Battery Development for CADRE, NASA's Shoebox-Sized Lunar Rovers

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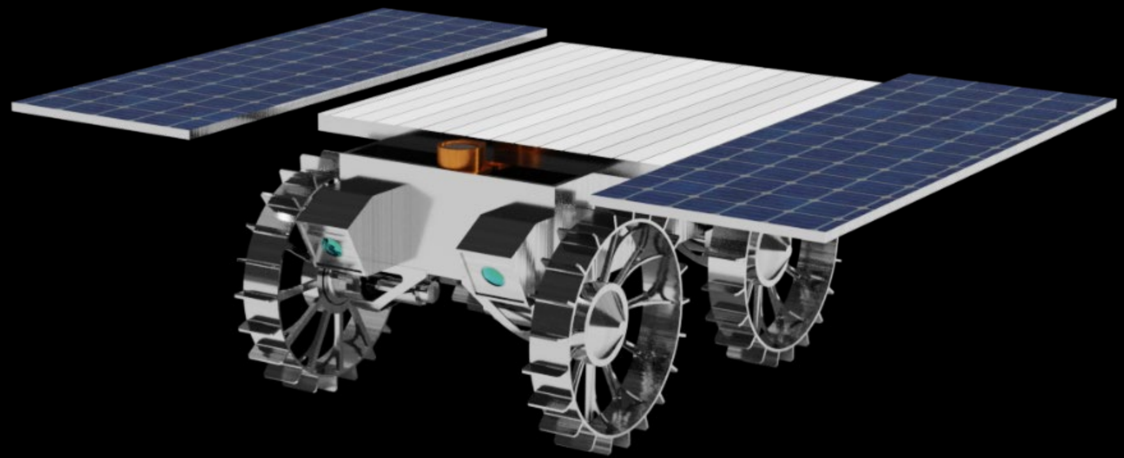

CADRE: Cooperative Autonomous Distributed Robotic Exploration

Jet Propulsion Laboratory
California Institute of Technology

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Outline

- Mission overview
- Key mission phases
- Cell selection
- Cell performance
- Self discharge
- Battery design
- Conclusions

Mission Overview

Jet Propulsion Laboratory
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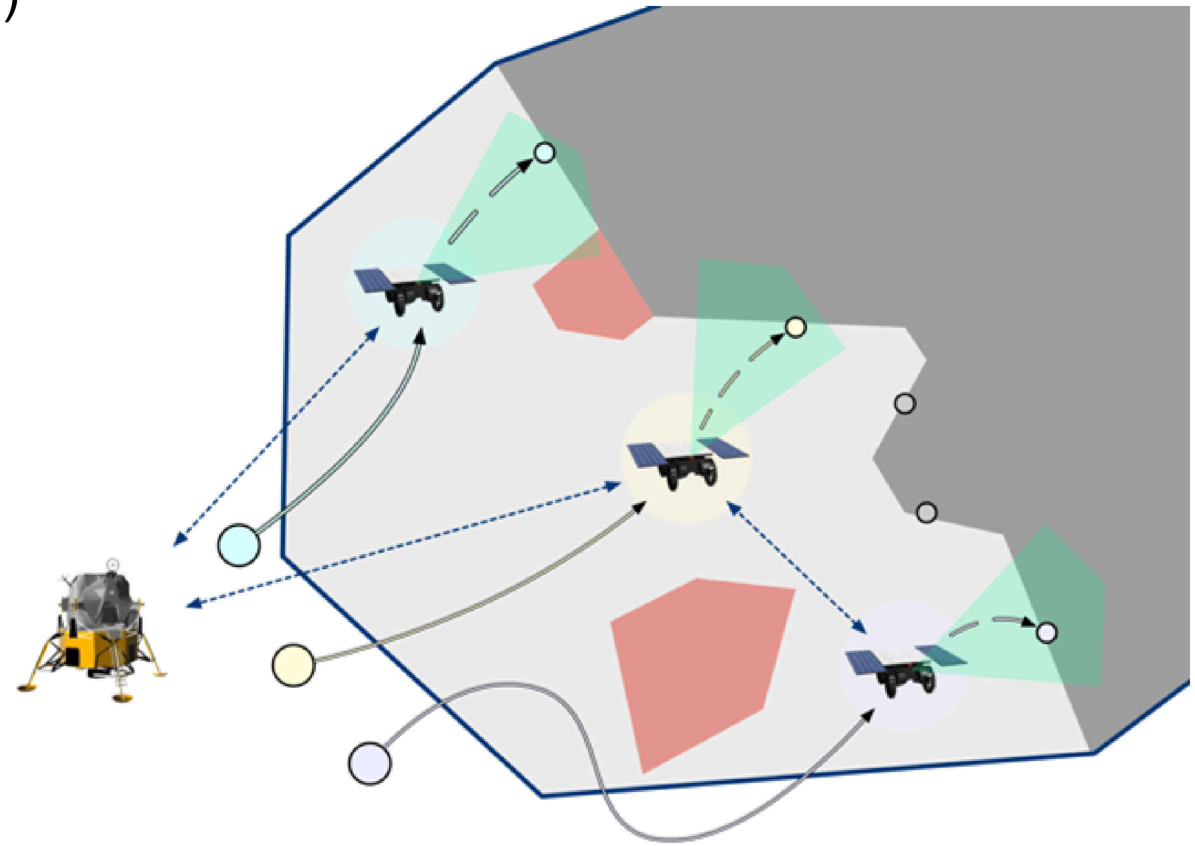
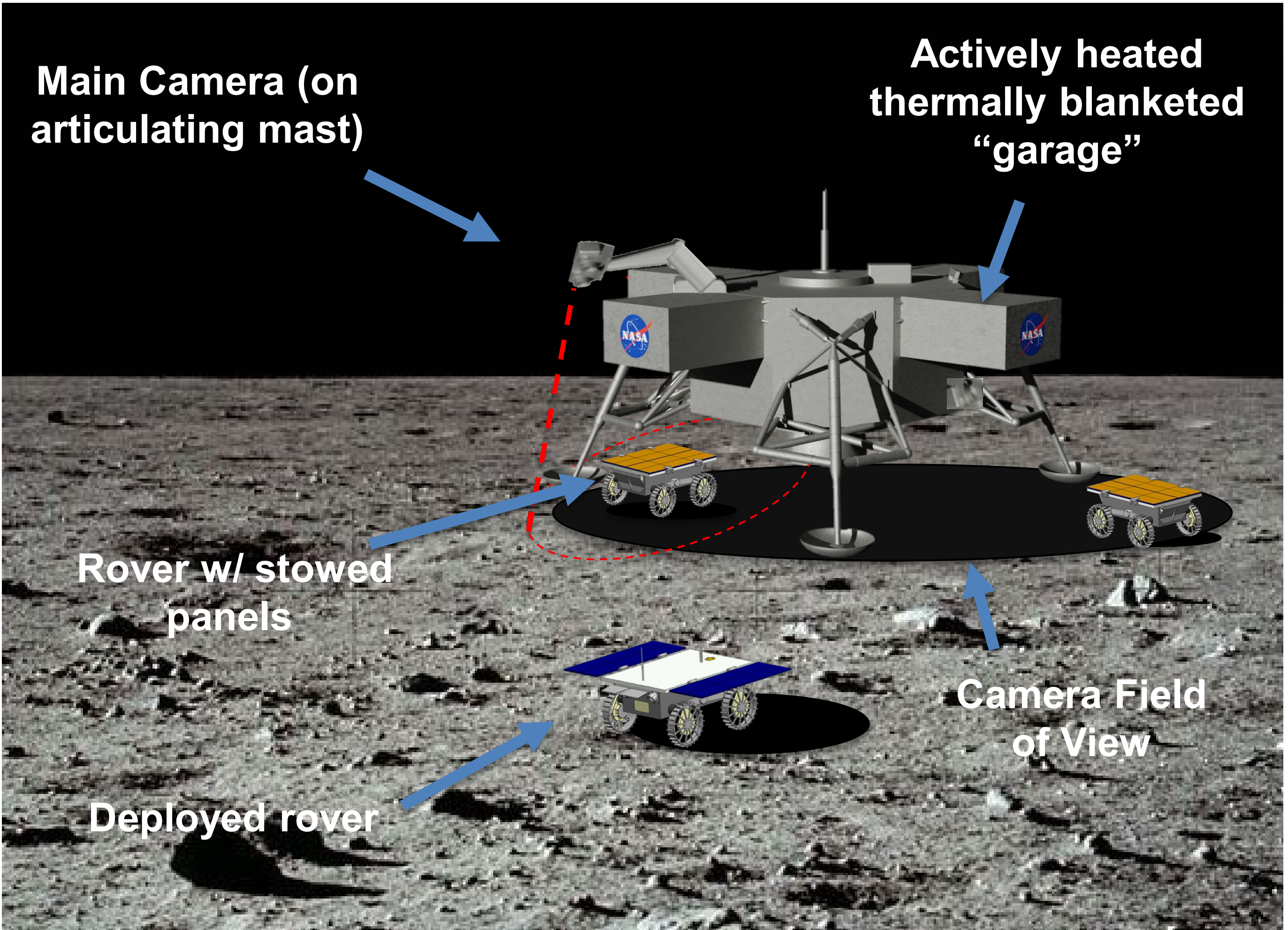
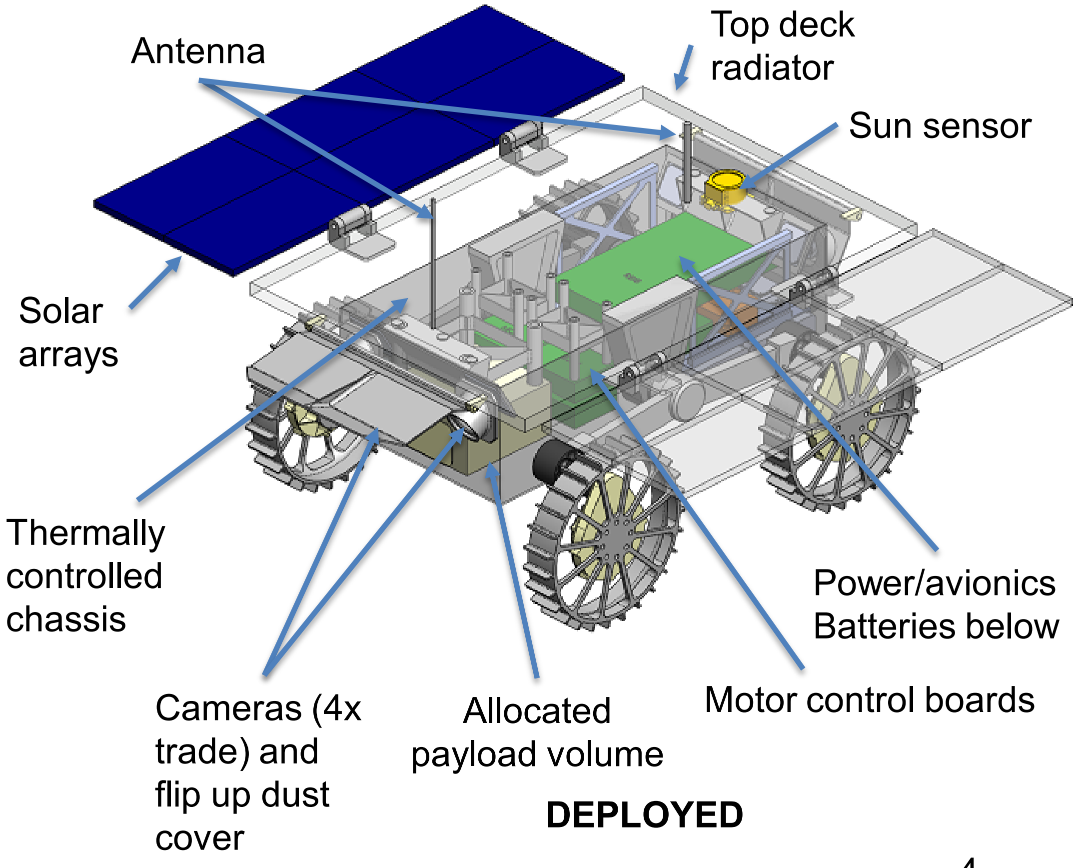
- CADRE is a tech demo to demonstrate that a network of robots can autonomously explore the daytime lunar environment
- Key autonomy: 1. Plan and Act Together, 2. Measure (and Sense) Together
- Mission lifetime: one lunar day (~14 Earth days)
- Components:
  - 4 rovers
  - Base station (same avionics)
  - Deployer
  - Payload(s)
- Mission class: 7120.8 – JPL type II tailored
  - Very different risk posture to typical JPL Class A, B, etc. missions



System Overview

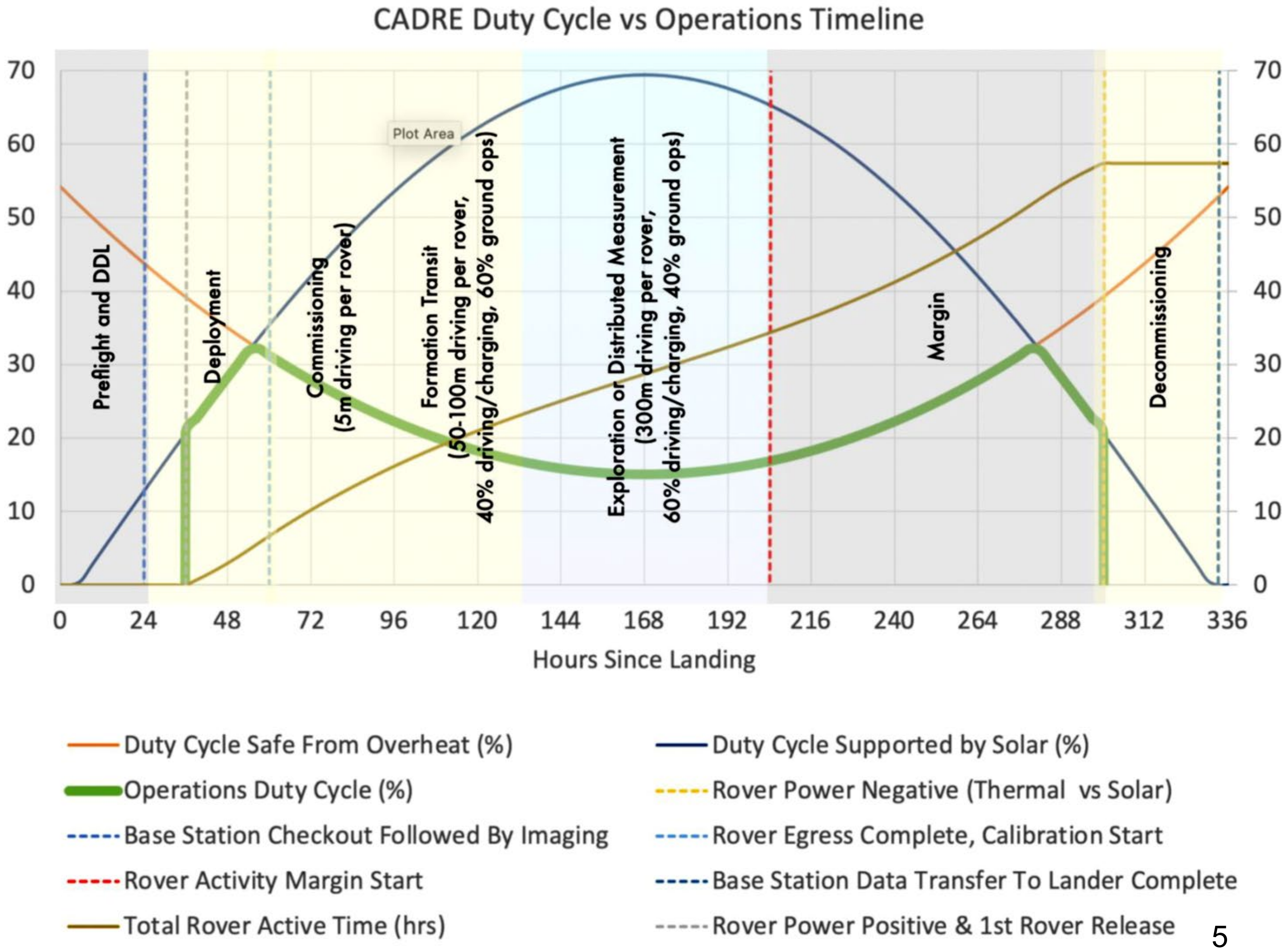
- CADRE will launch in 2024 on a CLPS lander
- Four small rovers with a base station (same avionics)
- Stereo camera on the lander provides context during operation
- Rovers and base station communicate over a local network and downlink to Earth through the lander



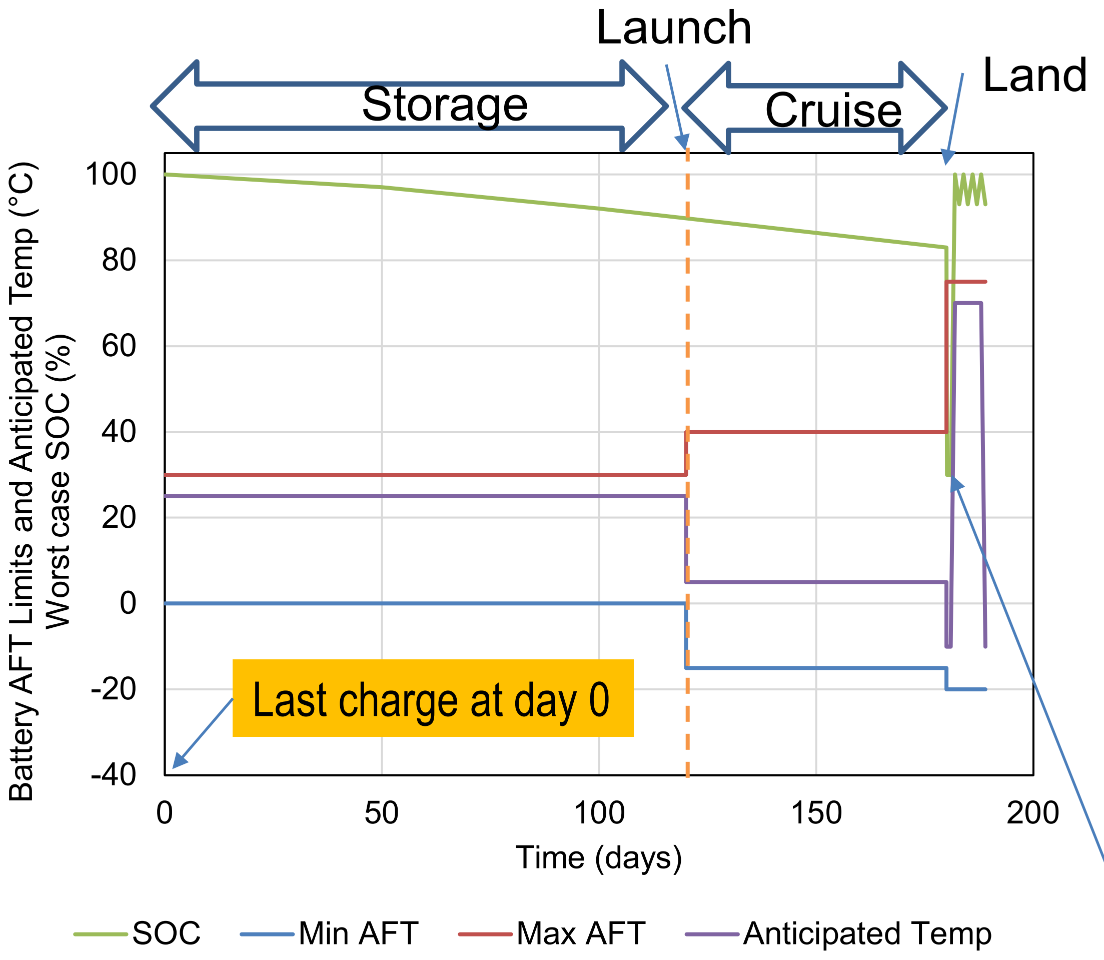


Mission Overview (cont.)

- Lunar environment is harsh
  - +120 °C during daytime
  - -170 °C at night (not required to survive)
- Rovers will land early in the day, starting off very cold and will be limited by solar power
- Rapid transition to duty cycle limitation to limit max temperature



Key mission phases

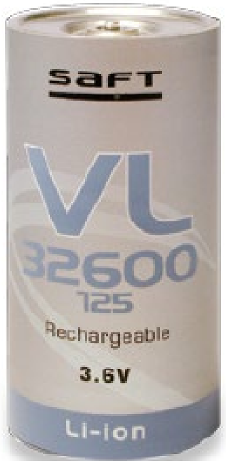


Only battery discharge right after landing, prior to solar array deployment

- Mission success hinges on being able to drive out of the lander shadow on battery power six months after the last charge
- Battery cannot be charged during storage or cruise
- Battery will perform **zero** cycles after solar array deployment
  - A battery cycle is defined as more than 50% of available capacity within DOD limits
  - Battery will still be used for load leveling
- AFT during lunar mission: -20 to +75 °C
- Power during driving: 50 W

Cell selection

- Initial concept developed around Saft VL 32600-125
  - Rated for operation up to 125 °C, allowing for plenty of headroom
  - Saft discontinued this model around 2019
- Other rechargeable options:
  - High temperature Ni-MH
    - High self discharge, poor specific energy
  - Custom Cells in Germany
    - Still developmental, poor specific energy, very expensive
  - Tadiran AA size TLI-1550
    - Small form factor, no data on cycling at temp.
  - Saft MP-xtd
    - Space heritage, +85 °C rated

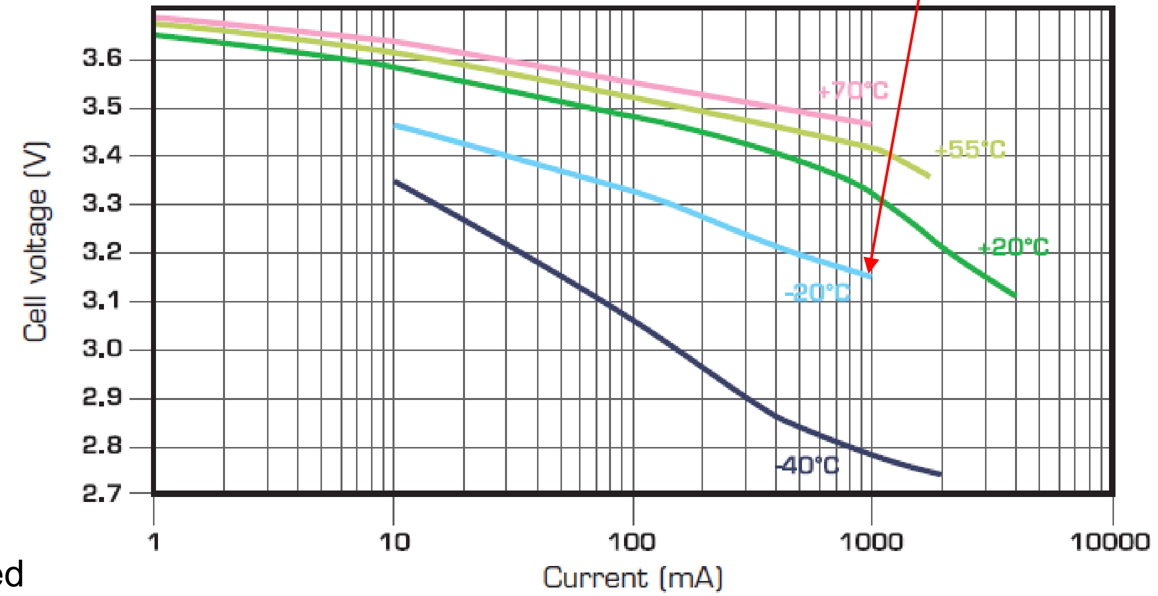


Cell selection (cont.)

- Primary cells were considered for this mission due to their advantages:
  - Higher maximum temperature (up to 150 °C)
  - Higher specific energy (~500 Wh/kg)
- Primary cells were ultimately discounted due to their disadvantages for this mission:
  - Cannot meet high power requirements, particularly at low temperature (most stressing case) without very large battery:
    - Mission needs 30 W at -20 °C
    - Highest current for "high power" LSH 20 cell at -20 °C = 1 A
    - Voltage at -20 °C, 1 A = 3.15 V = 3.15 W per cell
    - 10 cells required to meet requirement
    - Each cell is 100 g, so cell mass for battery = 1 kg (vs. 0.5 kg for 4 Li-ion)
    - Many cells would need to be procured to perform performance evaluation, qualification, testing, etc.
  - Would need to completely revise battery control electronics and add depassivation circuit
- JPL has been evaluating the MP-xtd cell at 85 °C for extended duration concepts
- The MP-xtd cells can support very high current at low temperature relative to any primary cell option
  - Once the solar panels are deployed, the battery is not significantly stressed but must provide load leveling

Performance of "high power" Saft $Li/SOCl_2$ cell rated for +85 °C is poor at high rate/low temp. HT version is even worse at high rate/low temp.

Saft LSH 20

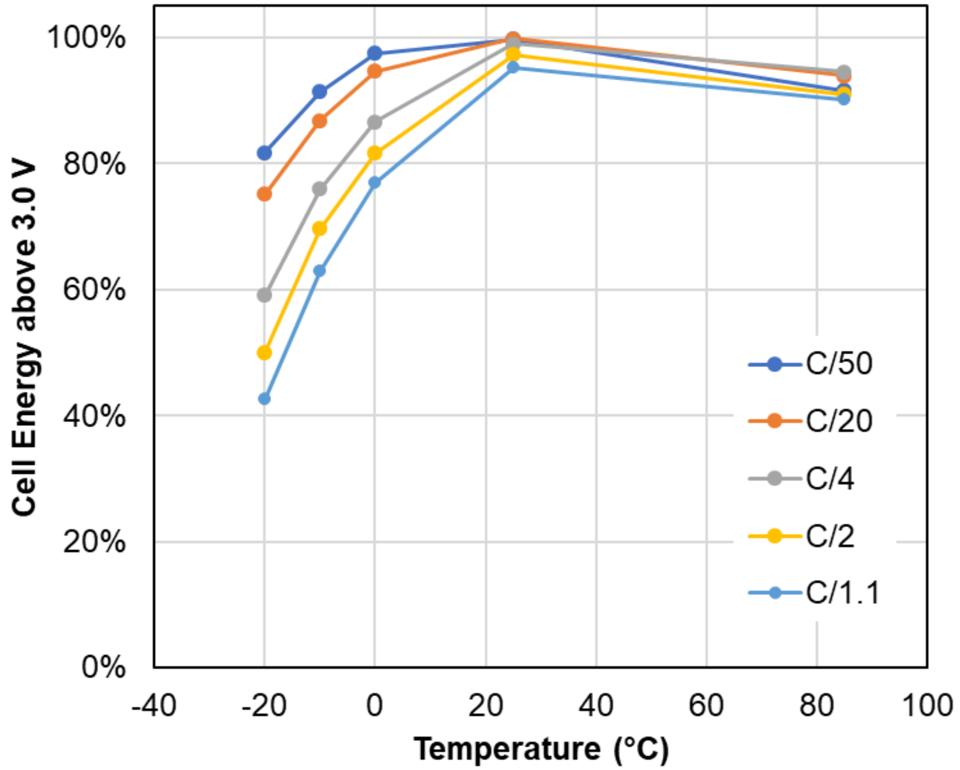


Voltage plateau versus Current and Temperature (at mid-discharge)

Cell temperature and rate performance

- Saft MP176065-xtd
  - Cell used in ESA ExoMars rover battery[1-2]
  - 5.6 Ah / 20.4 Wh
  - 11 A (2 C) continuous discharge / 22 A (4 C) pulse
  - Charging temperature range: -30 to +85 °C
  - Discharging temperature range: -40 to +85 °C
  - 150 Wh/kg and 264 Wh/l
- Cells deliver performance over an impressive range of temperatures and rates
- -20 °C, C/20 discharge delivers 75% of room temperature capacity
- Cell still capable of 1C discharge at -20 °C, delivering 43% of room temperature capacity
  - – Cell delivering between 15 and 20 W at this condition

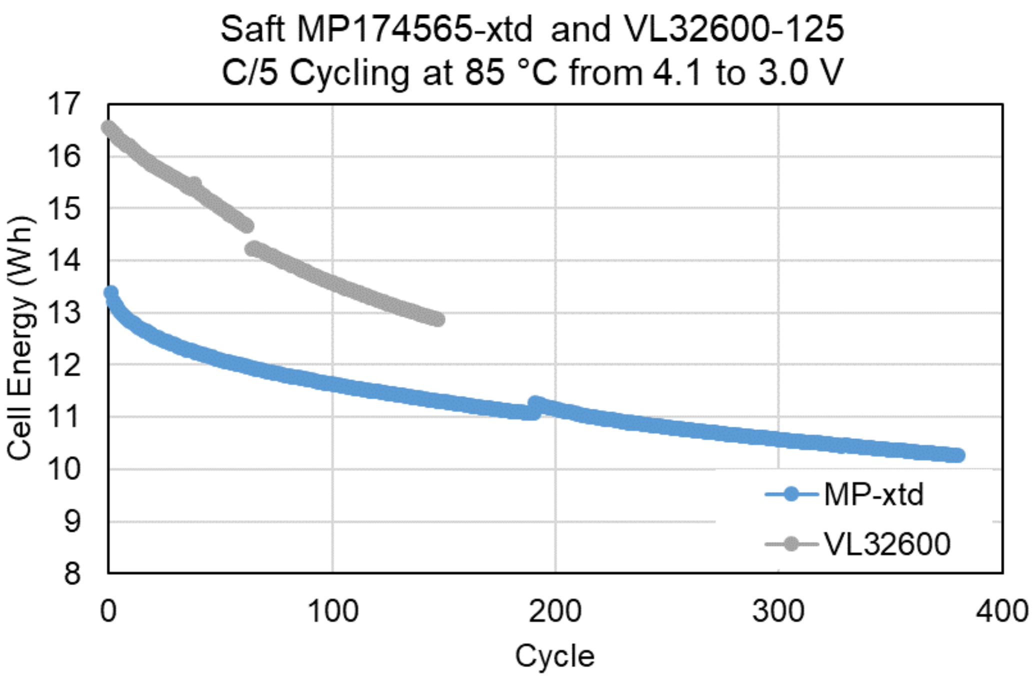
Saft MP176065-xtd discharge capacity vs. temperature at different rates



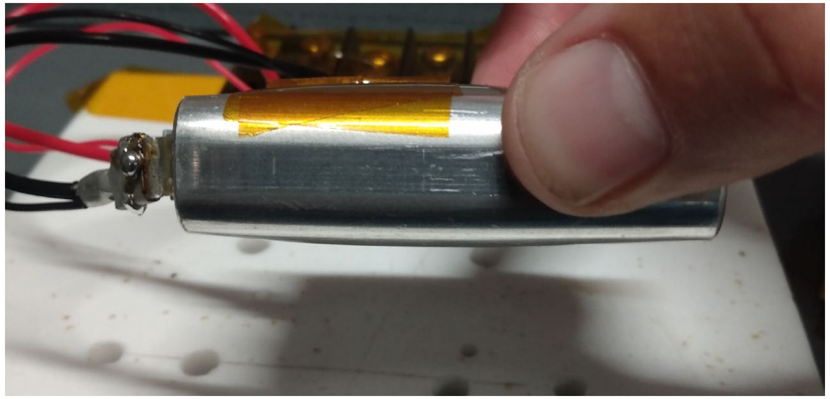
Cell charged at indicated temperature prior to discharge

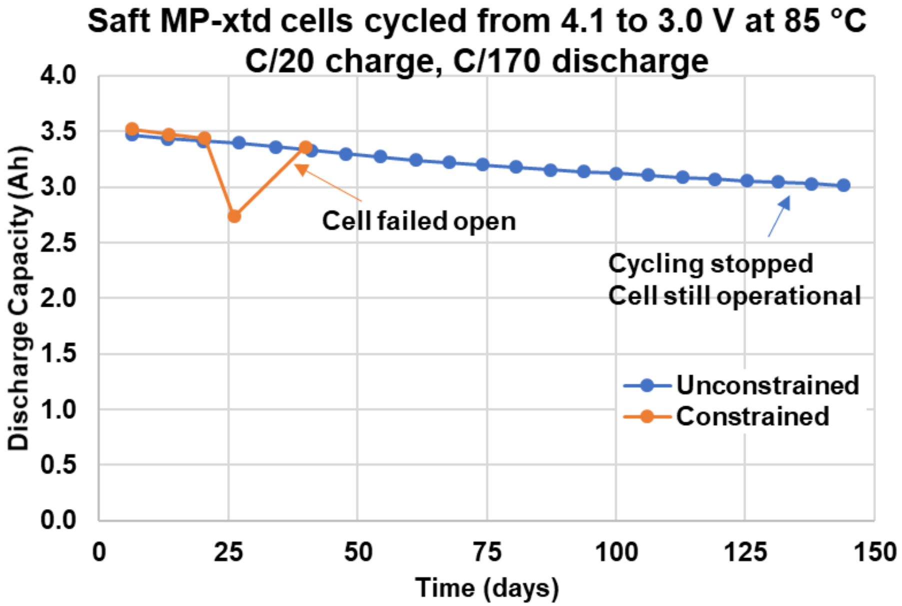
1. S. Amos and P. Brochard, *E3S Web Conf.*, **16**, 1–5 (2017).
2. H. Tricot and P. Brochard, *2019 Eur. Sp. Power Conf. ESPC 2019*, 1–4 (2019).

Cell cycle life performance

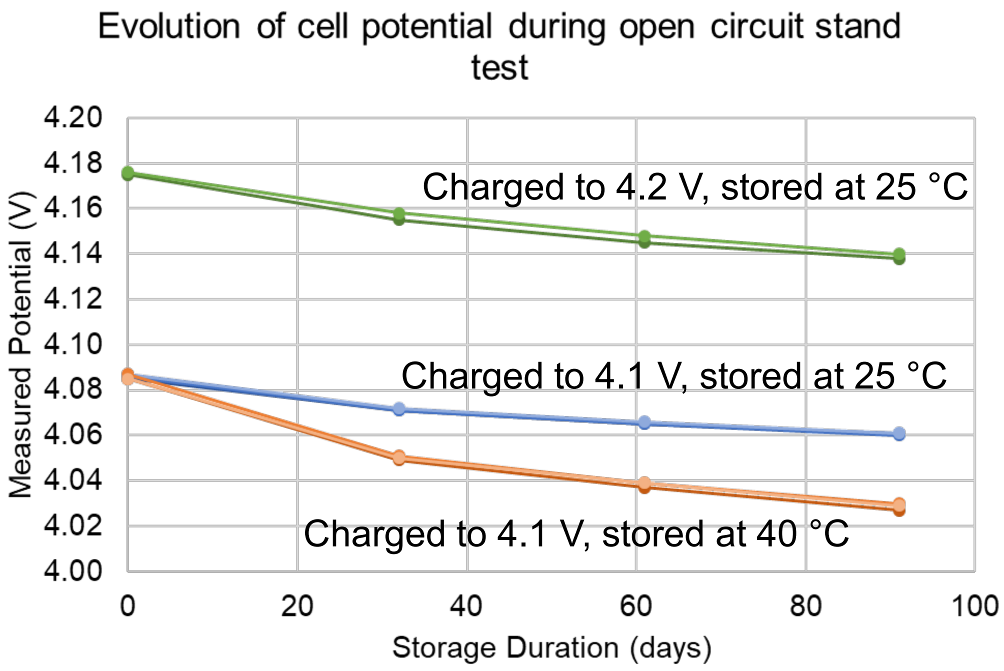


- MP-xtd cells perform similarly to VL32600-125 at +85 °C, C/5
- 380 cycles demonstrated
- Cells bulge substantially during operation at high temperature
- +3mm on each large side
- Top, bottom, and small sides do not change significantly
- Battery design must incorporate space to allow cells to swell





Self discharge testing

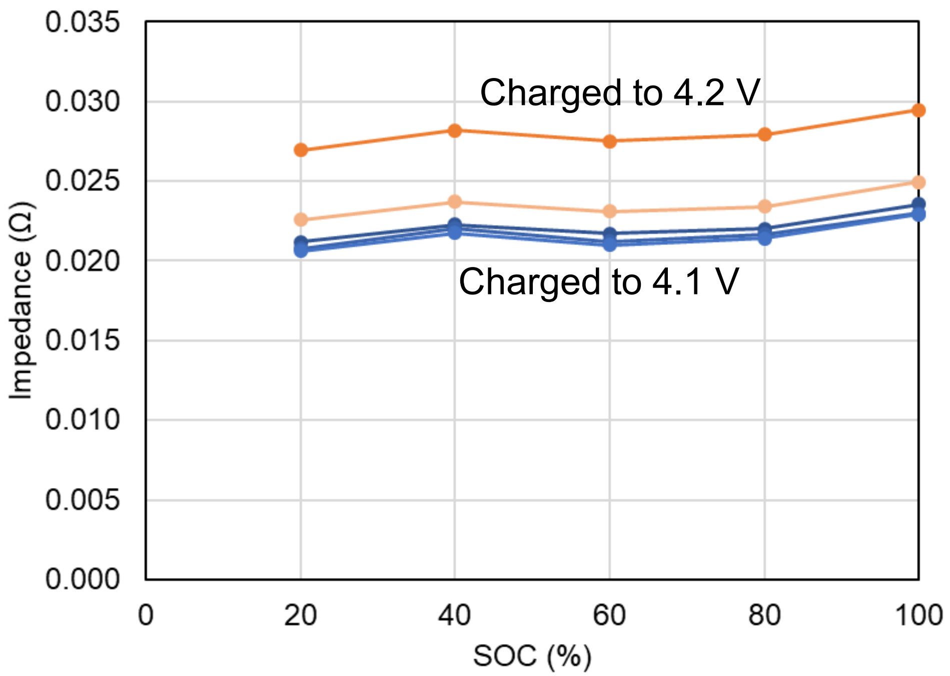


- Mission profile has long period between last charge and battery use
  - Up to 4 months at up to 30 °C
  - Up to 2 months at up to 40 °C
- OC storage test carried out on 8 cells:
  - 3x charged to 4.1 V, stored at 40 °C for 3 months
  - 3x charged to 4.1 V, stored at 25 °C for 3 months then 40 °C for 3 months
  - 2x charged to 4.2 V, stored at 25 °C for 3 months then 40 °C for 3 months
- Measured OCV and thickness every month
- Measured capacity and impedance before and after

Self discharge testing

6 month results:

- 4.1 V cells lost 11.1% energy on average
- 4.2 V cells lost 12.7% energy on average
- 4.2 V cells lost <1% reversible energy relative to 4.1 V cells
- 4.2 V cells impedance increased 18% relative to 4.1 V cells



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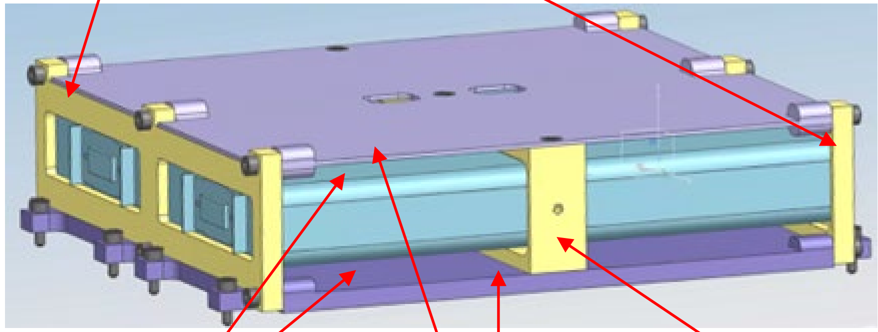
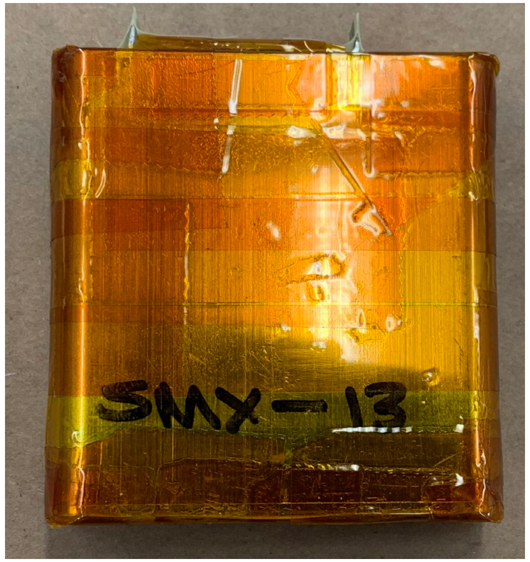
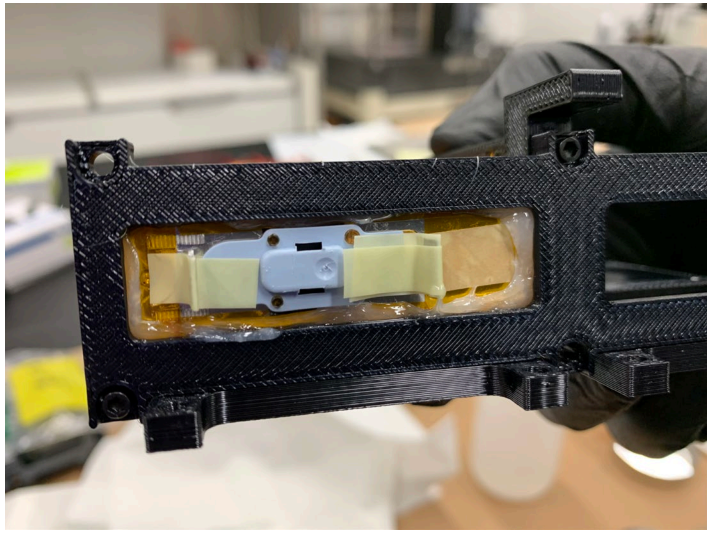
Battery design

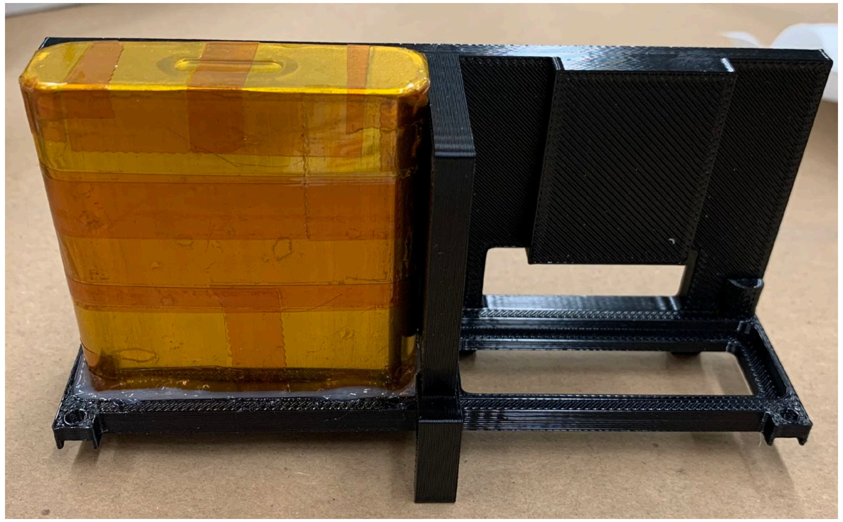


- 4s1p battery
- Cells housed in plastic and aluminum case with terminals pointing out
- Central aluminum rib used as heat sink
- Plastic (ultem) used close to terminals to maintain electrical isolation
- Cell terminals and vents pointing outward
- Cells to be wrapped in Kapton tape
  - Three layers on bottom, two layers elsewhere
- Cells held in place in pockets machined into aluminum and ultem
- Potting material used to bond cells into pockets
- No pressure applied on cells by housing
- 3 mm gap between large sides of cells and housing to allow for expansion

Battery Assembly



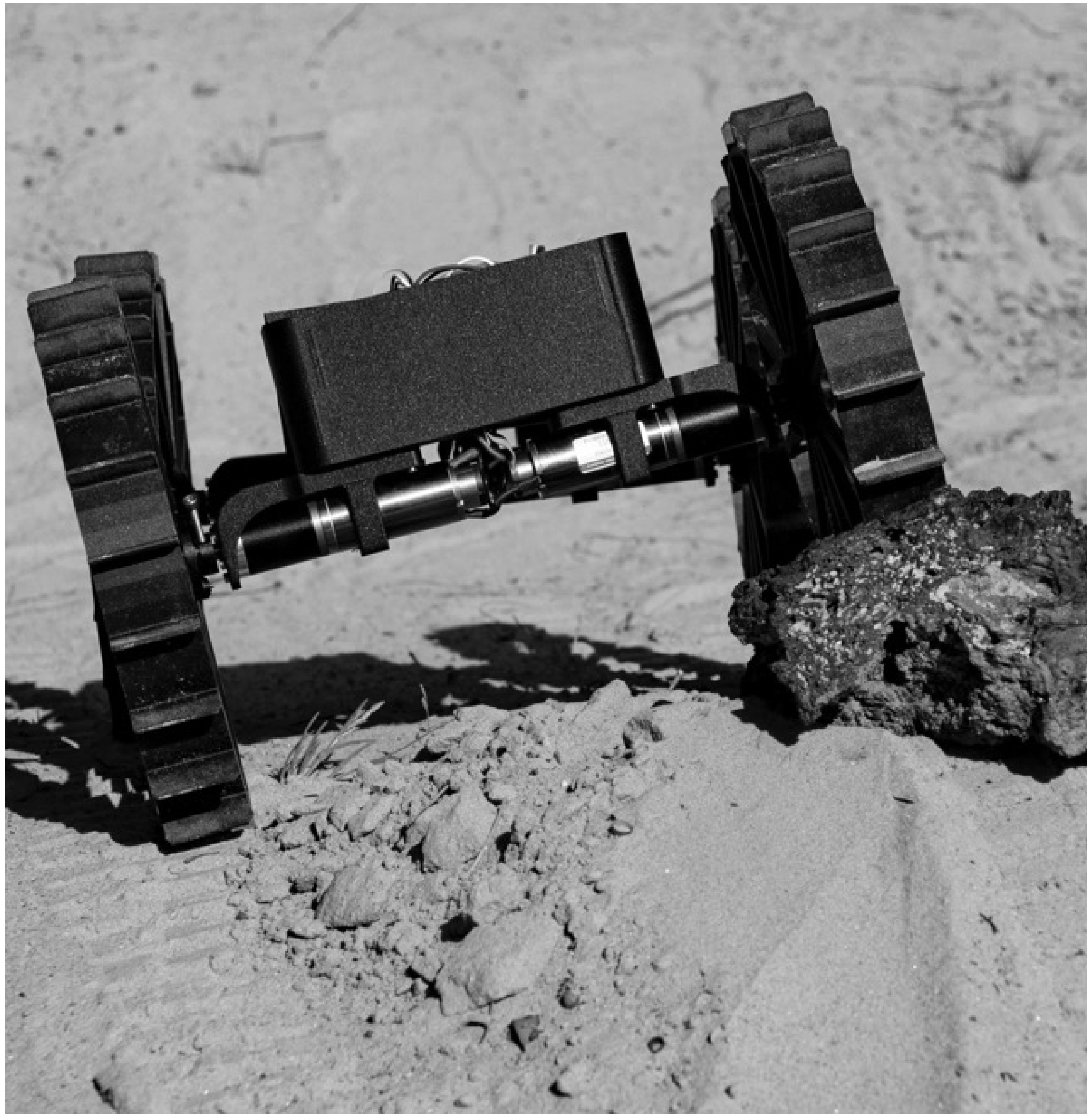




- Cell selection and battery assembly taking place at JPL
- Cells wrapped in Kapton tape (≥2 layers)
- Arathane 5753 with CAB-O-SIL used as potting material
- Cell tabs will likely be soldered
- PRTs affixed directly to cell sides
- Interface from battery to interface board through single Micro-D connector
- Entire assembly designed for easy removal and replacement

Conclusions

- CADRE presents a unique set of battery requirements:
  - AFT higher than any JPL-flown rechargeable Li-ion battery
  - No ability to charge during storage or cruise
  - Very stressing initial performance requirements upon landing



- Battery must survive at +85 °C and provide high power at -20 °C
- Short duration mission operations help with high temperature stability requirement
- Long term storage at 4.2 V leads to increased internal resistance
- Battery design and fabrication at JPL

Acknowledgements

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