Battery System Design, Testing, and Operation for the Mars Perseverance Rover and Ingenuity Helicopter

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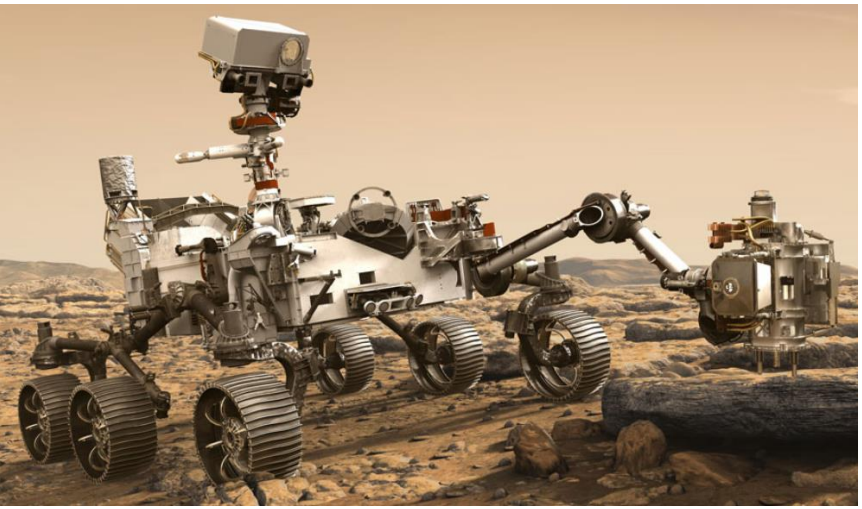
Overview

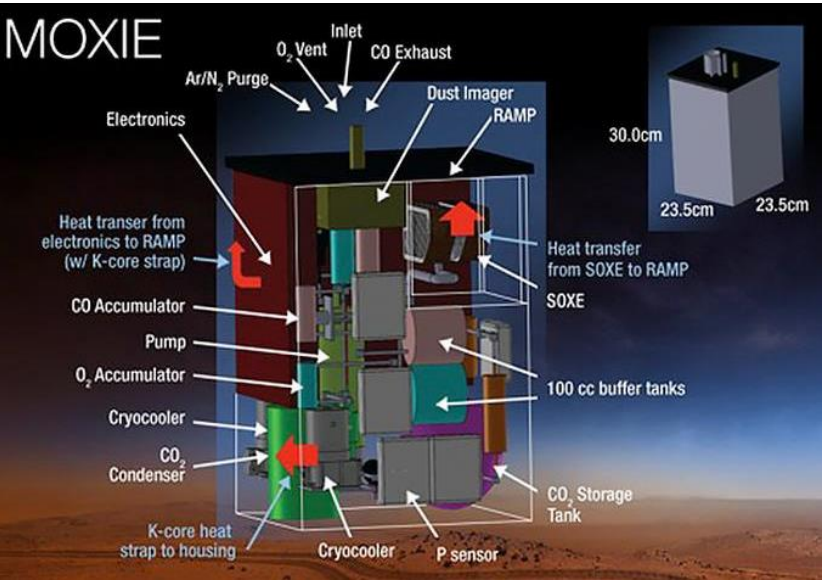
- M2020 Mission Goals
- Rover Battery
- Thermal Batteries
  - Baseload Resistor Assembly
- Helicopter Battery
- Operations
- Conclusions

Mars Perseverance Rover



Mission

- Search for signs of ancient microbial life:
  - Suite of instruments for biosignature detection
- Many other instruments (e.g. ground-penetrating radar for study of geologic structure of the subsurface; XRF with imager to determine the fine scale elemental composition)
- Drill to collect core samples of Martian rock and soil, then store in sealed tubes for pickup.
- Mars Helicopter to test the first powered flight on another planet
- CO_2 electrolyzer to generate in-situ O_2



Mars Perseverance Rover Battery

- Battery Design:
  - Cells fabricated at Yardney Division, EaglePicher
  - Batteries fabricated at EaglePicher, Joplin
  - 8s2p design
  - 24-32.8V, 43Ah nameplate capacity per string
  - Each string can be charged independently, discharged together
  - AFT: -20°C to +35°C
- MSL Cell Chemistry:
  - MCMB anode, NCO cathode, 1M $LiPF_6$ in 1:1:1 EC:DMC:DEC
  - Heritage chemistry that was used on MER, Phoenix, Juno, and Grail.
- M2020 Cell Chemistry:
  - Graphite anode, NCA cathode, 1M $LiPF_6$ in 1:1:1 EC:DMC:DEC
  - Lower cell impedance, lower impedance growth rate, slightly higher capacity
- Extensive qual and flight acceptance campaign at cell and battery level
  - Cell characterization/binning
  - Assembly electrical tests (Capacity vs. T, impedance vs. SOC, open circuit stand)
  - Assembly environmental test (TVAC, random vibe)

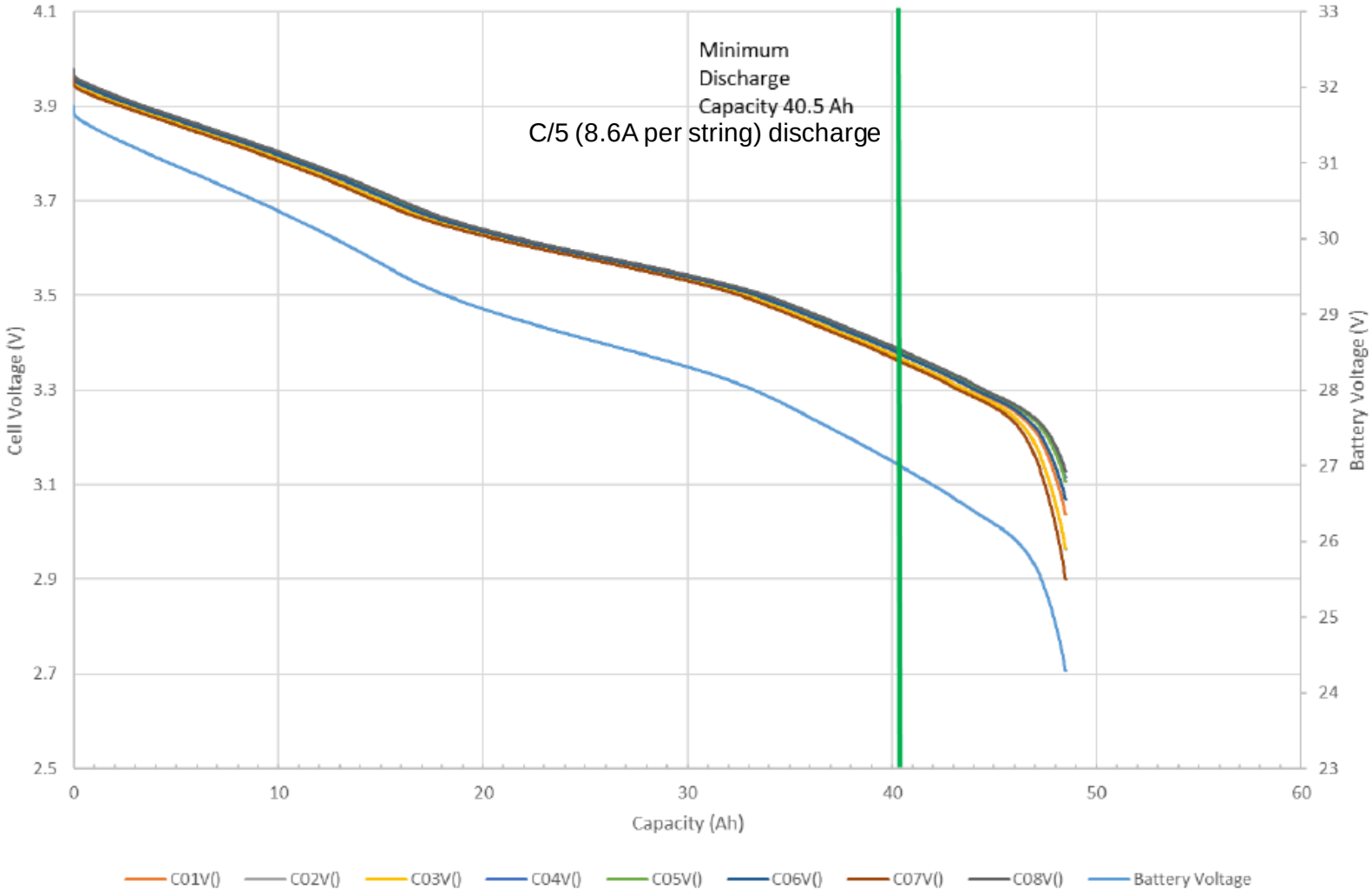
Mars Perseverance Rover Battery: Driving Requirements

- Energy of 2408 Watt-hours at 20°C
- Operating temperature range of -20°C to +30°C, with both charge and discharge permitted at these temperatures.
- Pulse current capability of 30A for 18 msec at all operating temperatures
- Cycle life of over 2010 cycles over the period of three Earth years at a maximum of 60% depth of discharge.
  - 670 cycles of up to 590 Wh at temperatures between 0°C and 30°C at 22A;
  - 670 cycles of 565 Wh at 10 A (max) between -20°C and 30°C;
  - 670 cycles of 1060 Wh between 0°C and 30°C at 22A.
  - 670 cycles of 1410 Wh between 0°C to 30°C at 16A.
- Calendar life of over seven Earth years
- Thermal gradient: no greater than 5°C difference cell to cell.

Rover Battery Assembly Unit (RBAU)

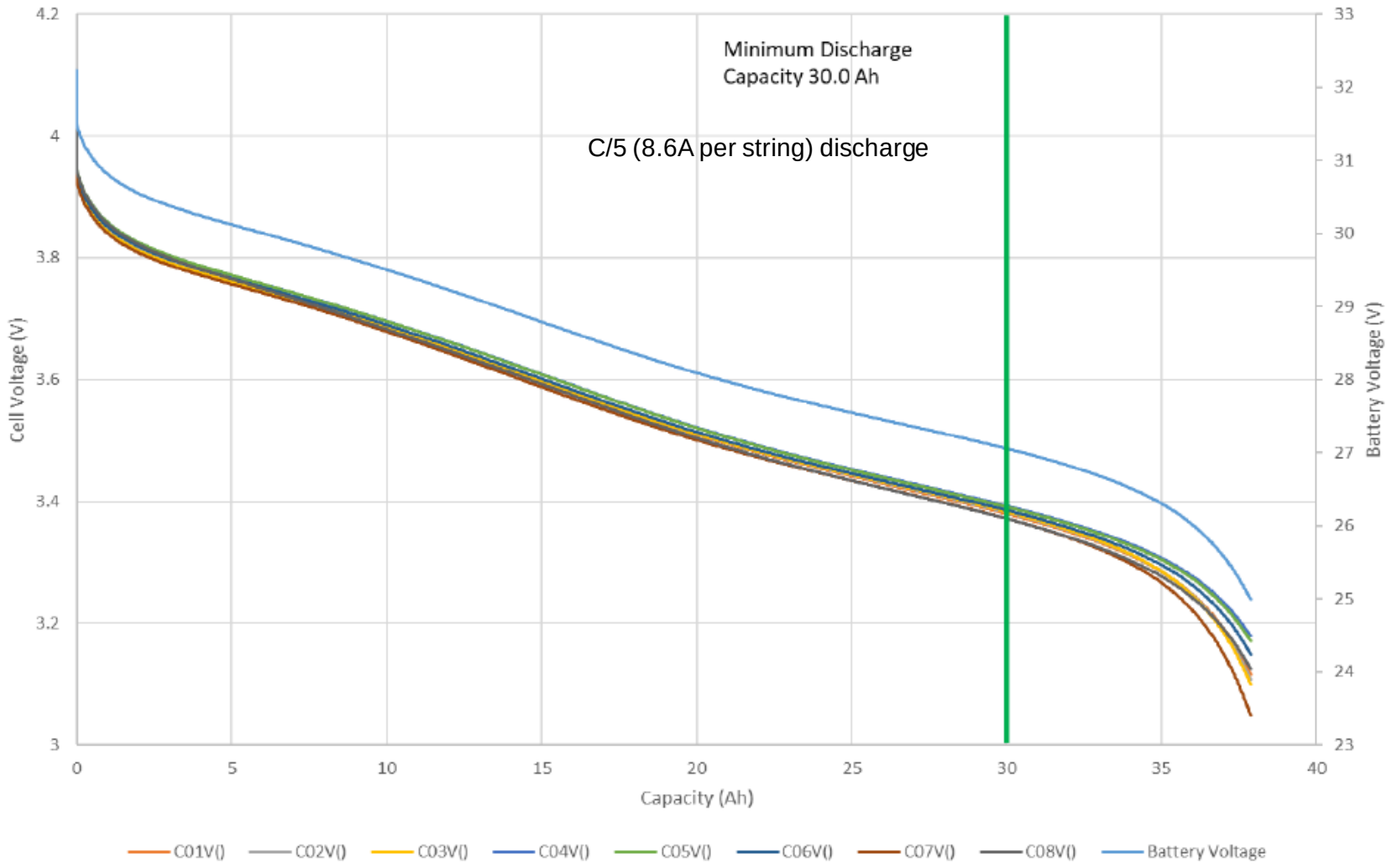
- Ti bipods elevate the assembly off the rover interface
- Numerous thermocouples on cells, case
- Thermostat-activated warm-up and survival heaters
- Mass: 29 kg

+35ºC Discharge after -20ºC Charge Test



Extensive qual and flight acceptance testing under a variety of thermal ambient/thermal vacuum testing conditions

-20ºC Discharge Capacity Test



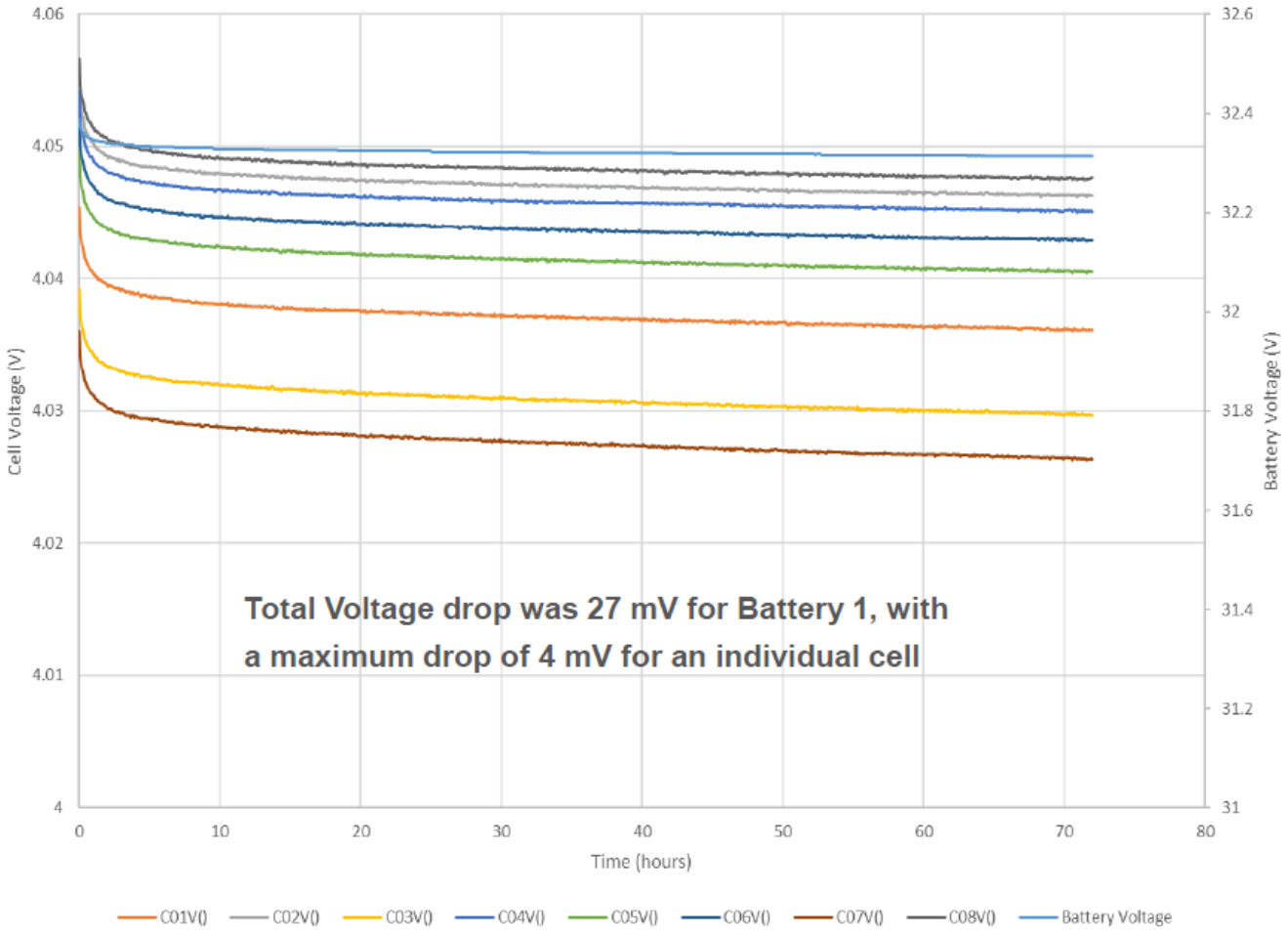
Extensive qual and flight acceptance testing under a variety of thermal ambient/thermal vacuum testing conditions

Post-Vibration Battery Impedance at 20°C

Battery String	SOC (%)	Initial Voltage (V)	Final Voltage (V)	Impedance (ΔV/ΔI) (mΩ)	Requirement (mΩ)
1	100	32.23	31.81	19.52	40
1	50	29.19	28.81	17.44	40
2	100	32.23	31.80	20.04	40
2	50	29.19	28.82	17.35	40

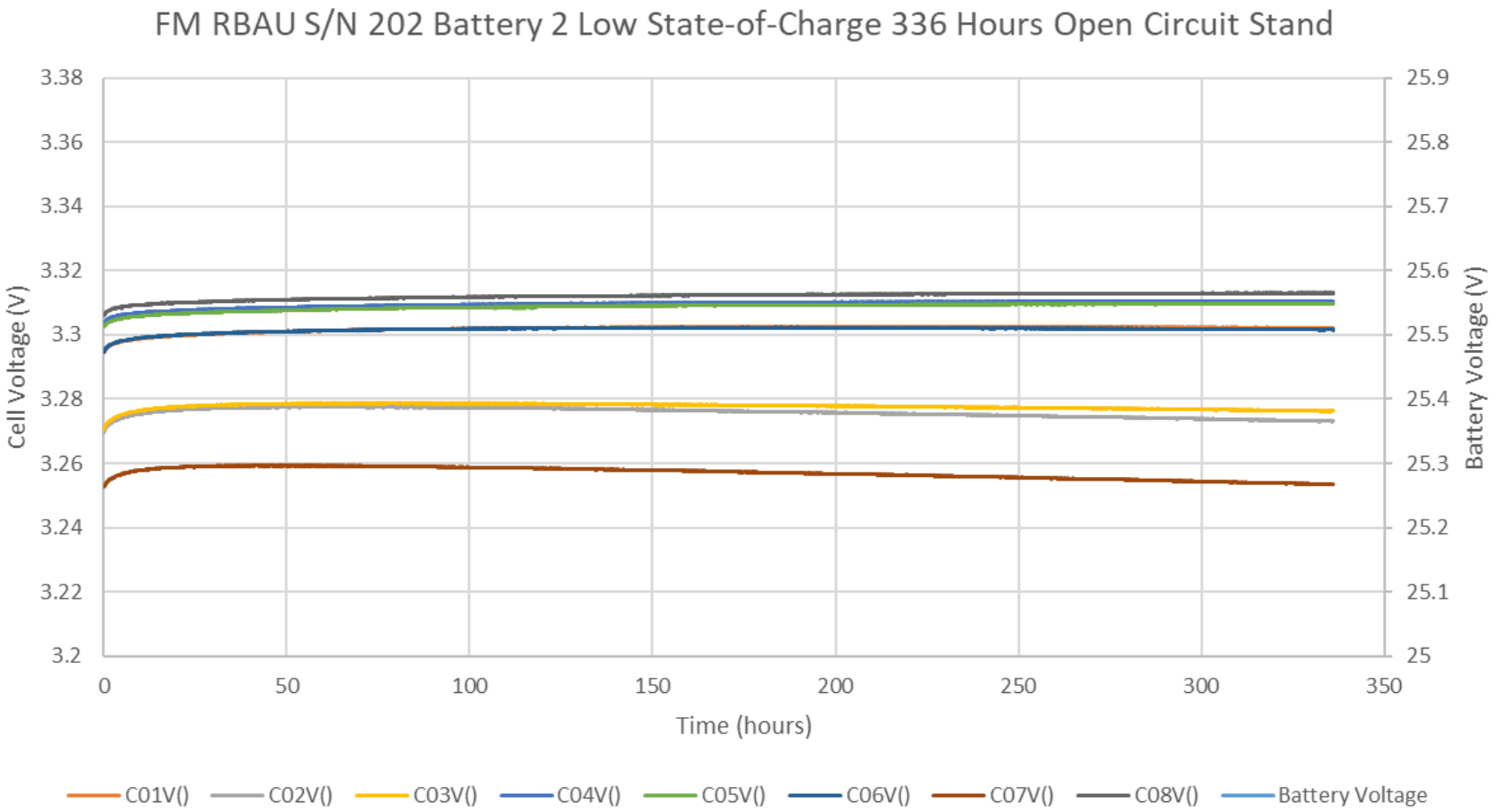
- *DC current-injection impedance measurements*
- *Impedance at 50% and 100% is very low, easily meets requirements*
- *No change in metrics (e.g. capacity, impedance) were observed after vibration*

Post-Vibration Top of Charge Stand Test



- *Open circuit voltage testing at top of charge*
- *Cells are individually monitored and balanced in flight by BCB*

14-Day Open Circuit Stand Test



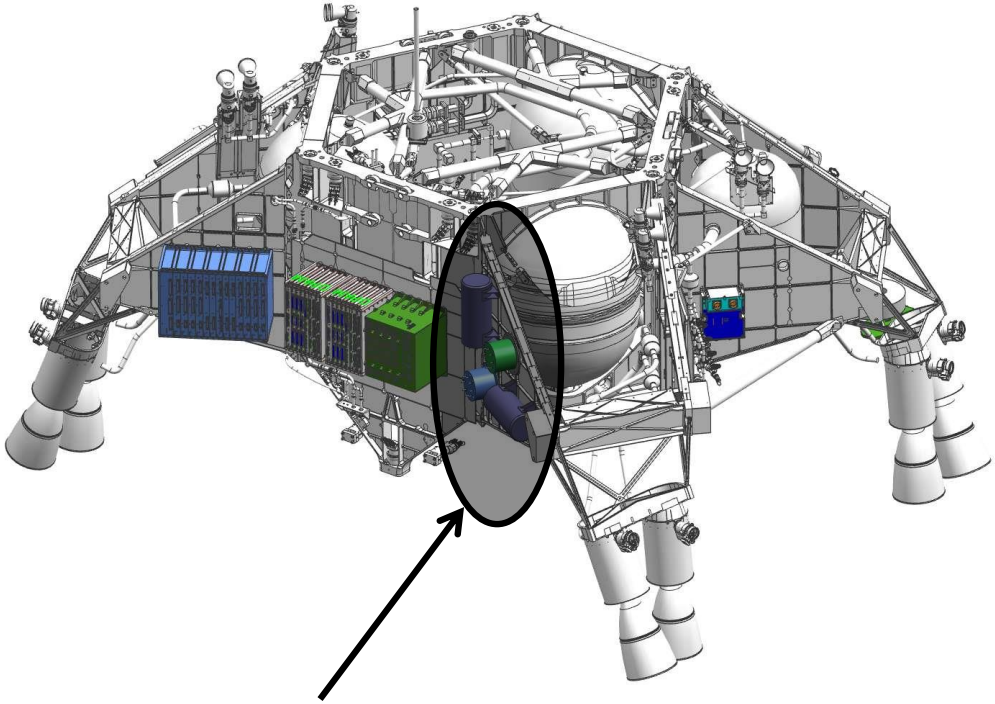
- *Open circuit voltage at bottom of discharge to observe any low-level self-discharge*
  - *Discharge 3V at C/5, C/10, C/20, C/100. Measure OCV for 14 days.*
  - *Also performed at cell level*
- *The worst case voltage drop for the FM RBAU is 6 mV after 14 days stand*
- *No indication of soft short.*

M2020 Descent Stage Thermal Batteries

M2020 Thermal Batteries:

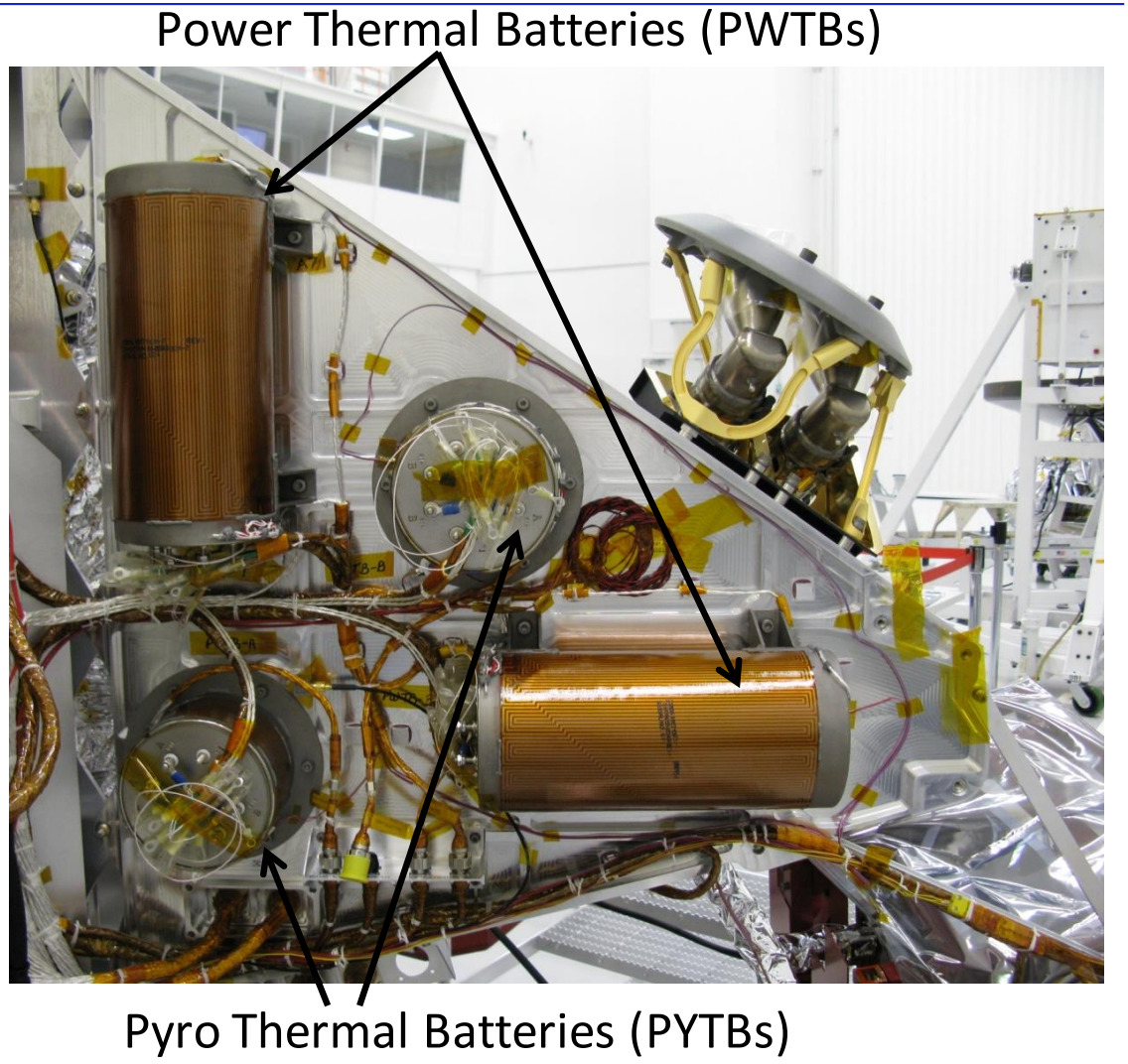
- MSL heritage design
- Reside on outrigger #4 on descent stage
- PWTBs: Provide power to descent stage during entry, descent, and landing (EDL)
- PYTBs: Fire pyrotechnic devices during EDL
- Batteries fabricated and qualified at vendor facility (EaglePicher Technologies, Joplin)
- Unactivated testing of batteries including activation circuit resistance, polarity, insulation resistance, etc. performed at JPL
- Survival heaters/PRTs and associated harnesses installed at JPL
- Additional tests to characterize performance carried out at JPL

M2020 Flight Descent Stage

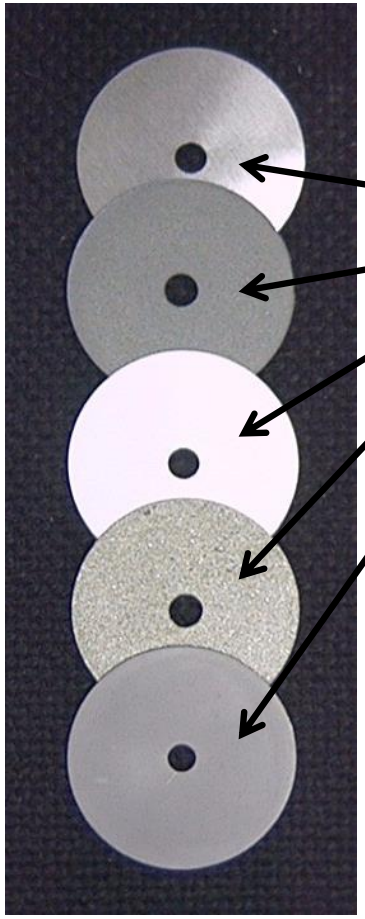


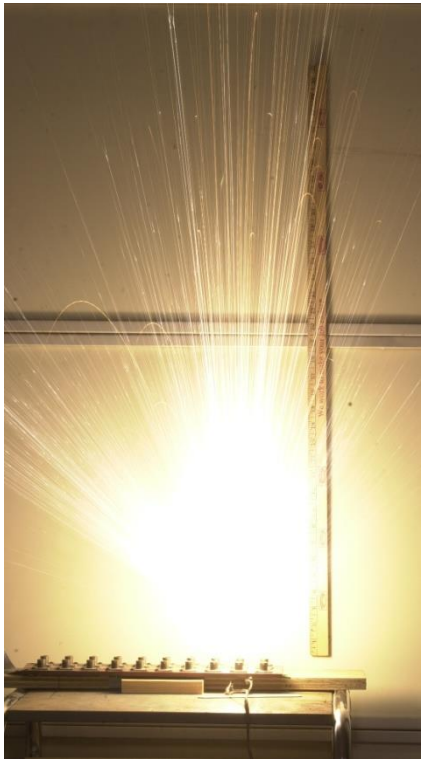
M2020 Descent Stage Thermal Batteries

- Batteries are single-use, long shelf life, high rate capability
- Inert until activated
- Activated with a current pulse across two sets of initiators to ignite the internal heat pellets
- Ignited heat pellets melt the electrolyte, operation of ca. 30 min.



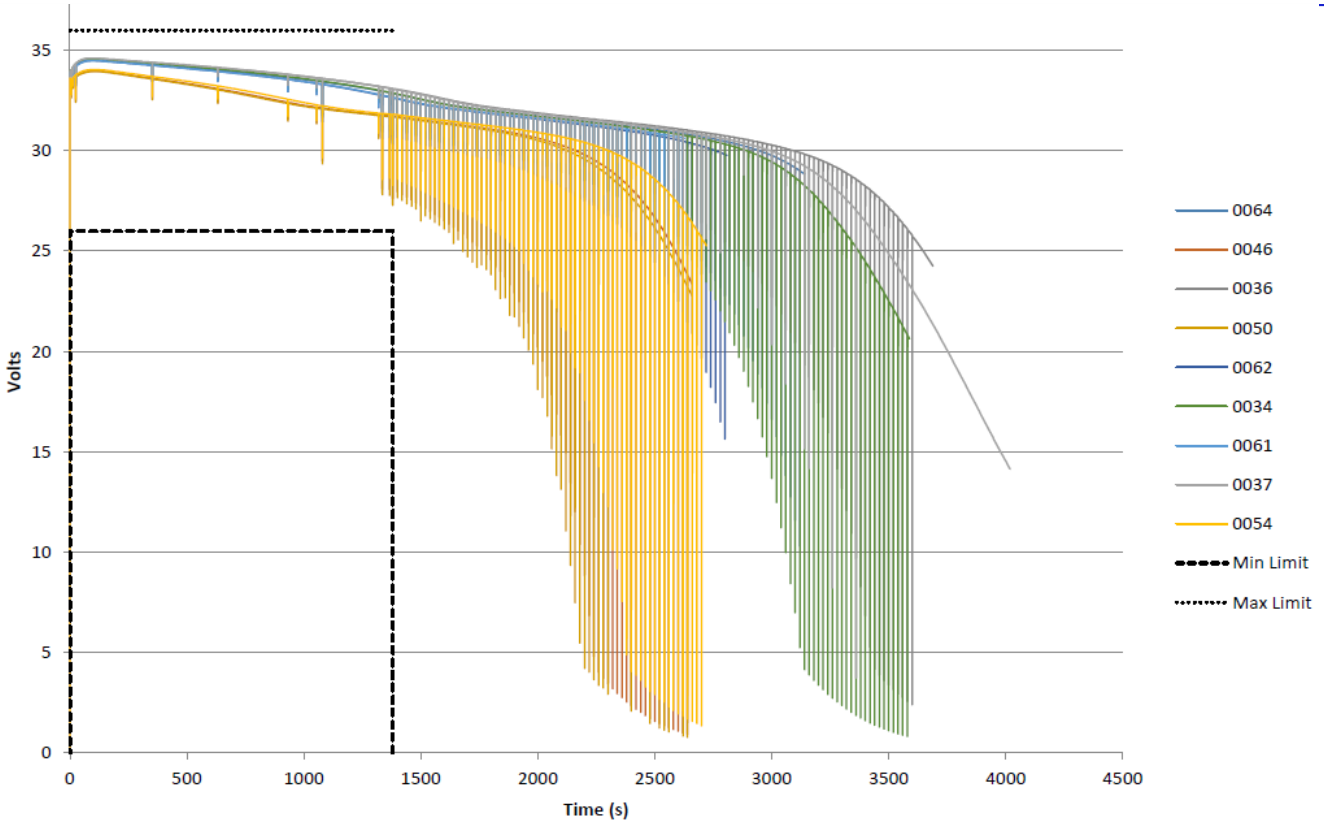
Thermal Batteries





Current pulse through pyrotechnic initiator (squib) ignites heat pellets through centerline, activating battery

Lot Acceptance Tests: PYTB

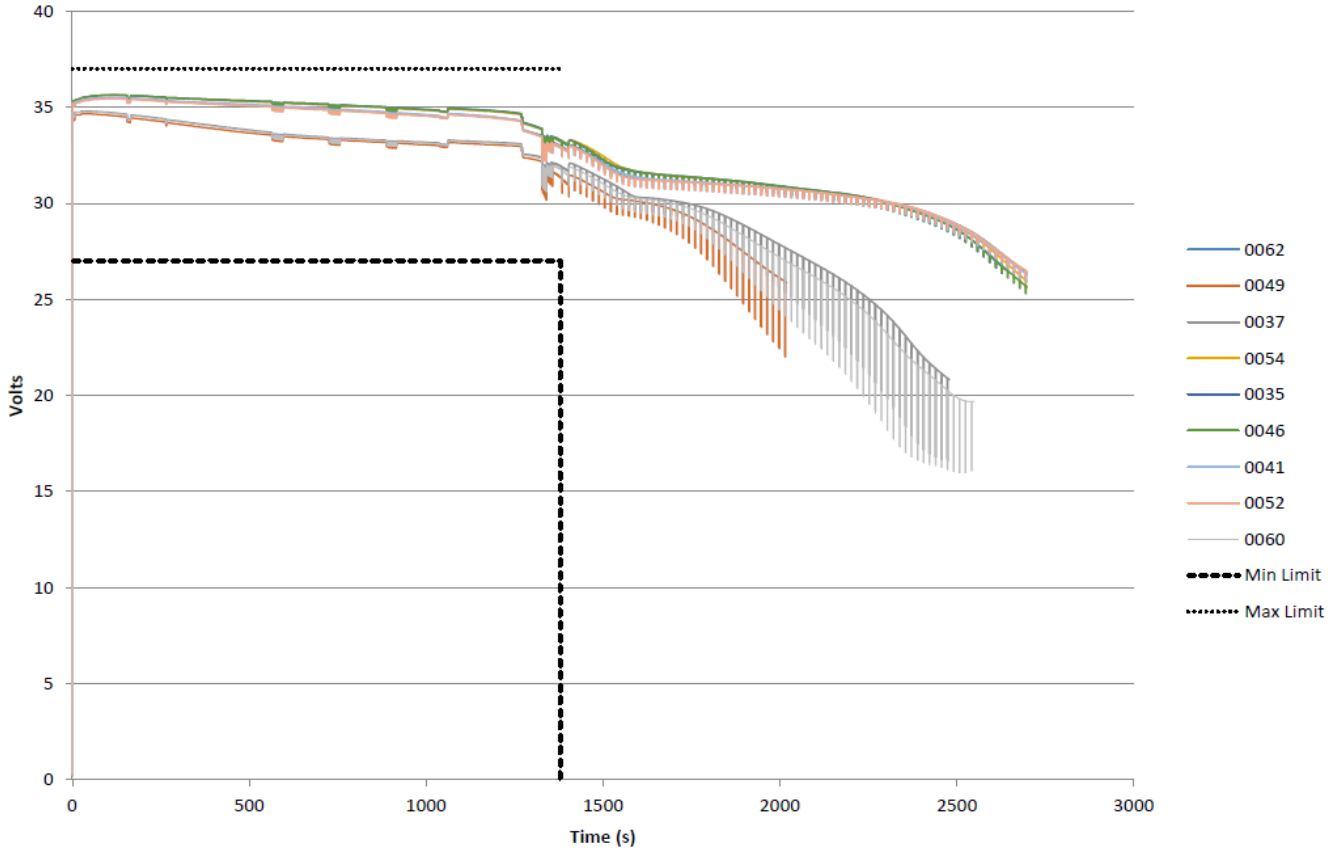


- Voltage: 26 to 36 V
- Rise Time: 1.0 sec max to >26 V
- Operating time after activation: 1380 s
- Shelf Life : > 4 years
- Pulse-type operation required in addition to a continuous load

<u>Load:</u>

- 1A constant baseload
- Up to 96 pulses
- 7A, 20 msec pulses
- 22 A (3 simultaneous pulses)
- 120 msec time between pulses

Flight Lot Acceptance Tests: PWTB



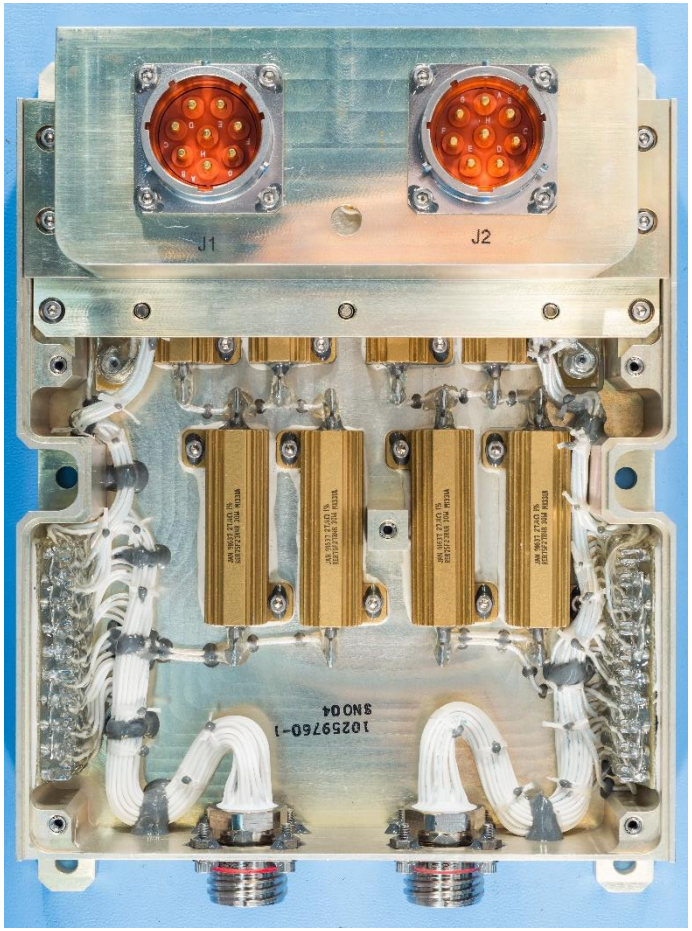
- Voltage: 27 to 37 V
- Rise Time: 1.0 sec max to >27V
- Operating time after activation: 1380 seconds
- Shelf Life : > 4 years
- Capacity (min): 6 Ah at >27V

<u>Load:</u>

- Complex load profile (≈1000 steps)
- Variable power loads 300-650W
- Superimposed 6 – 30A current pulses
- Tolerate a reverse current of 16A for 20 msec

Baseload Resistor Assembly (BLRA)

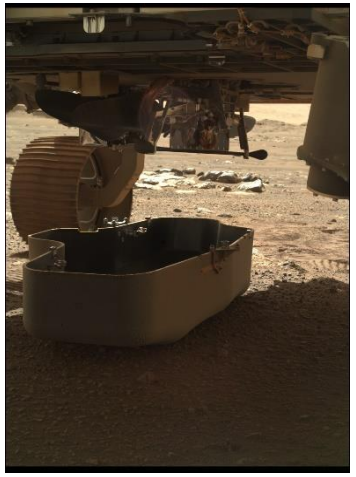
- BLRA distributes power from the A and B pyrotechnic thermal batteries to the pyro firing cards
- BLRA also provides a baseload for a bleed current to the PYTBs
  - Without the baseload, there is an increased chance that the PYTBs will short internally
  - 2 x 2 network of resistors provides a nominal 1 A baseload
  - A and B sides are electrically isolated from each other and do not share common connectors
  - Both sets of four 27.4Ω RER75 resistors in series + parallel arrangement offers some baseload redundancy in case of resistor failure
  - 27.4Ω baseload resistance yields 1.35 A BOL (PYTB at 37V) and 0.95 A EOL (PYTB at 26V)
  - Total power dissipated ≤ 100 W



M2020 BLRA (top cover removed)

Mars Helicopter: "Ingenuity"

- Six serial Sony SE US18650 VTC4 Li-ion cells (15.0 – 25.2V)
- Cell nameplate capacity = 2.00 Ah
- Cell max discharge rate = >25 Amps
- Cell manufacturer max charge voltage = 4.25V
  - Operational max charge voltage = 4.20V
- Power capability:
  - Continuous = 60 W x 6 cells = 360 W
  - Peak power = 85 W x 6 cells = 510 W
- Estimated BOL battery energy:
  - 25°C = 44.4 Wh
  - 0°C = 38.8 Wh
- Cell mass = 45.5g x 6 cells = 273g
- Cell balancing charge management present in architecture
  - However, this feature was not implemented in flight (i.e., not needed).
- Operational allowable flight temperature (high rate discharge): 10°C to 25°C
- Operational allowable survival temperature (low rate discharge): -15°C to 25°C
- Operational allowable surface temperature (low rate charge): -5°C to 25°C
- Non-operational allowable flight temperature: - 20°C to 45°C
  - Temperature range applies to cruise period
- Cells maintained at a low SOC during cruise (20-35% SOC)
- Primary mission is to complete five flights of increasing complexity as a technology demonstration.



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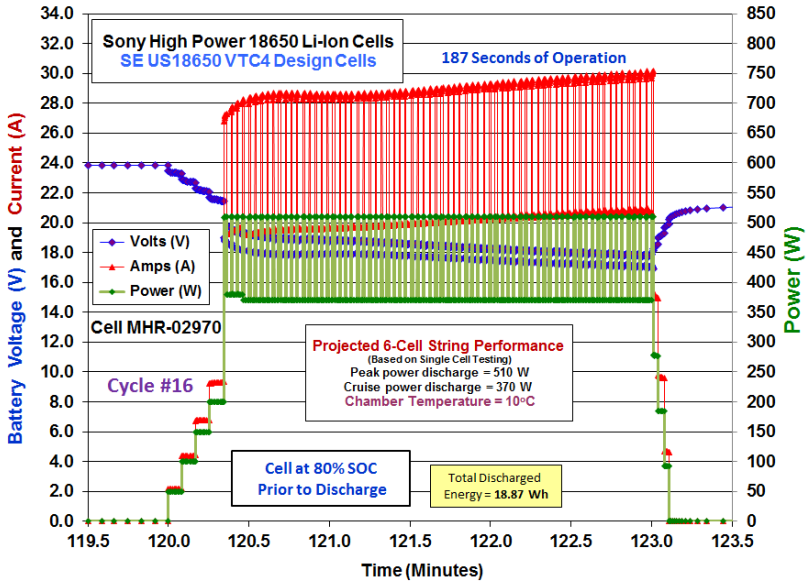
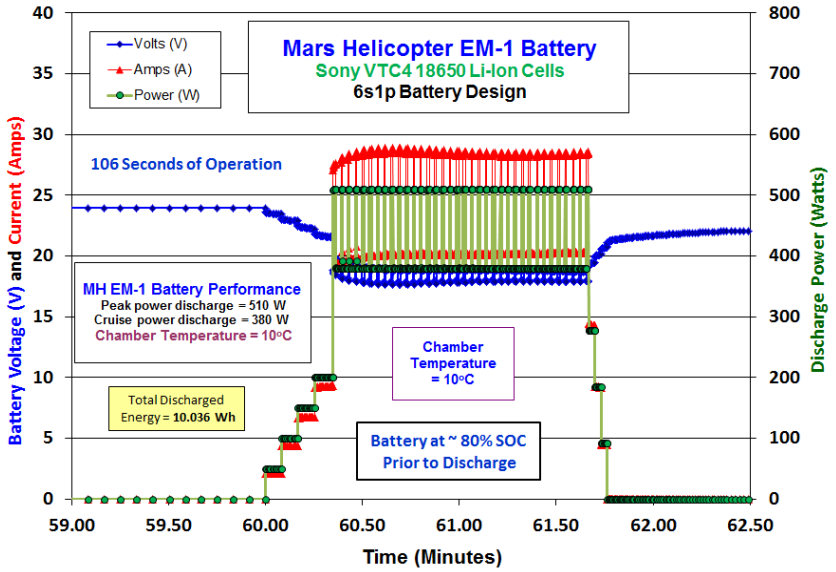
Performance of Sony SE US18650 VTC4 Li-ion Cells High Power Testing: 10ºC, 80% SOC, 72 Pulses





- The battery design is capable of supporting 187 seconds of high power operation under an aggressive load profile
  - 510W peak and 370W nominal power levels at the string level.
  - Initial Cell Temperature = 10ºC
- Maximum cell discharge current observed = 30.159A, Minimum battery voltage projected = 16.905 V
  - Actual flights had much more benign load profiles, and battery was heated to ~ 20ºC prior to flights.
- *To-date, 15 flights have been successfully completed on the surface of Mars, exceeding prime objective of completing 5 flights of increasing complexity.*
- *The Ingenuity Helicopter has flown a total of > 2.8 km on the surface of Mars !!*

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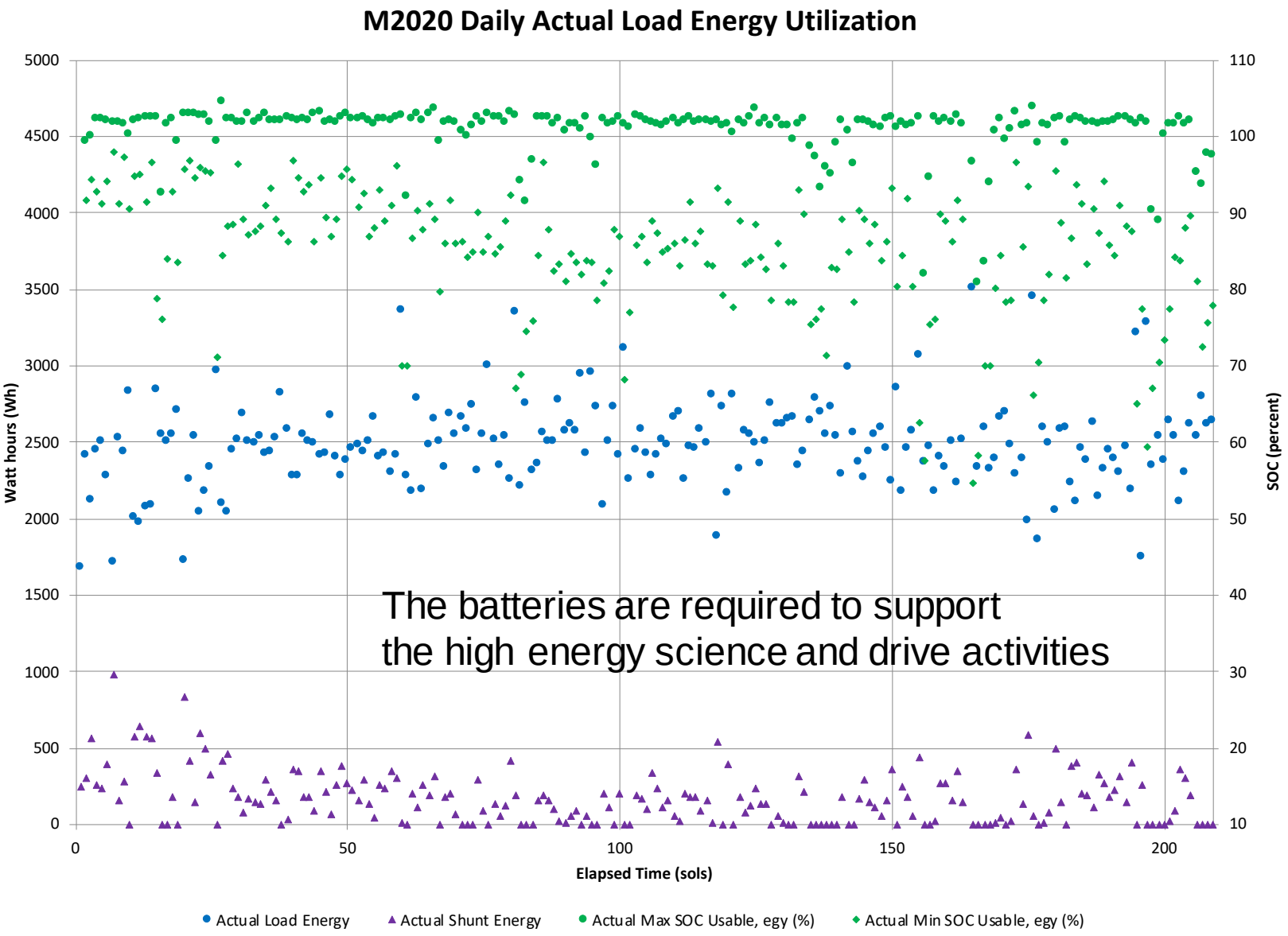
Surface Operations

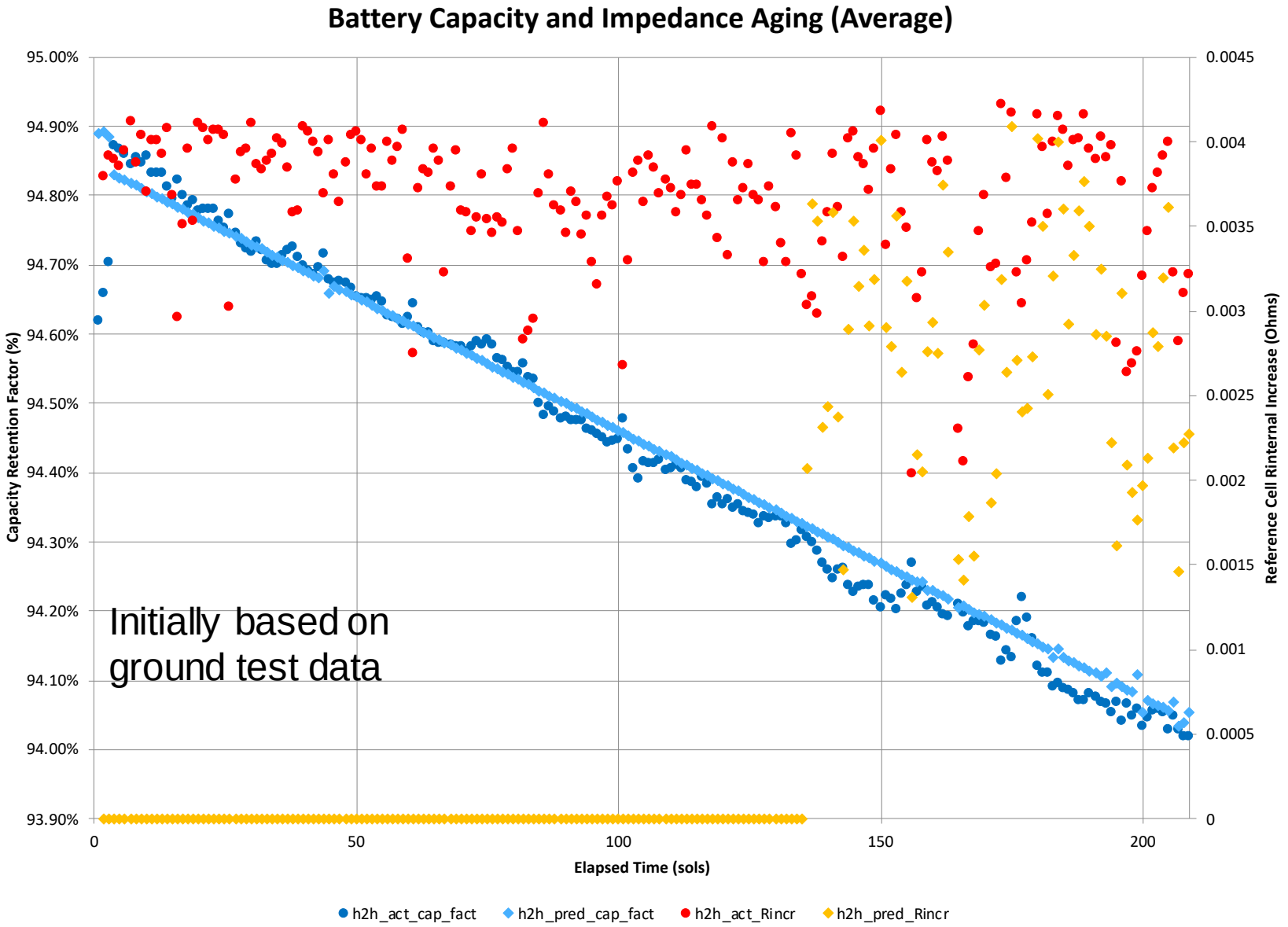
For rover surface operations, the following key battery metrics are monitored each sol:

- Bus and Battery Voltage
  - Expected to be between 29.3 V and 32.8 V
- Battery minimum SOC
  - Verify battery SOC is no lower than 40%
- Maximum battery discharge current
  - Verify battery discharge current does not exceed 12 A per battery
- Battery temperature
  - Verify that the model temperature is within 2°C of actual
- Battery cell voltage spread
  - Verify cell-to-cell voltage spread does not exceed 150 mV

Daily Actual Load Energy Utilization



Battery Capacity and Impedance Aging



Summary

- Mars 2020 mission required various power, energy storage, and distribution systems
  - Includes power and pyrotechnic thermal batteries, baseload resistor assemblies, rechargeable rover and helicopter batteries
- Wide range of qualification and flight acceptance tests were carried out at the cell and module level as a function of temperature, pressure, and dynamic conditions
- Mission operations closely monitors power and energy storage parameters
  - Provides feedback to mission regarding operational capabilities and lifetime projections
- To date, the mission has been successful with the power and energy storage elements working as planned.
  - 265 sols, 4 samples acquired, 2.7 km roved, 2.8 km flown

Acknowledgements

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Backup