Operation of Lithium-Ion Batteries in the Extreme Environments of Mars

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Batteries in Extremely Low Temperature Environments

University of Maryland
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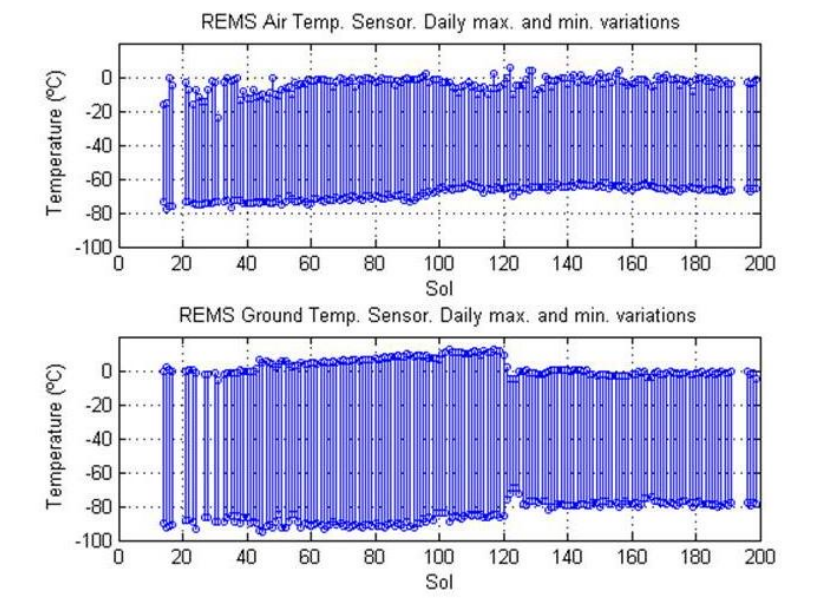
Overview

- Description of Mars Environment
- Overview of NASA Missions to Mars
- Thermal Management Approaches
- Power Operations Overview
- Low Temperature Battery Technology
  - 2003 MER Spirit and Opportunity Rovers
  - 2011 MSL Curiosity Rover
  - 2018 InSight Lander
  - 2021 M2020 Perseverance Rover & Helicopter
- Conclusions

Extreme Environment on Mars

Dusty and Cold

- Constant dust accumulation and chance of dust storms
- Depending upon the season and where the rovers land, the ground temperatures of Mars can reach -125°C and the average temperature is approximately -60°C.
- The Mars Curiosity rover, which landed in Gale Crater, measured ground temperatures as low as -90°C.
- Such extreme low temperature requires complex thermal management approaches and batteries capable of operating at low temperatures.

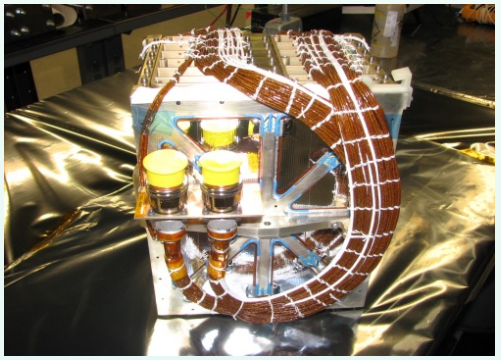


NASA Mars Landers and Rovers Using Large Cell Batteries

Mars Exploration Rovers (2003)

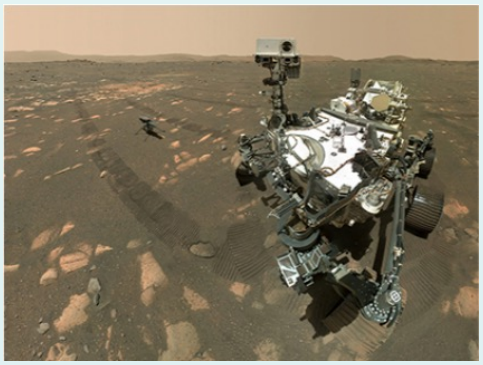

- Battery specific energy: 90 Wh/kg
- Operated on Mars 2004 – 2018

Mars Science Laboratory (2011)



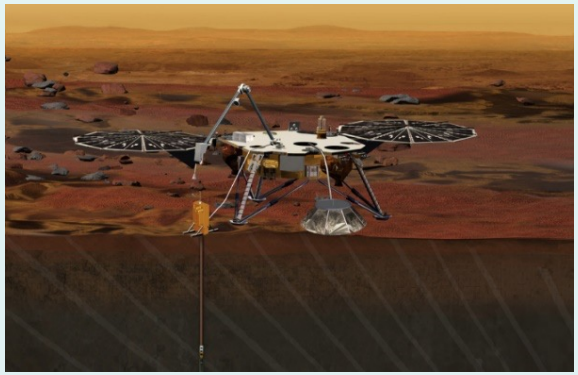

- Battery specific energy: 104 Wh/kg
- Operating on Mars since Aug. 2012

Mars 2020 Mission (2020)




- Rover Battery SE: 115 Wh/kg
- Helicopter Battery SE: 142 Wh/kg
- Operating on Mars since Feb. 2021

Mars InSight Mission (2018)



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

Extreme Environment on Mars

- Thermal Management Approaches
  - For Mars landers and rovers, the battery is contained in a Warm Electronics Box (WEB) which maintains the temperature > -20^{o}C through the use of active thermal control (i.e., battery temperature controlled with a combination of heaters and radiators).
  - For the MER Rovers, light weight Radioisotope Heater Units (RHUs) were used to heat the batteries. The power source for these rovers were photovoltaic solar arrays.
  - For the MSL and M2020 missions, a Radioisotope Thermoelectric Generator (RTG) was used as the power source. The RTGs produce excess heat that is used in the thermal management system through the use of heat pipes.
  - It is more critical to have good low temperature battery technologies on missions that utilize solar arrays.

Power Operations Overview

- The Power Operations team is responsible for the following:
  - ❑ Reviewing the power subsystem telemetry received each sol
  - ❑ Providing accurate power products and predictions for tactical mission planning
  - ❑ Generating strategic analyses and reports regarding power subsystem performance and trending
  - ❑ Testing of new flight software, ground data software and other spacecraft tool updates
  - ❑ Identifying and helping to resolve spacecraft anomalies

2003 Mars Exploration Rover- Rover Batteries

Rover Battery Requirements

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

- **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**

Cells contain 1.0M $LiPF_6$ EC+DMC+DEC (1:1:1) (Range of operation –30 to +40°C)

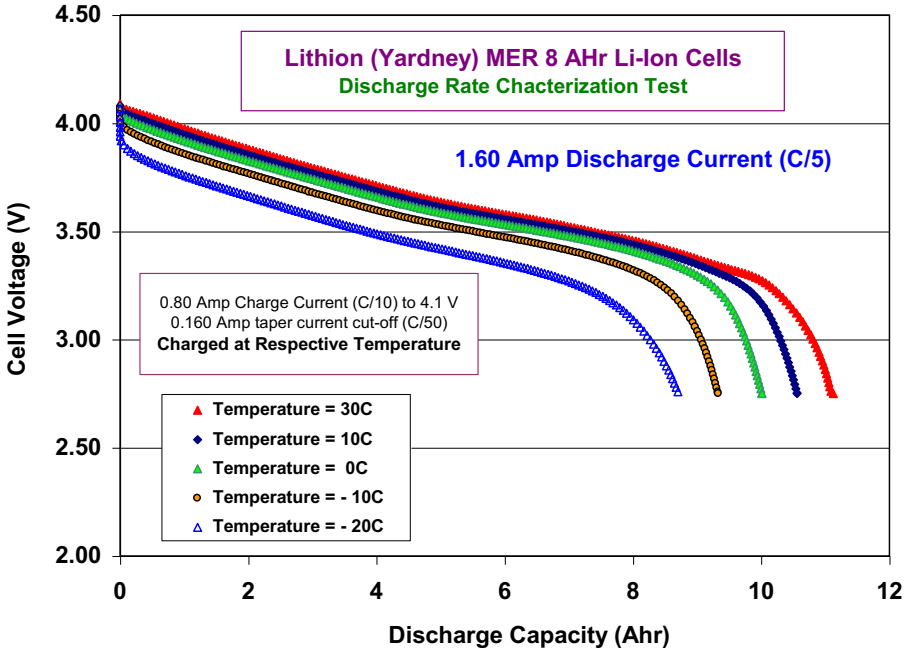
- ***Electrolyte developed at JPL in late 1990s for the MSP'01 Mission (cancelled).***
- ***Although the initial requirements limited to charging above 0°C, the chemistry was demonstrated to be very robust to charging down to -30°C.***

M. C. Smart, et. al., "Lithium-ion Batteries for Mars Missions", 2021 Space Power Workshop (Virtual), Manhattan Beach, CA, April 19, 2021.

Yardney 8 Ah Li-Ion Cells for Mars Exploration Rover (MER)
Discharge Rate Characterization at Various Temperatures

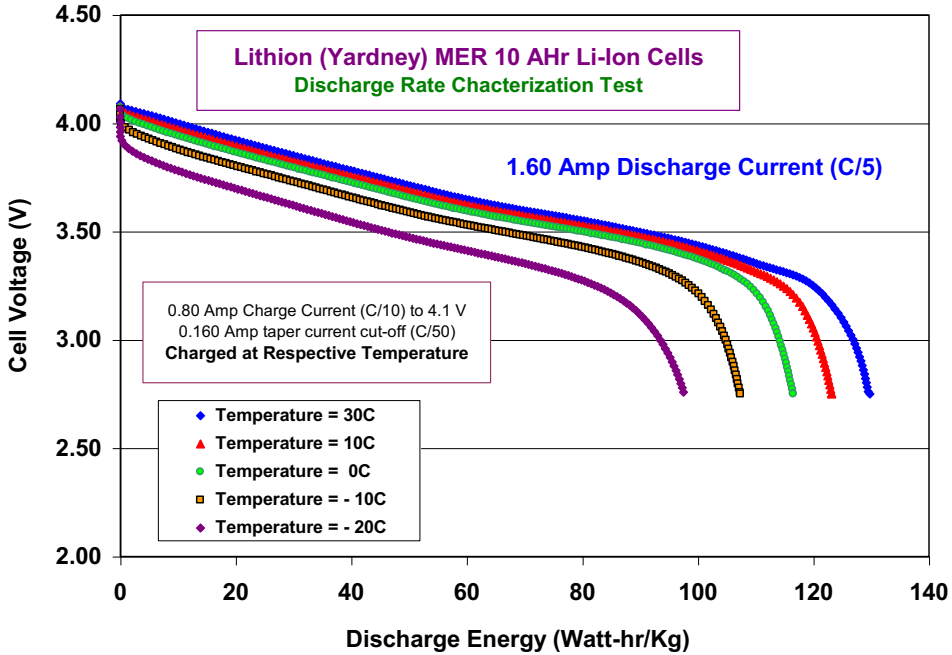
(C/5 Discharge Rate = 1.60 Amps)

Discharge Capacity (Ah)



	Capacity (AHr)	% of RT
30 C	11.122	100.00
10 C	10.561	94.95
0 C	10.012	90.01
-10 C	9.332	83.91
-20 C	8.700	78.22

Discharge Energy (Wh/kg)

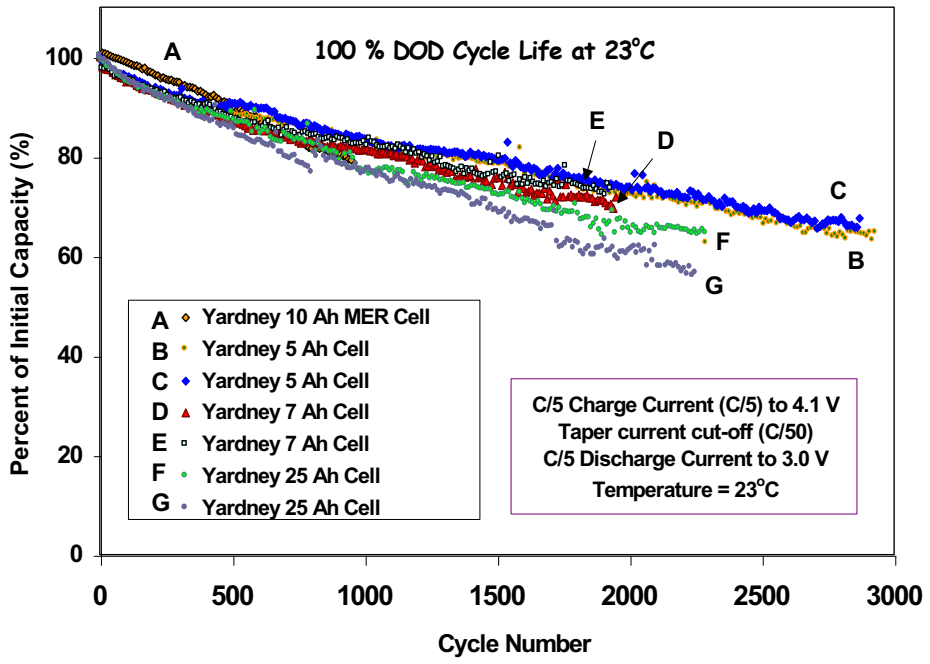


	Energy (WHr/Kg)	% of RT
30 C	129.77	100.00
10 C	123.61	95.25
0 C	116.50	89.77
-10 C	107.35	82.72
-20 C	97.50	75.13

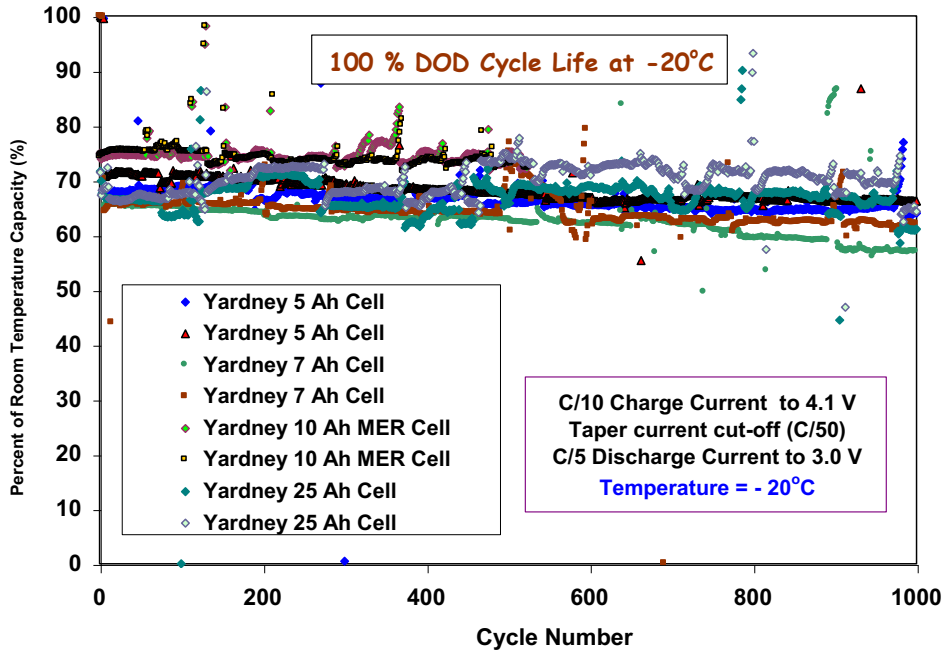
Cells contain 1.0M $LiPF_6$+EC+DMC+DEC (1:1:1) (Range of operation –30 to +40°C)

Performance Testing of Prototype Yardney Lithium-Ion Cells
100% DOD Cycle Life Performance

Temp = 23°C



Temp = - 20°C

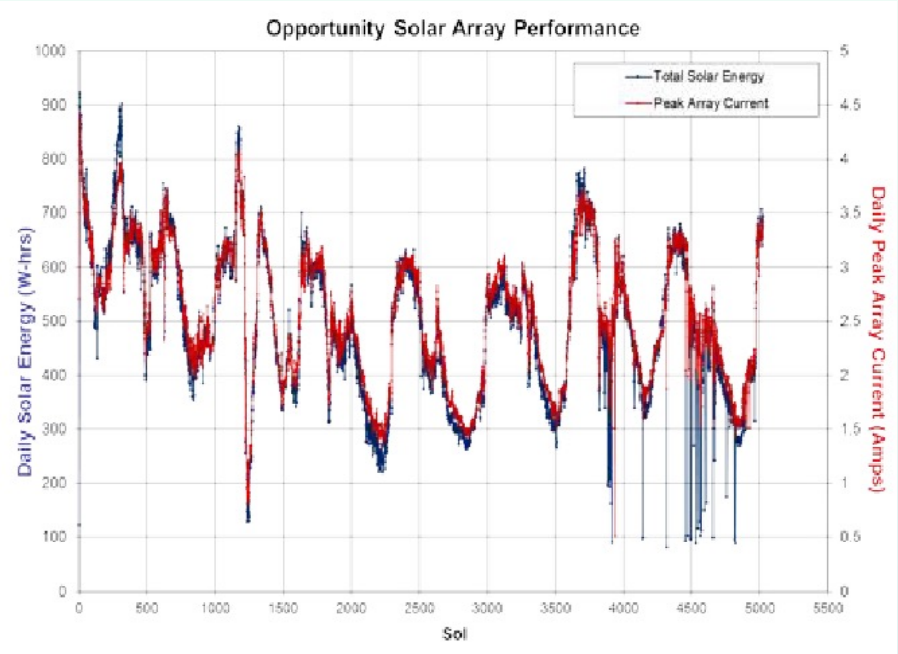


- Comparable cycle life performance obtained with a range of cell sizes fabricated by Lithion, Inc. (from 5 to 25 Ahr).
- Stable performance displayed when continuous cycling is performed at – 20°C (lower capacity fade rate compared to room temperature).

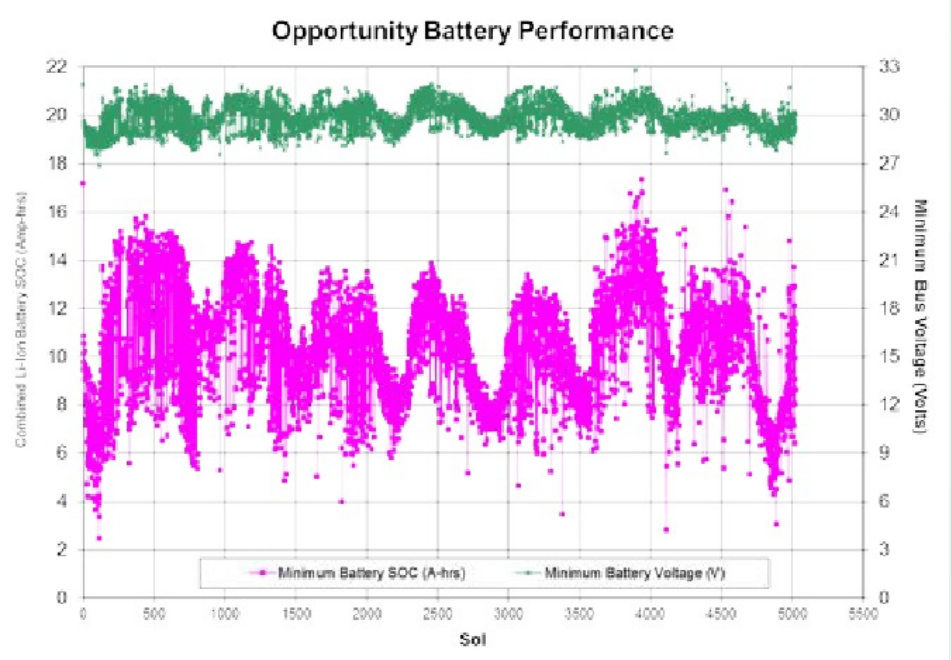
Mars Exploration Rover- Opportunity

Mission Telemetry Data

Solar Array Performance



Battery Performance



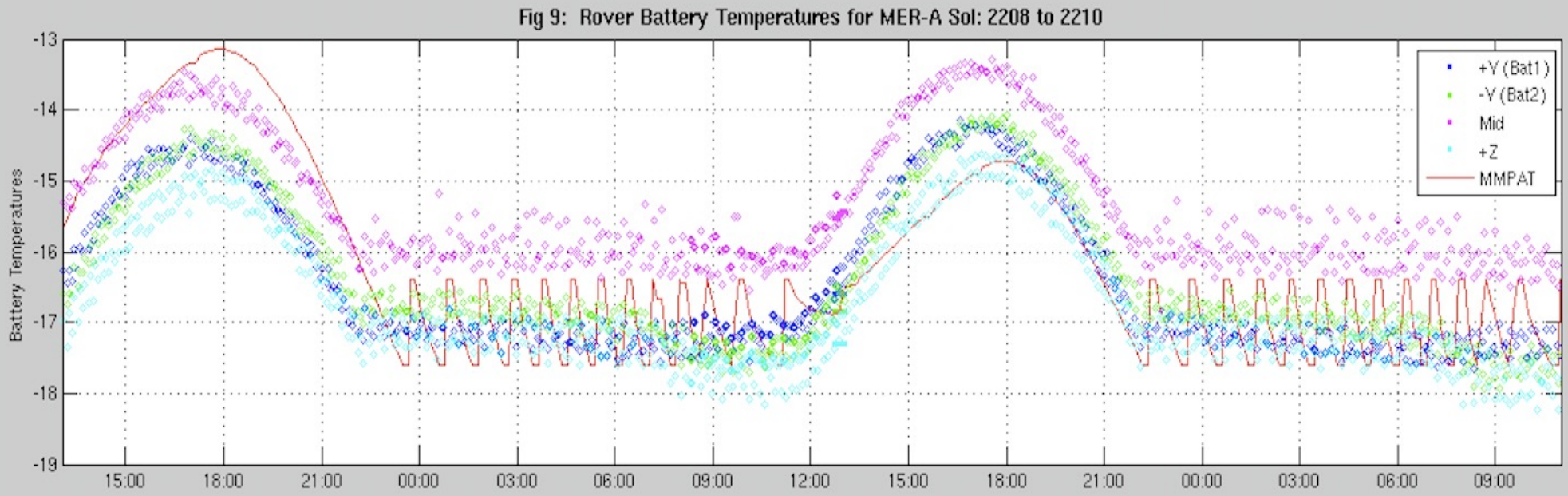
- Opportunity operated on the surface of Mars for over fourteen years until it stopped communicating on June 10, 2018.
- By this time, the rover had been operational for 5,111 sols, representing 57 times longer than the design requirement of 90 sols of operation.
- During its mission, the Opportunity 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.

Mars Exploration Rover - Spirit

Battery Temperature Telemetry (end of life)

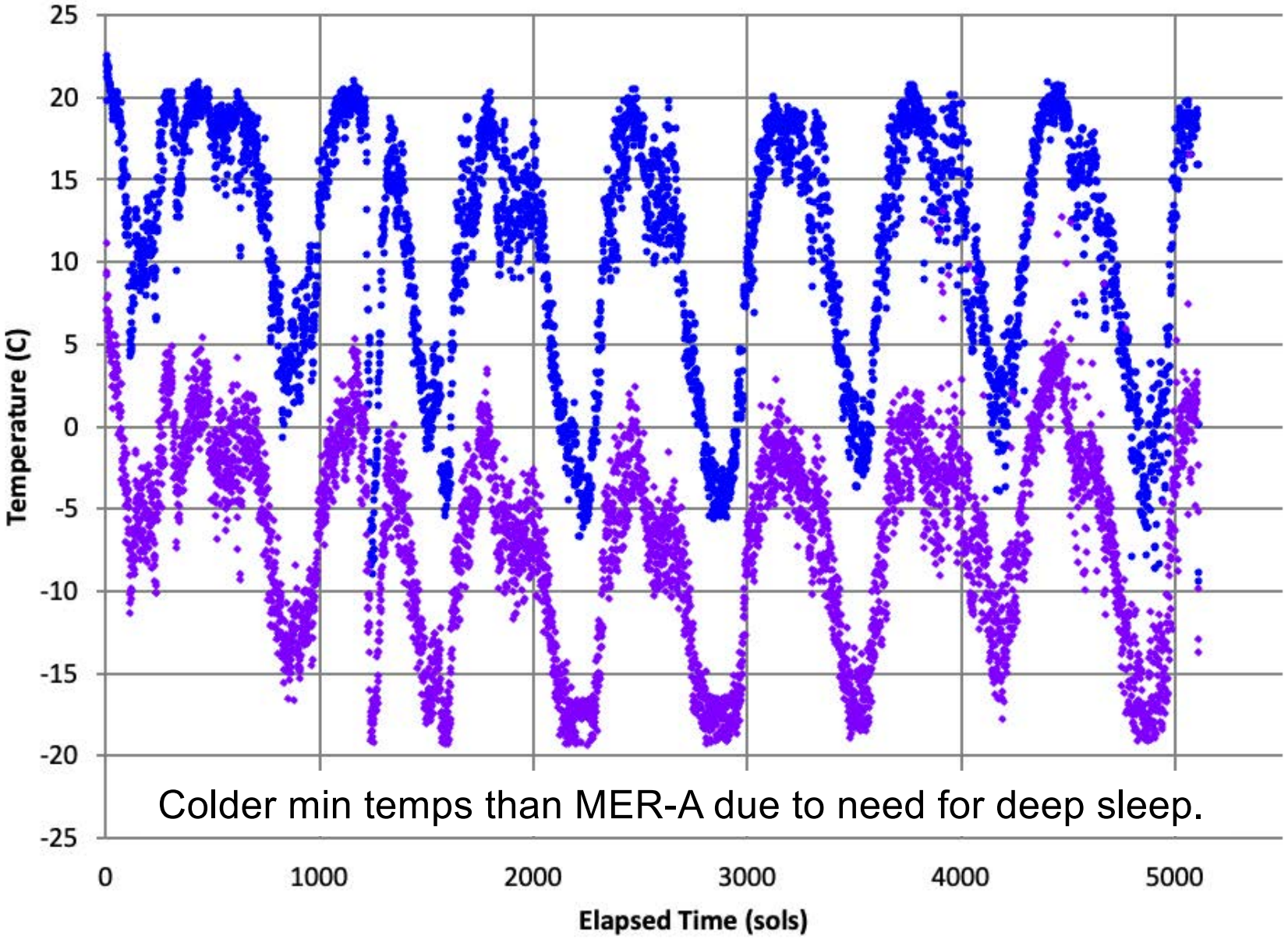
The most challenging times for the batteries during operations were when the batteries were coldest during Martian winter and significant dust storms.

For MER-A, the heaters kept the batteries warmer than -18 C, but this required many cycles of the battery heaters.



Mars Exploration Rover - Opportunity

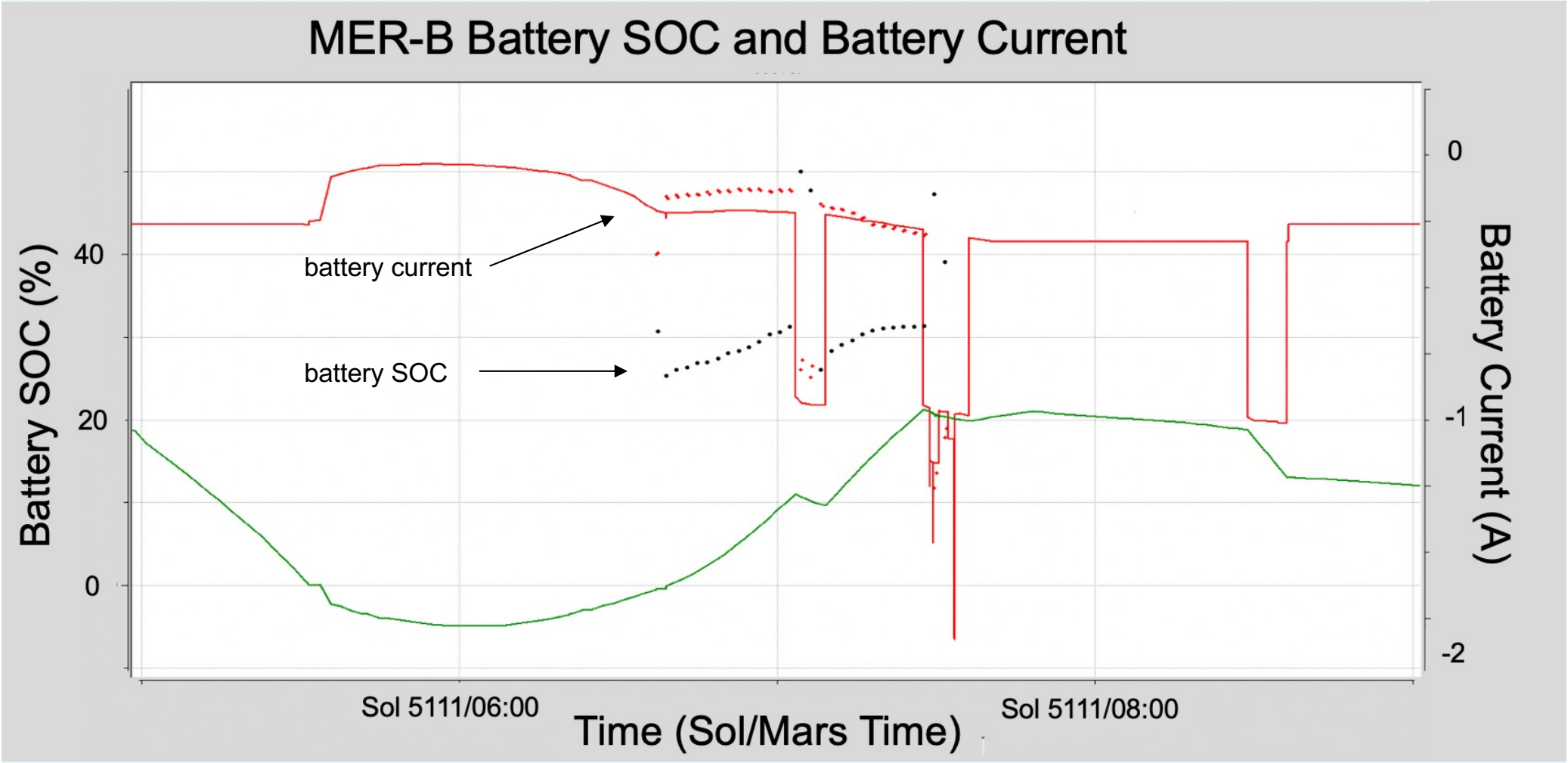
Mission Battery Max and Min Temperatures



Mars Exploration Rover - Opportunity

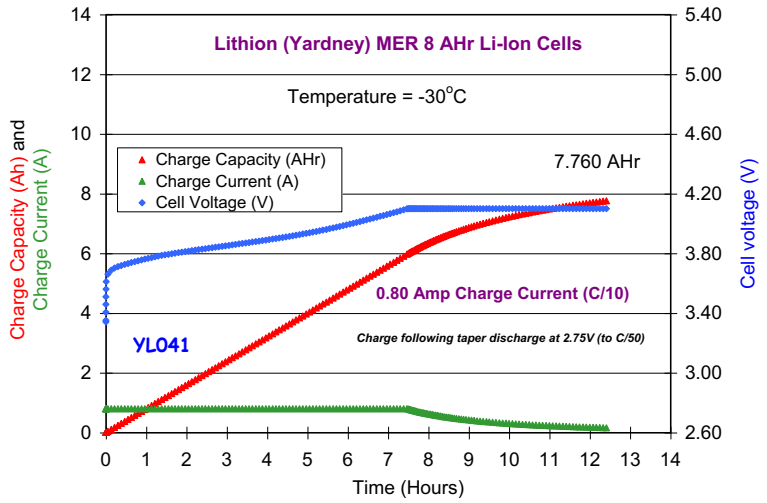
Battery State of Charge (end of life)

The last battery SOC telemetry received from MER-B. During the 2007 Martian dust storm, MER-B depended on the batteries for 3 weeks to survive.
The 2018 dust storm was more opaque, but the batteries granted an additional 5 sols.

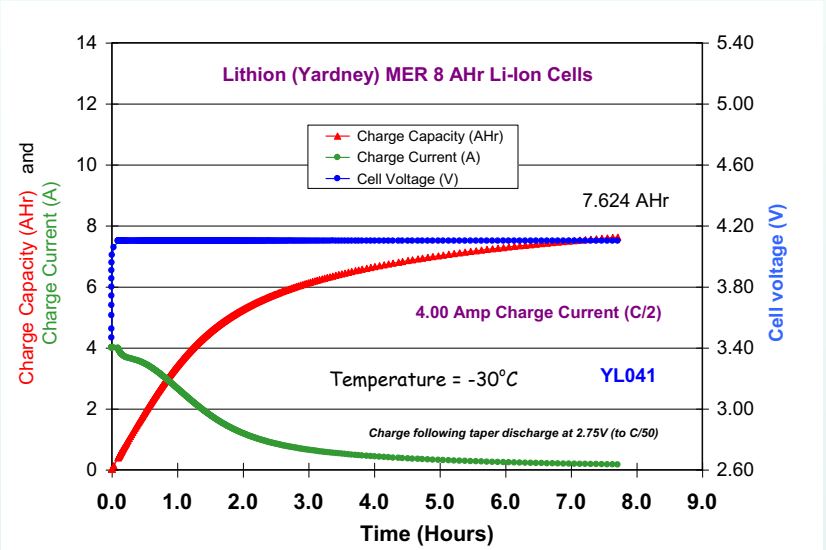


Lithion 8 Ah Li-Ion Cells for Mars Exploration Rover (MER)
Charge Rate Characterization at – 30°C

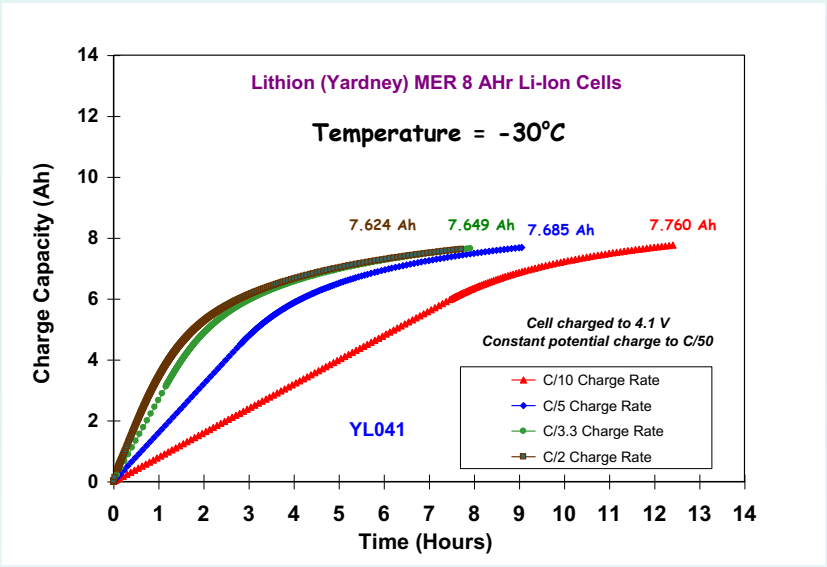
C/10 Charge Rate (0.80 A) to 4.1 V



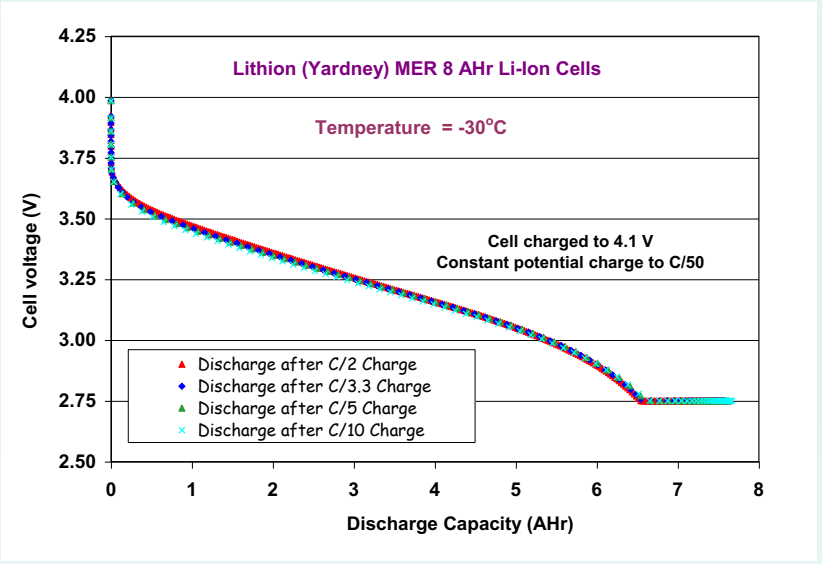
C/2 Charge Rate (4.00 A) to 4.1 V



Comparison of Different Charge Rates



Discharge After Charging at –30°C



Mars Science Laboratory (MSL) Curiosity Rover

- **Launch Date: November 26, 2011**
- **Landing Date: August 5, 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 3313 Sols to-date**
  - After 9 years and almost 27 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 3313, Curiosity had driven 16.5 miles (or 26.6 kilometers).**

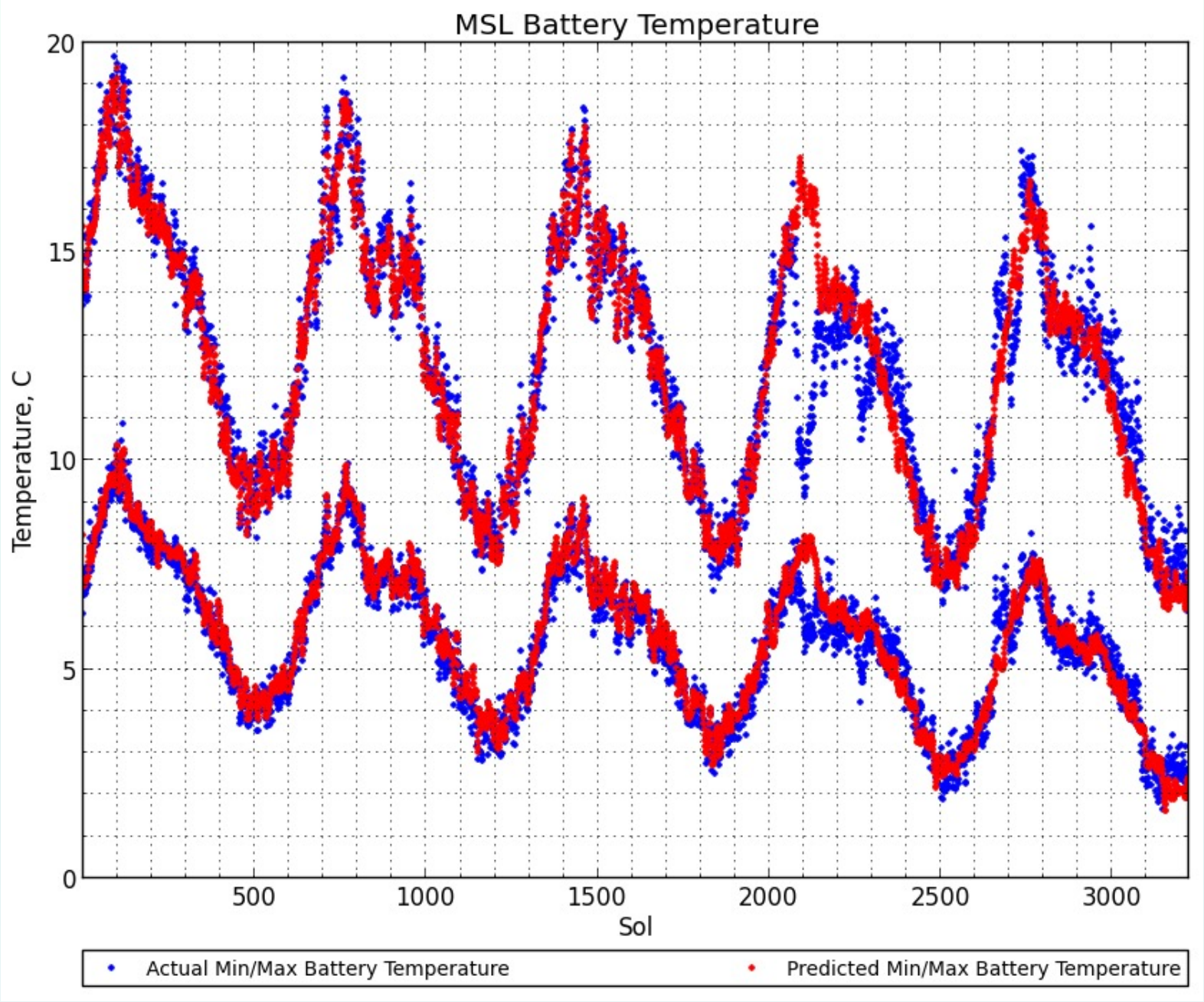
Battery Details

- 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

M. C. Smart, et. al., "Lithium-ion Batteries for Mars Missions", 2021 Space Power Workshop (Virtual), Manhattan Beach, CA, April 19, 2021.

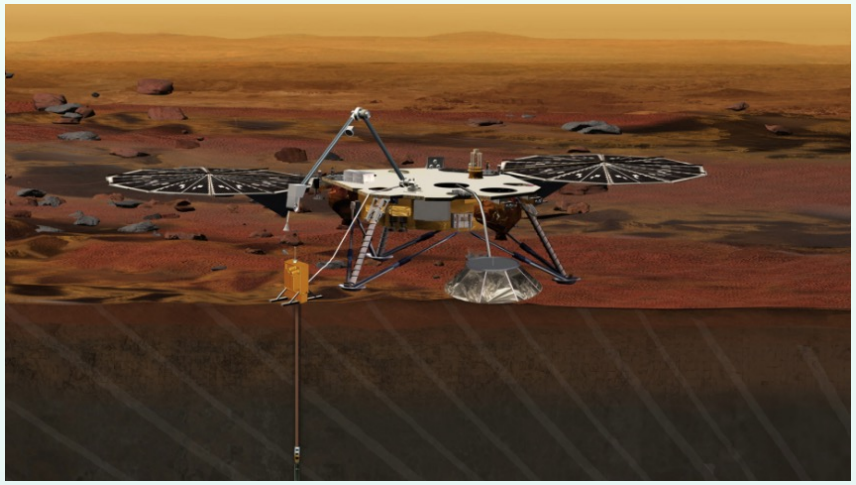
Mars Science Laboratory - Curiosity

Mission Telemetry Data



NASA's Mars InSight Lander

- **InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) is a NASA Discovery Program mission that placed a single geophysical lander on Mars to study its deep interior.**
- **The mission consists 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 attempted 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 a Marsquake for the first time.**
- **InSight has been successfully operating for over 1000 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°C to +50°C
- **Operating Temperature Range: -30° to +35°C**
- **Required Life: ~ 4 years**
- **Surface Life: over 709 Sols of operation**
- **Fabricated by Yardney Technical Products, Inc**

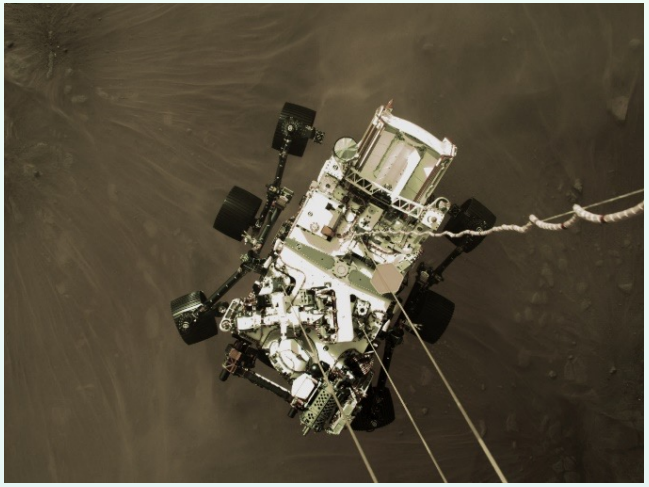
Battery Contains the Next Generation JPL Low Temperature Electrolyte:

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

M. C. Smart, et. al., "Lithium-ion Batteries for Mars Missions", 2021 Space Power Workshop (Virtual), Manhattan Beach, CA, April 19, 2021.

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°C to +40°C.
- **Operating Temperature Range: -20° to +30°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 %)

Summary

- NASA has an active interest in sending spacecraft to Mars
  - There are currently 4 active NASA spacecraft on the surface (Curiosity, InSight, Perseverance and Ingenuity) and 3 operating in orbit (Odyssey, MRO and MAVEN)
  - NASA, in cooperation with ESA, will send future missions to Mars to collect samples from the surface and return them to Earth
  - NASA also plans to establish a human presence on Mars with the Artemis program
- Mars is an extreme environment for spacecraft
  - Martian dust is a great challenge for solar powered spacecraft. The solar-powered NASA missions Pathfinder, Spirit and Opportunity had end-of-life events that were all related to dust accumulation or dust storms.
  - The Martian surface temperature is an average of -63 C (-81 F), and can range from 30 C (86 F) to -140 C (-284 F).
  - In multiple instances, the batteries on the MER rovers were able to provide enough support to allow the MER rovers to survive dusty conditions and the extreme seasons.
- Batteries that are capable of operating at low temperature are important for on-going NASA missions at Mars

Acknowledgements

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