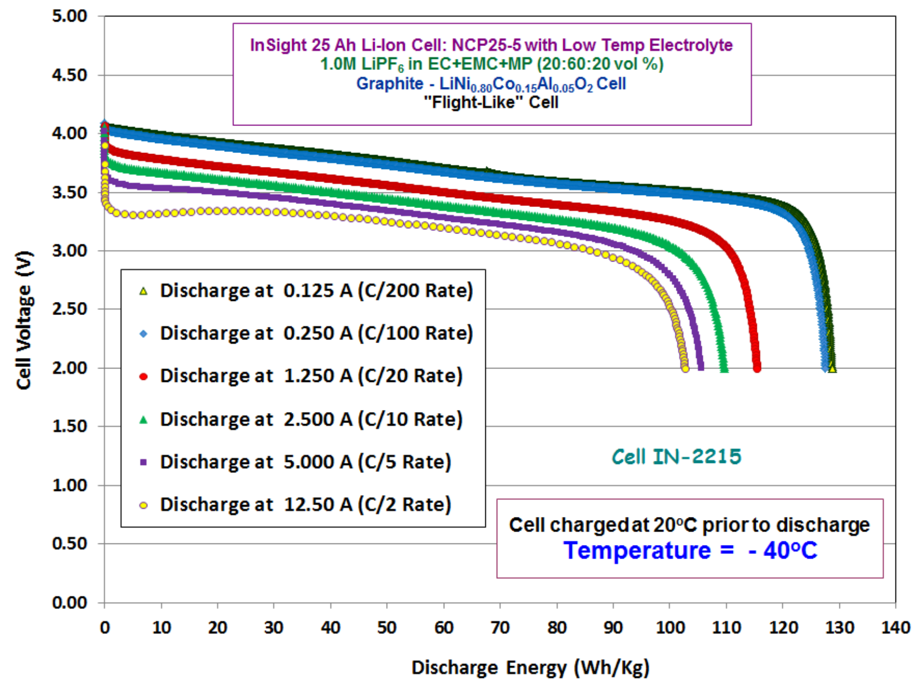
## Status of Group 5 Cell Testing

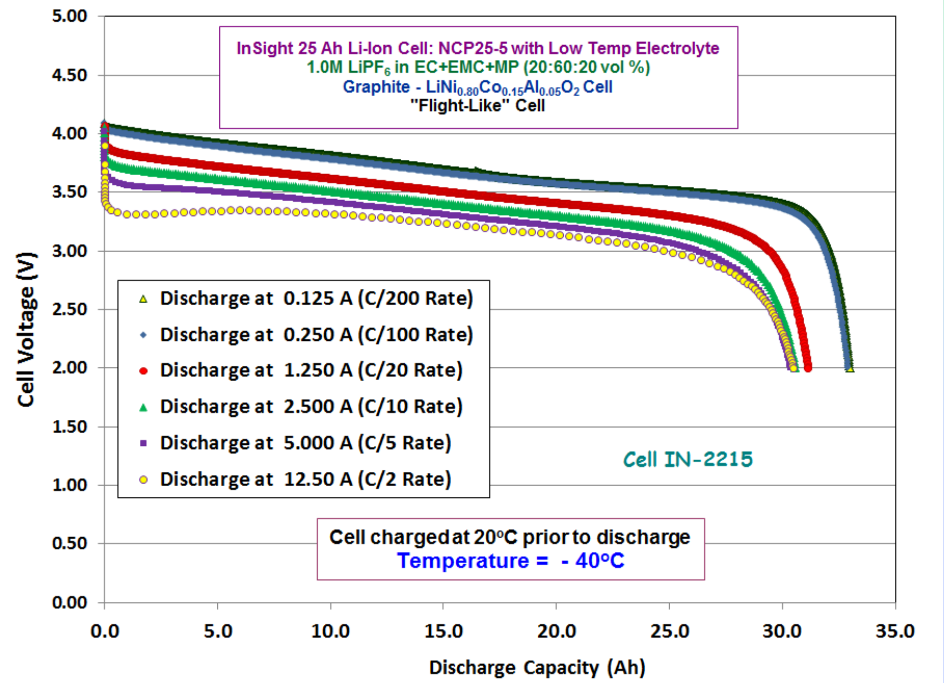



- ***Flight-like mission simulation cells were tested to determine BOM performance.***
- ***After being subjected to acceptance testing, long term cruise simulation, and 24 months of post-cruise storage, only 2.0 % capacity loss or less was observed at all three temperatures.***

# Performance Testing of InSight Yardney NCP-25-6 Cells

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



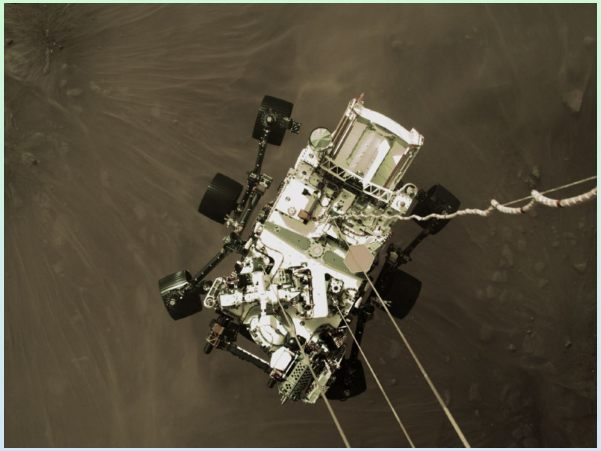




- The next generation InSight chemistry containing the MP-based low temperature electrolytes delivers good rate capability at -40°C , delivering over 102 Wh/kg at a C/2 rate (or 12.50A).
- Demonstrates that technology is well suited to support high power transmission events.

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.

# NASA's Mars 2020 Perseverance Rover

- **One key objective of the Mars Perseverance Rover is study the astrobiology of the planet and to search for signs of ancient microbial life.**
- **The rover will also study the geology of Mars and the past climate.**
- **It will also be the first mission to Mars in which rock and regolith samples are collected for return to Earth with the assistance of a future retrieval (or "Sample Return") mission.**
- **The rover also carries a Mars Helicopter named "Ingenuity", that will serve as a technology demonstration.**
- **Science Instruments On-Board**:.
  - Mars Environmental Dynamics Analyzer (MEDA)
  - Mastcam-Z (advanced camera system)
  - Planetary Instrument X-ray Lithochemistry (PIXL)
  - Scanning Habitable Environments with Raman &
  - Luminescence for Organics and Chemicals (SHERLOC)
  - Mars Environmental Dynamics Analyzer (MEDA)
  - The Radar Imager for Mars' Subsurface Experiment (RIMFAX),
- **The Mars 2020 mission was launched successfully on July 30, 2020 and it landed on February 18, 2021 in Jezero Crater, Mars.**



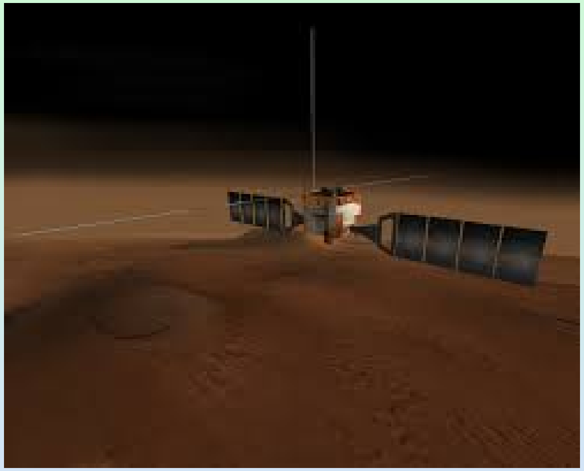
## Battery Details

- Two 8-cell batteries (connected in parallel)
- Large capacity prismatic cells (43 Ah nameplate)
- 24-32.8 V (MSL Battery Design)
- Qualification Temperature range: - 30$^{o}$C to +40$^{o}$C.
- **Operating Temperature Range: -20$^{o}$ to +30$^{o}$C**
- **Required Life: ~ 4 years**
- **Surface Life: 1,003 Sols of operation.**
- **Fabricated by Eagle Picher Technologies, Inc.,**

***Battery Contains the Next Generation NCA-Based Chemistry and the JPL Low Temperature Heritage Electrolyte: 1.0M $LiPF_6$ in EC+DEC+DMC (1:1:1 v/v %)***

# Mars Express

- Mars Express is a mission that is being conducted by the European Space Agency (ESA) to explore the planet Mars.
- The mission was launched on June 2, 2003 and has been in operation orbiting Mars for over 17 years.
- The Mars Express mission represents the second longest surviving active spacecraft orbiting around another planetary body other than Earth, only being surpassed by the 2001 Mars Odyssey
- The Mars Express mission holds the record for the longest surviving mission with Li-ion batteries in planetary exploration.
- As of 2017, the battery had entered the 16th eclipse season and by 2015 had completed over 33,600 cycles, with the majority (26,409 cycles) being very shallow depth of discharge (i.e., less than 0.25 Wh).
- Each battery is connected to a separate battery charge-discharge regulator.

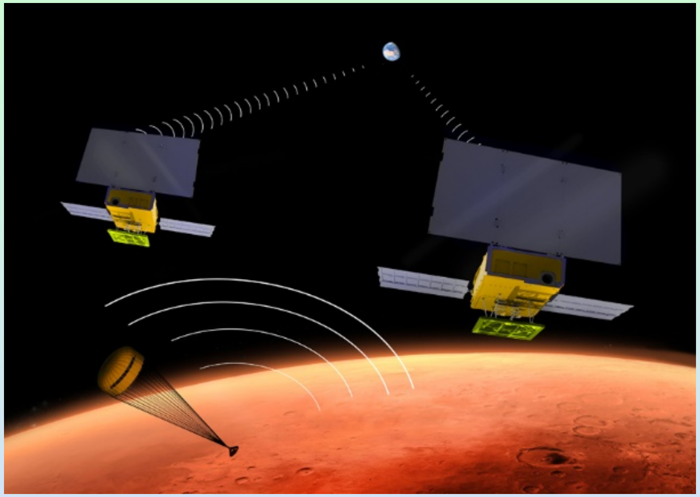


## Battery Details

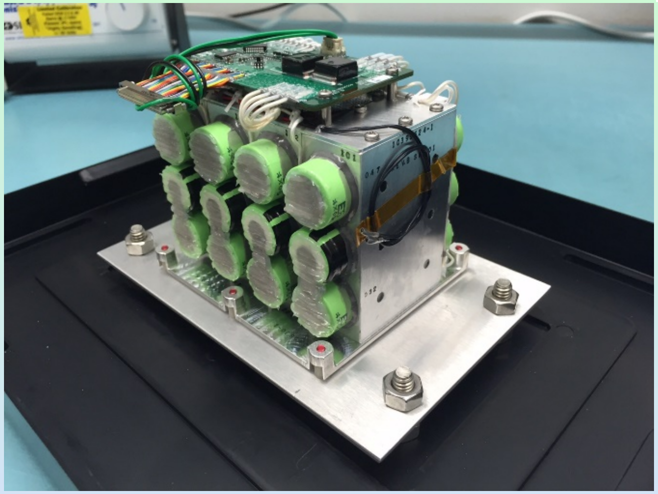
- Three identical 6s16p modules
- Small COTS 18650-size Sony HC Li-ion cells
- 67.5 Ah Nameplate Capacity
- **Required Life: ~ 4 year mission**
- **Operational Life: > 17 years**
- **Fabricated by ABSL (UK)**


- D. Z. Genc and C. Thwaite, "Proba-1 And Mars Express: An ABSL Lithium-Ion Legacy," Proceedings of the 9th European Space Power Conference, held 6-10 June 2011 at Saint Raphael, France. ESA SP, Vol. 690.
- G. Dudley, R. Blake, and L. Lucas, Mars Express Lithium Ion Batteries Performance Analysis", E3S Web of Conferences, 16, 06002 (2017).

# Mars Cube One (MarCO) on InSight



**MarCO (6U CubeSat) successfully demonstrated in Nov. 2018**



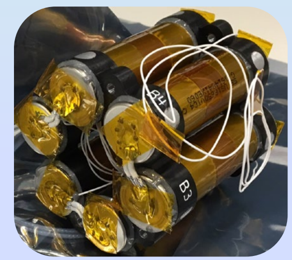
**MarCO battery pack**

- CubeSats are much smaller spacecraft (1U = 10 cm x 10 cm x 10 cm and 1-2 kg)
- The twin communications-relay CubeSats, constitute a technology demonstration called Mars Cube One (MarCO) on InSight.
    - A Technology Demonstration of communications relay system for mission-critical events (i.e., for the 2018 InSight entry, descent, & landing (EDL)).
- The basic CubeSat unit is a box roughly 4" square.
- MarCO's design is a six-unit CubeSat, with a stowed size of about 14.4" x 9.5" X 4.6"
- Battery consisted of Panasonic NCR-B 18650 Li-ion cells in 3s4p configuration.
- *Both MarCO-A and MarCO-B succeeded in a flyby of Mars, relaying data to Earth from Insight as it landed on Mars.*

F. C. Krause, J. A. Loveland, J. M. Steinkraus, M. C. Smart, E. J. Brandon, and R. V. Bugga, "Implementation of Commercial Li-ion Cells on the MarCO Deep Space CubeSats", *Journal of Power Sources*, **449**, 227544 (2020).

# Description of Currently Planned Li-Ion Battery for Mars Helicopter "Ingenuity" Technology Demonstration

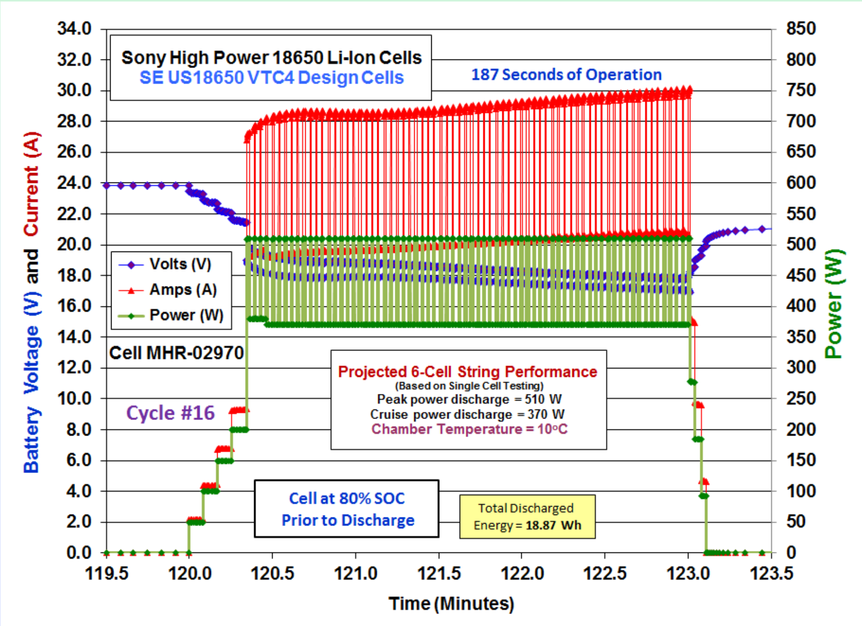
- **Description of Li-Ion Battery for Mars Helicopter Ingenuity:**
  - **Battery consists of six (6) Sony SE US18650 VTC4 Li-ion Cells**
  - **Cell Nameplate Capacity = 2.00 Ah**
  - **Cell Maximum Discharge Rate = >25 Amps**
  - **Cell Manufacturer Maximum Charge Voltage = 4.25V**
- **Architecture consists of 6 cells connected in series (nominal 15.00V – 25.20V)**
  - **Continuous power load capability= 60 W x 6 cells = 360 W**
  - **Peak power capability= 85 W x 6 cells = 510 W**
  - **Estimated BOL battery energy at 25°C = 44.4 Wh**
  - **Estimated BOL battery energy at 0°C = 38.8 Wh**
  - **Maximum Charge Voltage = 25.20V (or 4.20V per cell)**
  - **Estimated cell mass = 45.5g x 6 cells = 273g**
  - **Cell balancing charge management present in architecture**
  - **Operational Allowable Flight Temperature (AFT) Range=0°C to 25°C**
    - **Temperature of the interface prior to discharge**
    - **Operational Allowable Survival Temperature (AFT) Range = - 15°C to 25°C**
  - **Non-Operational Allowable Flight Temperature (AFT) Range = - 20°C to 45°C**
    - **Temperature range applies to cruise period**
    - **Cells will be maintained at a low SOC during cruise (20-50% SOC)**

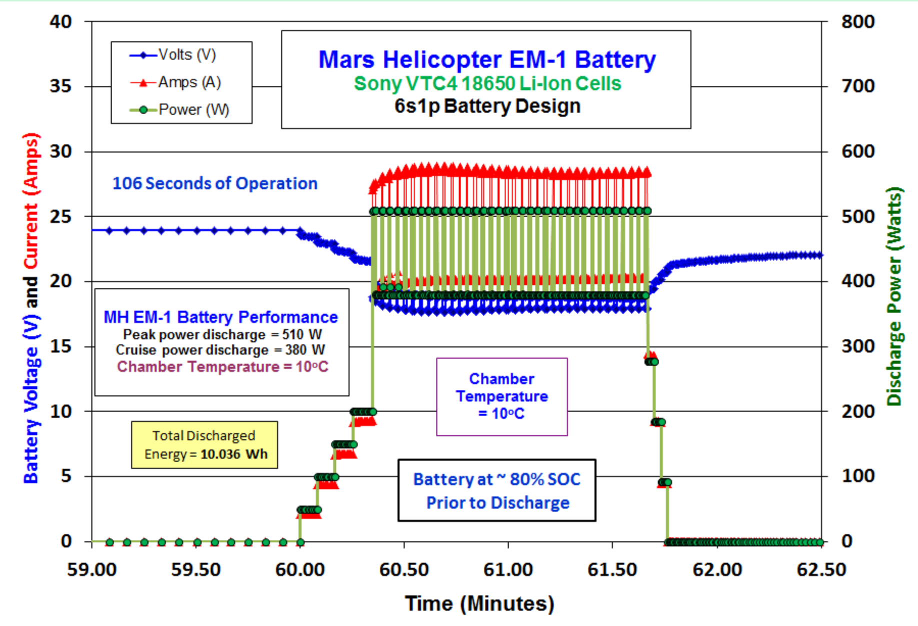


M. C. Smart, F. C. Krause, J. P. Jones, B. V. Ratnakumar, A. Lawrence, E. Brandon, B. Burns, G. A. Carr, J. Balaram, M. Aung, and A. Ulloa-Severino, "The Performance Evaluation of 18650-Size Lithium-Ion Cells and Batteries for Future NASA Missions", Pacific Power Source Symposium 2019, Waikoloa, Hawaii, January 6, 2019.

# Performance of Sony SE US18650 VTC4 Li-ion Cells

## High Power Testing: 10°C, 80% SOC, 72 Pulses




- The Sony VTC4 cell design is capable of supporting 187 seconds of high power operation under an aggressive load profile, corresponding to 510W peak and 370W nominal power levels at the string level
- Initial Cell Temperature = 10°C
- **Maximum cell discharge current observed = 30.159A**
- **Minimum battery voltage projected = 16.905 V**

**Prototype battery demonstrated to support peak power demands.**
**Performance was confirmed on the flight battery during acceptance testing.**

M. C. Smart, F. C. Krause, J. P. Jones, B. V. Ratnakumar, A. Lawrence, E. Brandon, B. Burns, G. A. Carr, J. Balaram, M. Aung, and A. Ulloa-Severino, "The Performance Evaluation of 18650-Size Lithium-Ion Cells and Batteries for Future NASA Missions", Pacific Power Source Symposium 2019, Waikoloa, Hawaii, January 6, 2019.

# Conclusions

- **Custom large format cells have enabled a number of missions**
  - An Interagency effort helped to establish the "heritage" Li-ion chemistry.
  - Long life and wide operating temperature range provided.
  - EaglePicher/Yardney Division battery designs have been used on a number of missions to explore the solar system.
- **The design life for many missions has been dramatically exceeded**
  - The Opportunity battery wet life exceeded 16 years and completed over 5,000 cycles over a wide temperature range setting a record for the longest operation on the surface of Mars.
  - The Curiosity battery has completed over 3,000 Sols, and has driven over 15 miles (or 24 kilometers), far exceeding the 686 Sol requirement.
  - Other missions have met or exceeded requirements.
  - A number of missions are still on-going, including MSL Curiosity, InSight, and the newly landed M2020 Perseverance Rover.
- **COTS 18650 cells have also been adopted for Mars Mission.**
  - The MarCO CubeSat successfully employed Panasonic 18650 cells.
  - The Mars Helicopter Ingenuity possesses high power Sony 18650 cells.

# Acknowledgments

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