The Use of COTS Lithium-ion Batteries for NASA JPL Missions

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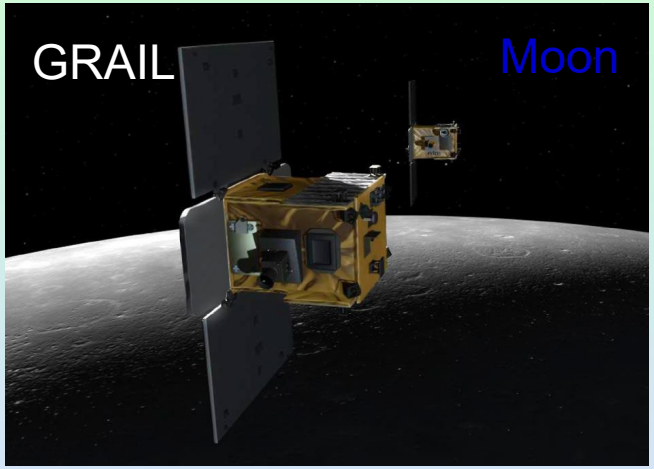
2022 Space Power Workshop (Virtual)

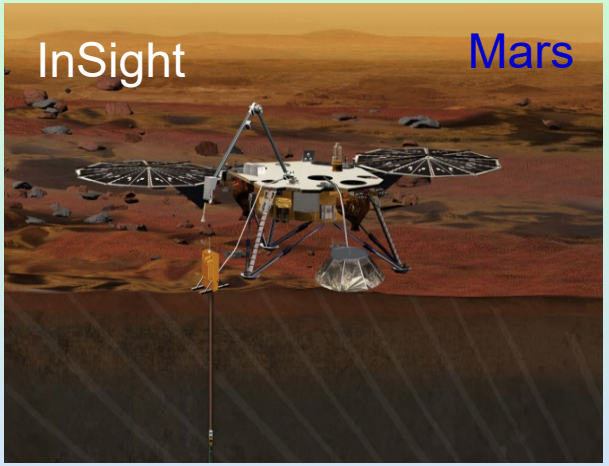
April 28, 2022

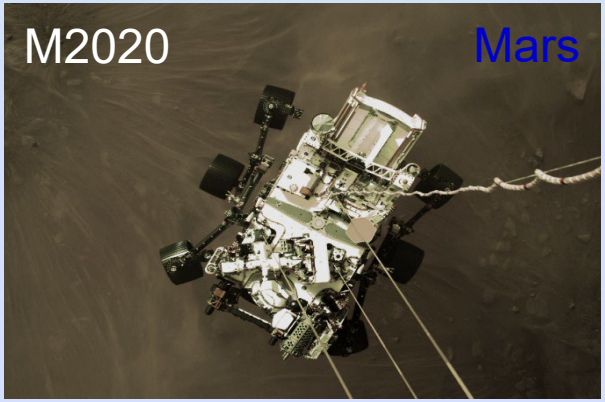
Outline

- Overview of State-of-Practice (SOP) Large Format Rechargeable Batteries
- Examples of NASA Missions with SOP Small Cell Rechargeable Batteries
- The Planned Europa Clipper Mission
  - Battery description and driving requirements
  - Cell level performance testing
  - Module level performance testing
  - 8s16p Pre-Qualification Battery
- The Mars Helicopter “Ingenuity” Battery
  - Battery description and driving requirements
  - Cell level and module level performance testing
  - Acceptance testing of flight battery
  - Telemetry data of flight battery operation on Mars
- Conclusions

Large Cell Li-Ion Battery Applications for Solar System Exploration

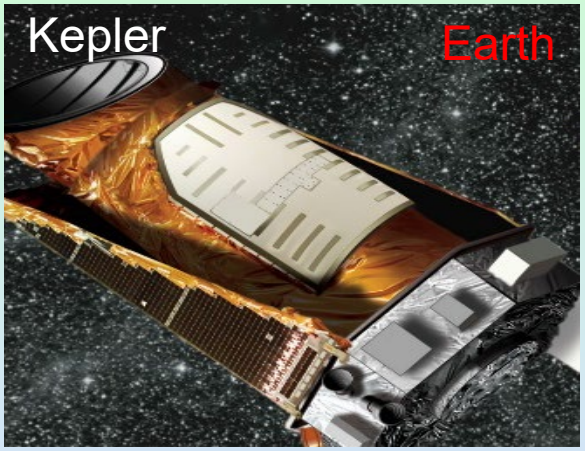


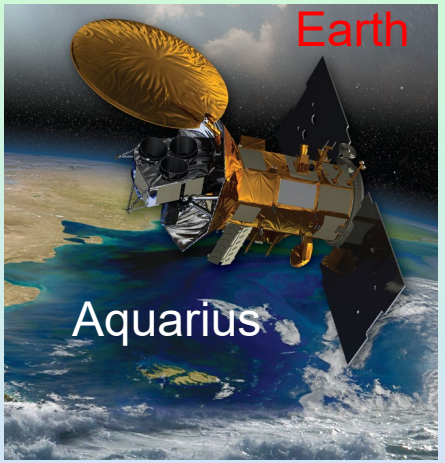


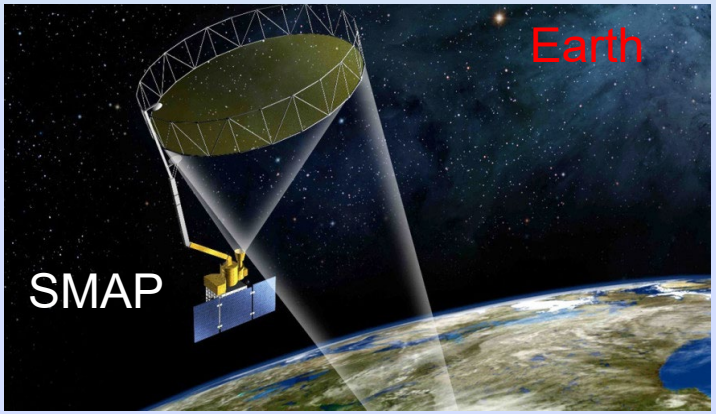


- Large cell format batteries have been successfully used on a number of planetary missions.
- Rechargeable Li-ion batteries provide power during launch, and power during eclipses and night time operations with solar arrays, and for load-levelling with both solar arrays and radioisotope thermoelectric generator power sources

Small Cell COTS 18650 Li-Ion Battery Applications







- Small format 18650 cells (Sony/ABSL):
  - Mars Express, 2003
  - Kepler, 2009
  - Lunar Reconnaissance Orbiter (LRO), 2009
  - Aquarius, 2011
  - NuSTAR, 2012
  - SMAP, 2014
  - OSIRIS REX, 2016

- The use of COTS 18650-size Li-ion cells have been used on a number of NASA missions.
- Approach does not require individual cell monitoring and control.
- These batteries utilized the Sony HCM 18650 cell.

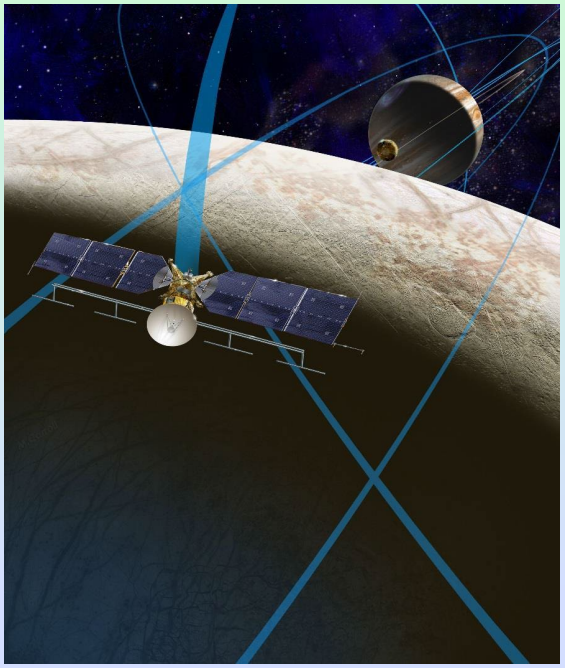
NASA's Planned Europa Clipper Mission

➢ **Anticipated Launch Date: 2024**

- **NASA's planned Europa mission would conduct a detailed reconnaissance of Jupiter's moon Europa and investigate its habitability for life.**
- **The mission would send a radiation tolerant spacecraft into a long, looping orbit of Europa to perform repeated close flybys.**

➢ **Planned NASA-selected Instruments**:.

1) Plasma Instrument for Magnetic Sounding (PIMS)
2) Mapping Imaging Spectrometer for Europa (MISE)
3) Europa Imaging System (EIS)
4) Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON)
5) Europa Thermal Emission Imaging System (E-THEMIS)
6) Mass Spectrometer for Planetary Exploration/Europa (MASPEX)
7) Ultraviolet Spectrograph/Europa (UVS)
8) Surface Dust Mass Analyzer (SUDA)



Artist's concept Image courtesy NASA/JPL-Caltech

Key Driving Battery Requirements

- **Long life = 11 years (long cruise period)**
- **High specific energy (*Sony HCM cells do not provide the desired energy*)**
- **High radiation tolerance**
- **Low magnetic signature**
- **Compliance to iESD requirements**
- **Operating Temperature Range: 0° to +30°C**

NASA's Planned Europa Mission: Lithium-Ion 18650 Cell Chemistry Assessment

- Comparison of COTS Cells Evaluated: High Specific Energy Designs
- Based on Voltage Range of 3.0V to 4.10V.
  - **LG Chem MJ1 18650 Cells**
    - Specific Energy = ~ 225 Wh/kg
    - Cell Capacity = 2.853 Ah
    - Maximum Discharge rate = 10 Amps
  - **Molicel ICR-M 18650 Cells**
    - Specific Energy = ~ 205 Wh/kg
    - Cell Capacity = 2.620 Ah
    - Maximum Discharge rate = 6.2 Amps
  - **Molicel ICR-J 18650 Cells**
    - Specific Energy = ~ 168 Wh/kg
    - Cell Capacity = 2.133 Ah
    - Maximum Discharge rate = 10 Amps
  - **Panasonic NCR-A 18650 Cells**
    - Specific Energy = ~ 213 Wh/kg
    - Cell Capacity = 2.620 Ah
    - Maximum Discharge rate = 6.2 Amps
  - **Panasonic NCR-B 18650 Cells**
    - Specific Energy = ~ 232 Wh/kg
    - Cell Capacity = 2.960 Ah
    - Maximum Discharge rate = 4.87 Amps

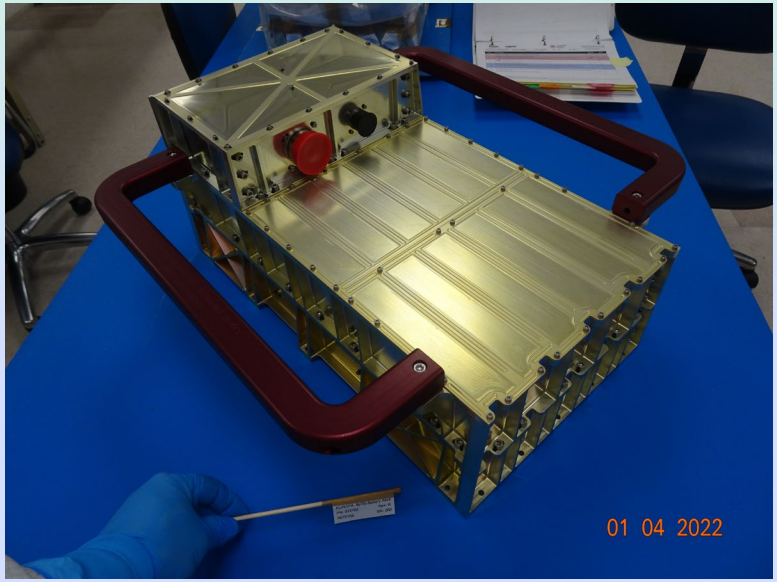
Electrical performance tests performed:

1. Cycle life performance under various conditions
2. Storage life testing at the cell level (at 0°C and +25°C)
3. High temperature storage characterization (+30°C)
4. 8-Cell module 100% DOD cycle life testing at +20°C
5. 8-Cell module long term storage life testing at +0°C
6. Discharge and charge rate characterization testing
7. Radiation tolerance (subjected to ^{60}Co gamma rays)

- The LG Chem MJ1 cell was identified as the most viable option for the Europa Clipper Mission.
- The LG Chem MJ1 cell displayed the following favorable attributes:
  - Excellent specific energy
  - Good calendar and cycle life
  - Excellent radiation tolerance
  - Desirable sloping voltage curve
  - High discharge rate capability

NASA's Planned Europa Mission:
Baseline Li-Ion Battery

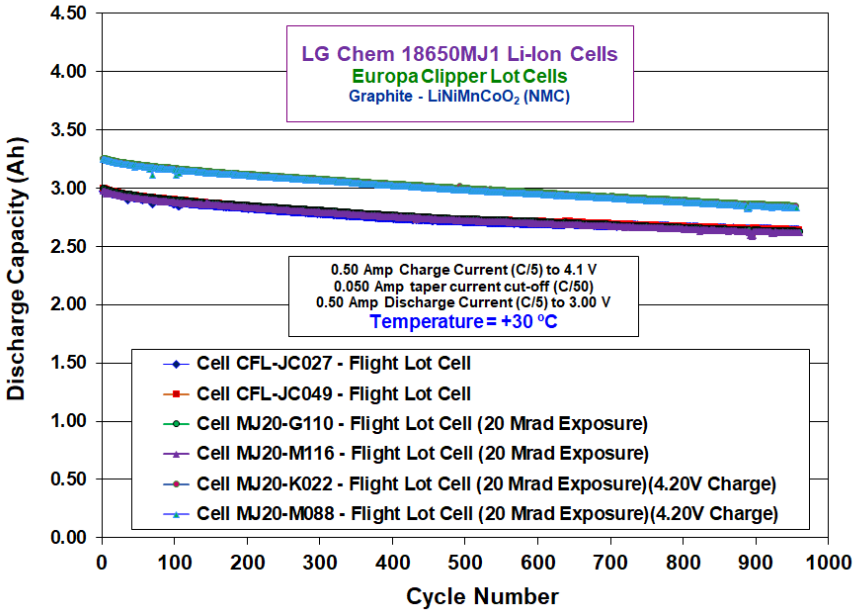
- **Baselined Europa Clipper Li-ion Battery:**
- **Three 8s72p Modules connected in parallel**
  - **LG Chem MJ1 18650 Li-ion Cells**
- **Nominal Voltage range: 26.0V to 32.80V**
- **Nameplate Capacity = 180 Ah each 8s72p**
- **AFT Range = 0°C to +30°C**
- **Total Energy at 0°C (BOM) = > 14,100 Wh**
  - **For 3 x 8s72p connected in parallel**
- **Mass = 36.7 kg each 8s72p module**
- **Low Magnetic Signature Design**
- **Implemented i-ESD Mitigations in Design**
- **Low Cycle Life Requirement =**
  - **< 100 Cycles up to 70% DOD**
- **Benign charge and discharge rates required.**
- **Battery designed and fabricated by EnerSys/ABSL**



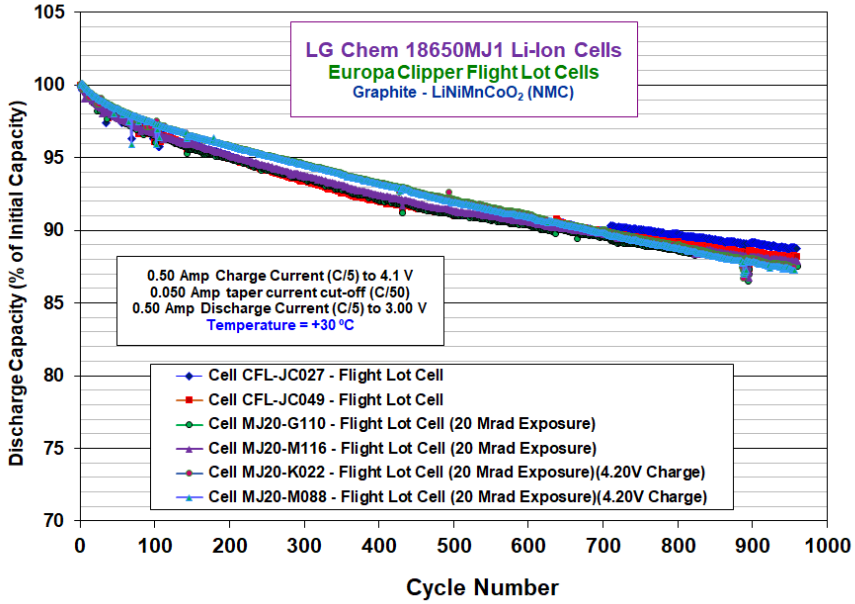
NASA's Planned Europa Clipper Mission:
Li-Ion Cell Level Testing: Cycle Life Performance

- ***Results of 100% DOD Cycle Life Testing +30°C of LG Chem MJ1 Cells***

Discharge Capacity (Ah) at 30°C



Percentage of Initial Capacity (%) at 30°C



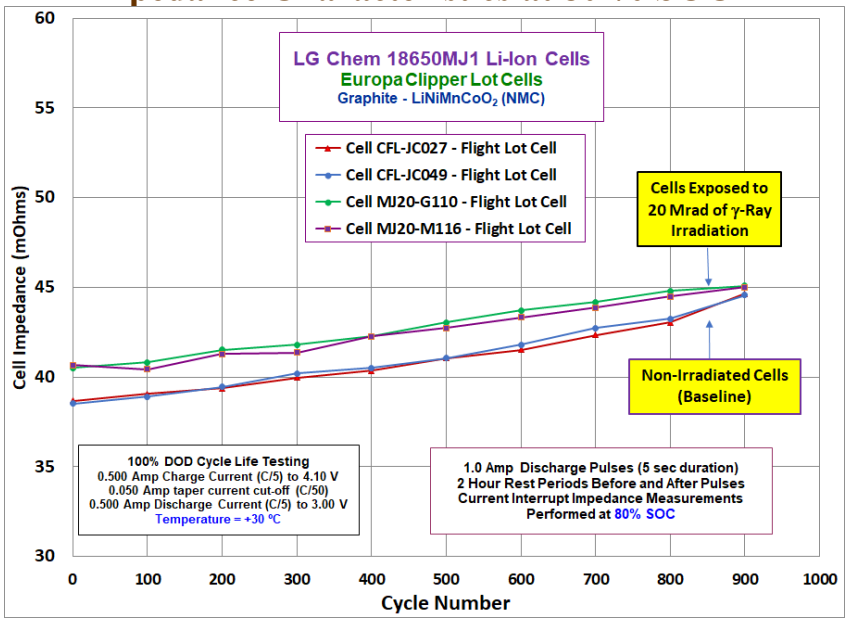
- **No significant impact of radiation upon the cycle life performance at +30°C was observed with LG Chem MJ1 cells up to 20 Mrad levels.**
  - **Baseline cells : After 300 cycles, cells displayed 2.7946 Ah and 93.52 % % capacity retention.**
  - **20 Mrad cells : After 300 cycles, cells displayed 2.8000 Ah and 93.62 % % capacity retention.**
  - **20 Mrad cells : After 300 cycles, cells displayed 3.0718 Ah and 94.54 % % capacity retention (4.20V Charge)**

M. C. Smart, F. C. Krause, B. V. Ratnakumar, A. Ulloa-Severino, L. Bienvenu, and T. Mault, "The Use of High Specific Energy 18650-Size Li-Ion Cells with Good Radiation Tolerance for Missions to the Outer Planets", 2020 Conference on Advanced Power Systems for Deep Space Exploration, Pasadena, CA, October 28, 2020.

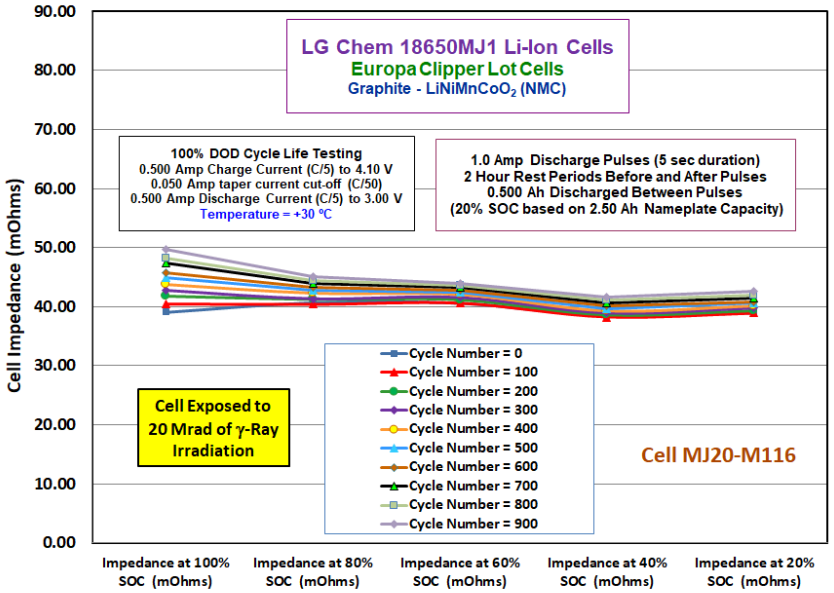
NASA's Planned Europa Clipper Mission:
Li-Ion Cell Level Testing: Cycle Life Performance

- ***Results of 100% DOD Cycle Life Testing +30°C of LG Chem MJ1 Cells***

Impedance Characteristics at 80 % SOC



Impedance Characteristics vs. Cell SOC



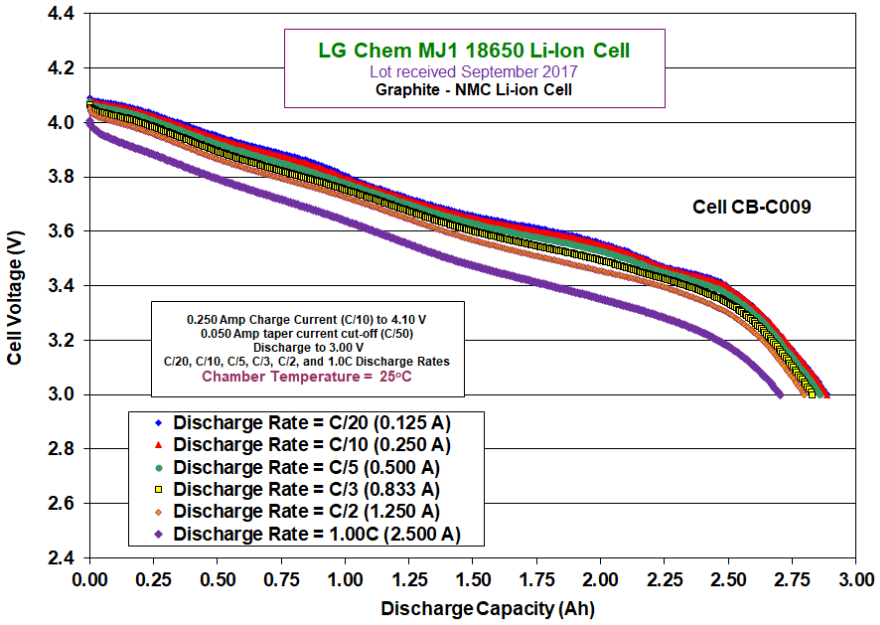
- **Initially, a modest increase in the cell impedance is observed with the cells that were subjected to 20Mrad of g-ray irradiation. However, the growth in impedance of the irradiated cells with cycling is comparable (if not better) that the baseline cells that were not irradiated.**
- **In general, the LG Chem MJ1 cell display impressive impedance growth characteristics, with less than 16% increase observed (at 80% SOC) for all cells after completing 900 cycles (100% DOD).**

M. C. Smart, F. C. Krause, B. V. Ratnakumar, A. Ulloa-Severino, L. Bienvenu, and T. Mault, "The Use of High Specific Energy 18650-Size Li-Ion Cells with Good Radiation Tolerance for Missions to the Outer Planets", 2020 Conference on Advanced Power Systems for Deep Space Exploration, Pasadena, CA, October 28, 2020.

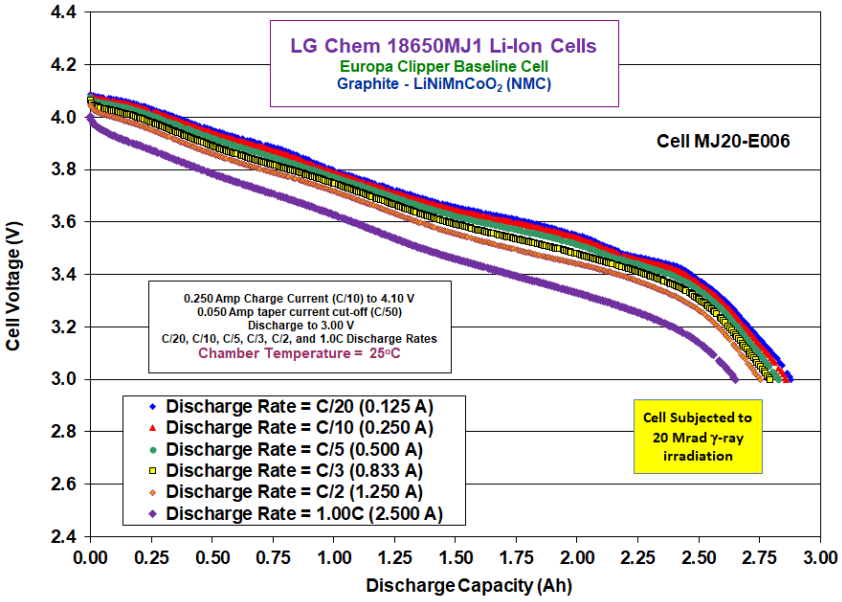
NASA's Planned Europa Clipper Mission:
Li-Ion Cell Level Testing: Discharge Rate Performance

- ***Results of discharge rate testing at 25°C: Impact of radiation***

Discharge Capacity (Ah) at 25°C (No Irradiation)



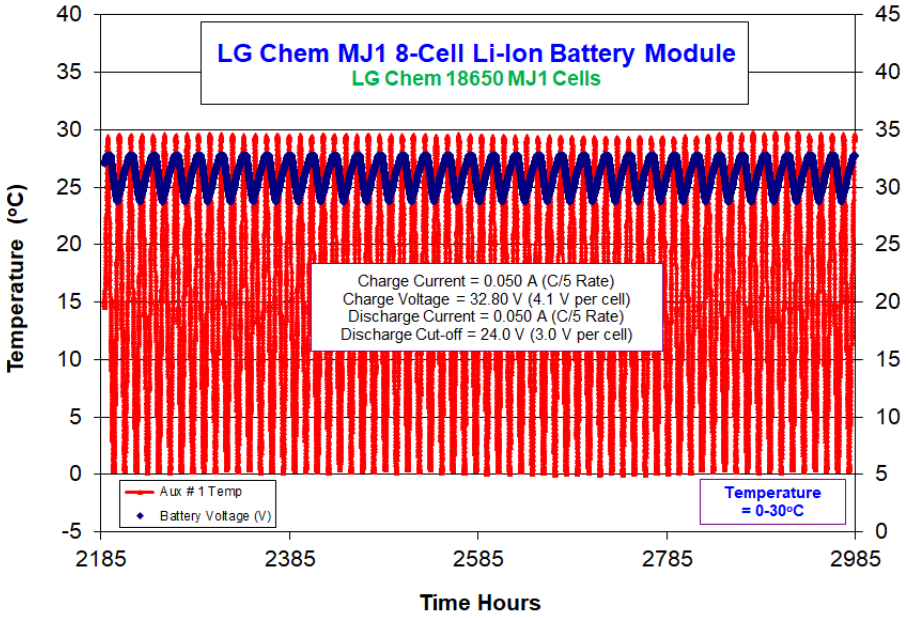
Discharge Capacity (Ah) at 25°C (Exposed to 20 Mrad γ-rays)

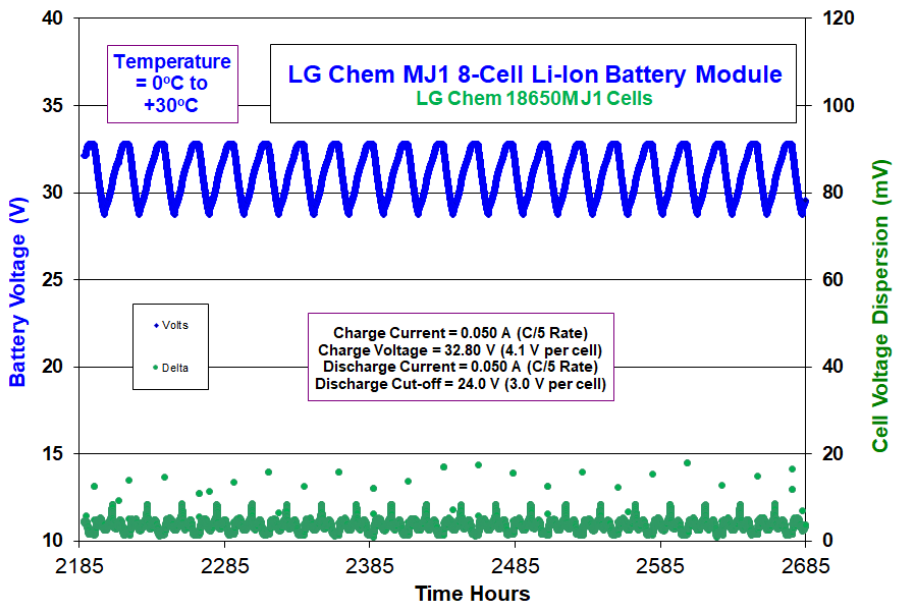


- **The impact of radiation upon the rate capability of LG Chem MJ1 cell is modest.**
  - **Upon irradiation with 20 Mrad, a decrease of < 2.0% capacity was observed for all discharge rates.**
  - **The most significant decrease was observed at high rate (1C) and lower temperatures.**

NASA's Planned Europa Clipper Mission:
Li-Ion String Level Testing: 100% DOD Cycle Life

- ***Thermal Cycling of 8s1p String: 70% DOD Cycling from 0°C to +30°C***



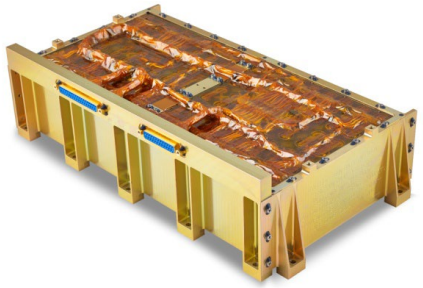


- **Thermal cycling was implemented on an 8s1p string over the AFT range.**
  - **Over 270 operational thermal cycles completed on the module.**
  - **Minimal cell to cell voltage dispersion observed throughout the testing (< 10mV).**
  - **Prior to thermal cycling, the module successfully completed 800 cycles (100% DOD) at +30°C.**
  - **No impact observed as a result of the thermal cycling.**

NASA's Planned Europa Clipper Mission:
Pre-Qualification Battery Program: ABSL "Flight-like" 8s16p

❑ *Objective of Pre-Qualification Battery Program*

- To address planetary protection and mission requirements, the batteries used for the Europa Clipper mission were initially expected to be exposed to high levels of radiation
- The Pre-Qualification Battery effort was initiated as a means to validate using ^{60}Co as planetary protection (PP) approach. Besides the cells, the electrochemically inert battery materials had not been exposed to high levels of radiation previously.
- To envelop PP and mission exposure, the battery was subjected to a total of 20 Mrad of γ-ray irradiation.
  - 12 Mrad for PP sterilization
  - 8 Mrad for Mission Requirements (4 Mrad TID x 2 for Qual)
- After irradiation, the battery was subjected to full qualification testing:
  - **Functional characterization**
  - **Electrical characterization**
  - **Random vibration testing**
  - **Pyro-shock testing**
  - **Thermal vacuum testing**
  - **Post-environmental testing characterization**



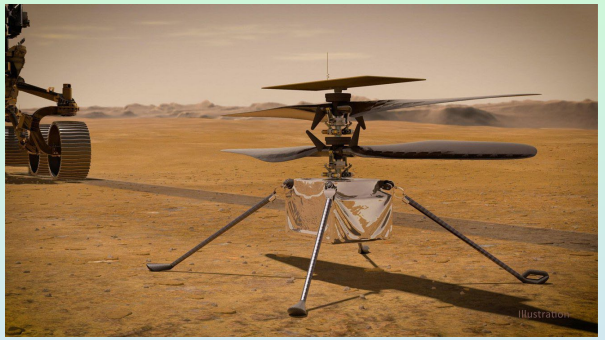
The battery successfully passed this qualification testing.

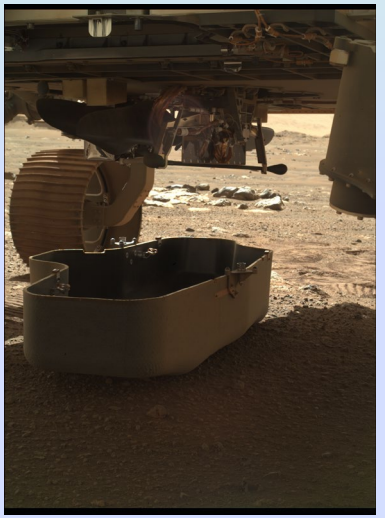
- ***Ultimately, irradiation of the batteries with ^{60}Co for PP compliance was determined not to be necessary.***
- ***Therefore, this tests represents a large amount of margin with respect to the radiation tolerance.***

M. C. Smart, F. C. Krause, B. V. Ratnakumar, A. Ulloa-Severino, L. Bienvenu, and T. Mault, "The Use of High Specific Energy 18650-Size Li-Ion Cells with Good Radiation Tolerance for Missions to the Outer Planets", 2020 Conference on Advanced Power Systems for Deep Space Exploration,

Li-Ion Battery Used on Mars Helicopter "Ingenuity": Use of COTS High Power Sony VTC4 18650 Cells

- **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, but not used.
  - 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 maintained at a low SOC during cruise (<35% SOC)

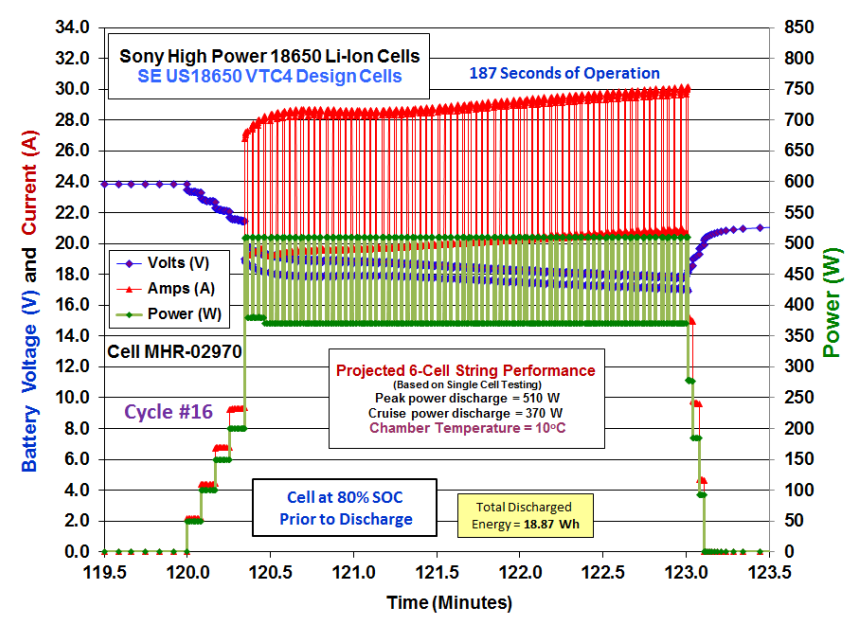


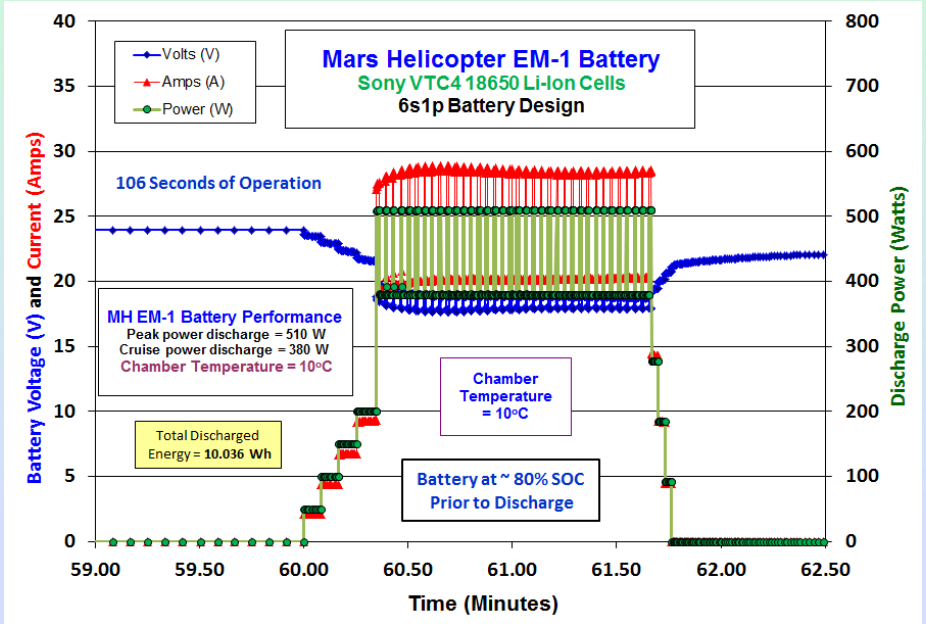


M. C. Smart, F. C. Krause, J. P. Jones, B. V. Ratnakumar, A. Lawrence, E. Brandon, B. Burns, G. A. Carr, J. Balaram, M. Aung, and A. Ulloa-Severino, "The Performance Evaluation of 18650-Size Lithium-Ion Cells and Batteries for Future NASA Missions", Pacific Power Source Symposium 2019, Waikoloa, Hawaii,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

Performance of Sony SE US18650 VTC4 Li-ion Cells

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





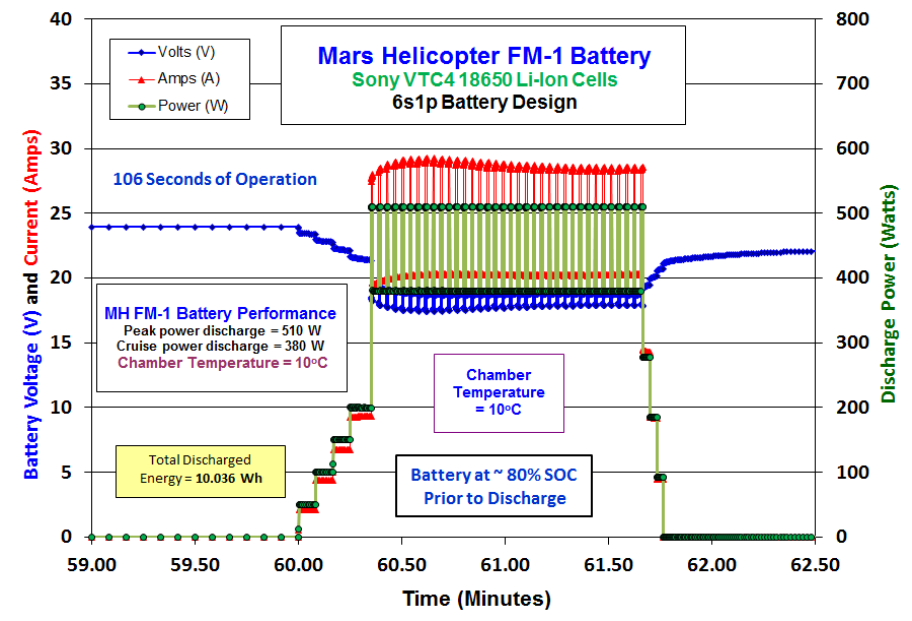
- The Sony VTC4 cell design is capable of supporting 187 seconds of high power operation under an aggressive load profile, corresponding to 510W peak and 370W nominal power levels at the string level
- Initial Cell Temperature = 10°C
- **Maximum cell discharge current observed = 30.159A**
- **Minimum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

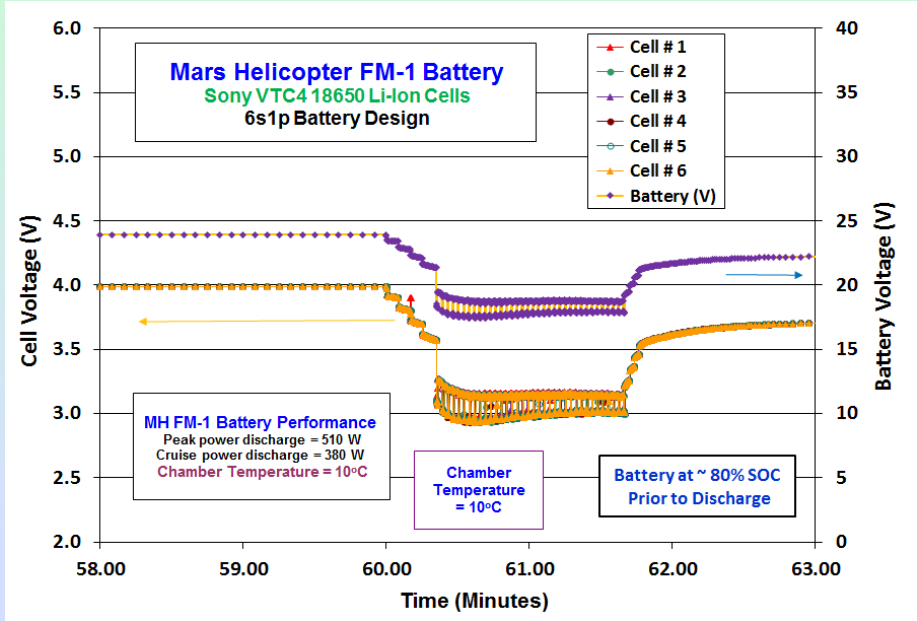
Prototype battery demonstrated to support peak power demands.
Performance was confirmed on the flight battery during acceptance testing.

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.

Acceptance Testing of Ingenuity Flight Battery

High Power Testing: 10°C, 80% SOC

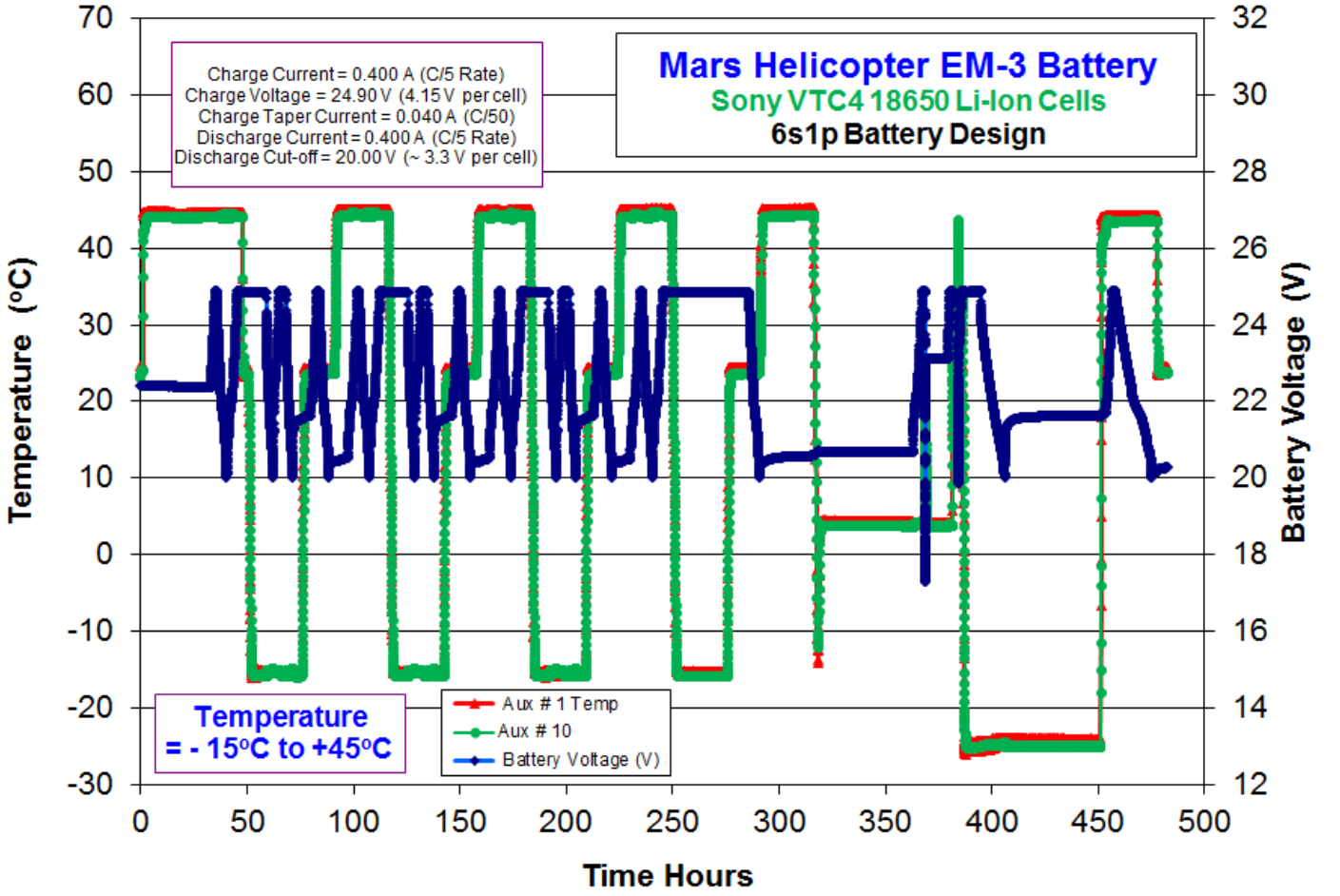




- The flight battery was demonstrated to support 106 seconds of high power operation prior to integration.
- Aggressive load profile used: 510W peak and 370W nominal power levels at the string level
- Initial Cell Temperature = 10°C
- Additional battery level acceptance testing included: (1) capacity and DC resistance testing at +25°C and 0°C, and (2) 72 hour capacity retention testing.
- Additional battery level acceptance testing included: (1) capacity and DC resistance testing at +25°C and -5°C, and (2) low rate discharge (3W) at -15°C for nighttime survival operations.

Flight battery demonstrated to support peak power demands.
Performance was comparable to EM batteries and individual cell testing.

Qualification Testing of EM Battery
Thermal Ambient Operational Testing

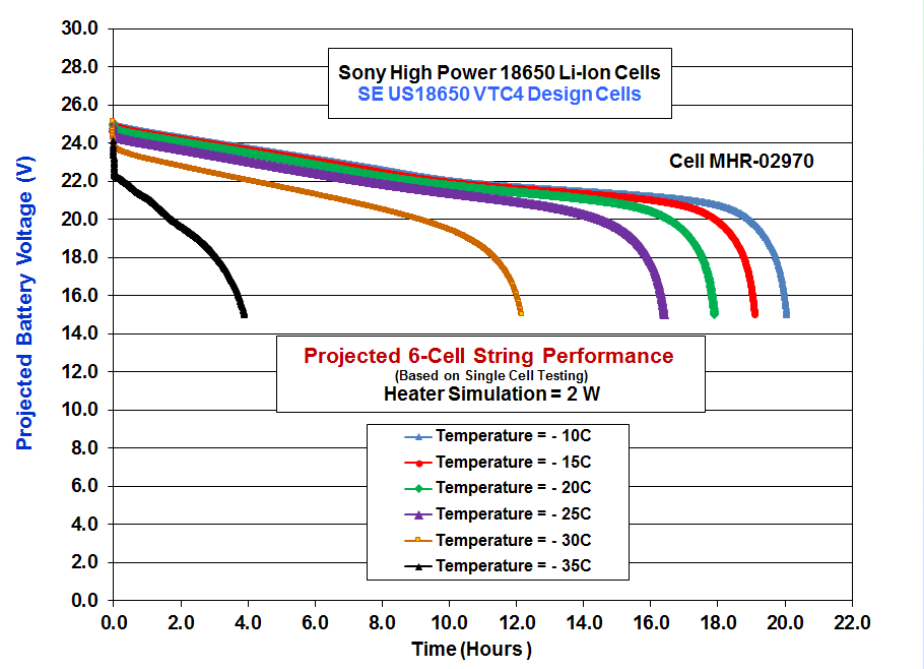


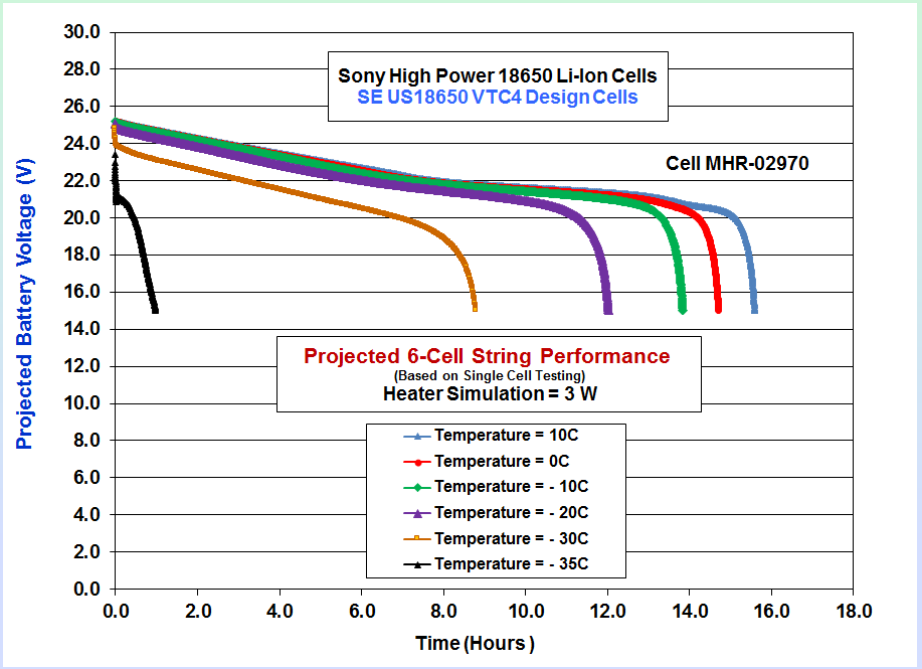
- Operational cycles performed = 3.5
- Non-operational cycles performed = 1
- Surface operation qualification temperature range = -15°C to +45°C.
- Flight operation qualification temperature range = 5°C to +35°C.
- Low power operation qualification temperature range = - 25°C to +45°C.
- Time at +45°C = 166.8 Hr
- Time at - 15°C = 95.1 Hr
- Time at - 25°C = 63.3 Hr

Flight battery demonstrated to support peak power demands.
Performance was comparable to EM batteries and individual cell testing.

Performance of Sony SE US18650 VTC4 Li-ion Cells

Simulation of Survival Operations: Battery Projections

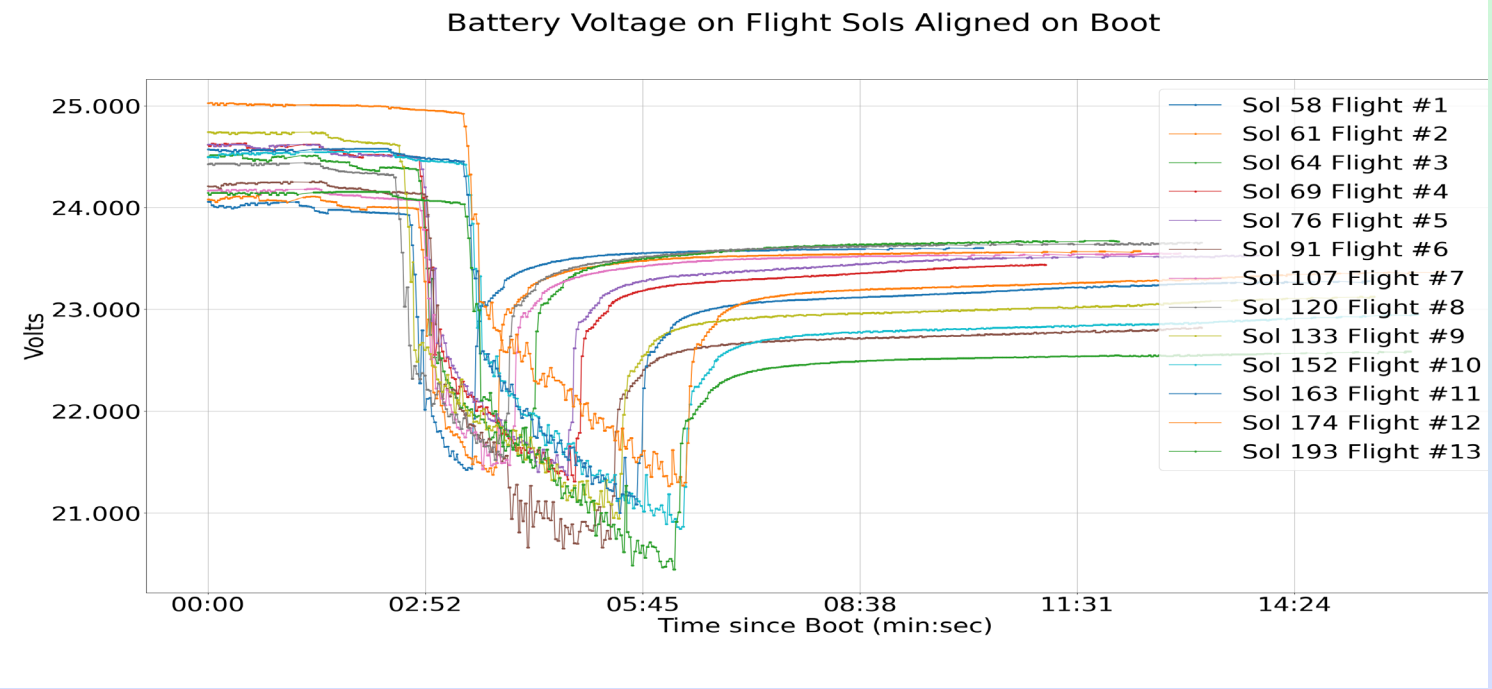




- Early on, effort was focused upon attempting to minimize the heater energy consumption during the night. This can be achieved by lowering the heater set-point.
- Lowering the heater set-point lowers the thermal management energy consumption.
  - Nominal heater set-point = -15°C
- Cell level testing demonstrated the capability of supporting low temperature operation.
- Battery has been heated to the proper temperature prior to flight on the surface of Mars.

Ingenuity Battery Operation on Mars

Telemetry Data of Flight Battery



- **The Ingenuity Helicopter battery has performed well on Mars.**
- **Very consistent performance has been obtained, with battery voltage > 20V observed.**
- **Minimal cell to cell voltage dispersion observed (< 10 mV to-date).**
- **Ingenuity has completed 24 flights, flown > 5 km (>42 minutes airborne).**
- **Ingenuity has completed over 365 sols of autonomous operation after deployment from rover.**
- **Far exceeded primary technology demonstration objective of 5 flights over a 30 sol period.**

T. Tzanetos, et. al., "Ingenuity - Mars Helicopter Technology: Demonstration to Operations Demonstration", IEEE Aerospace, Big Sky, Montana, Mar 5 - Mar 12, 2022 (submitted for publication).

Conclusions

- COTS 18650 format cells have enabled a number of missions
  - ABSL batteries utilizing Sony HCM cells have been successfully used on many missions.
  - Architecture does not require individual cell monitoring and control.
  - Cells contain internal safety devices for added protection.
- The Planned Europa Clipper Mission Li-ion Battery
  - COTS LG Chem MJ1 18650 cells have been baselined for use.
    - Cells display excellent cycle life and high specific energy.
    - Cells display excellent tolerance to high radiation environments.
  - Module level testing has demonstrated low cell to cell voltage dispersion
  - Pre-qualification battery has been demonstrated to have good radiation tolerance.
- The Mars Helicopter “Ingenuity” Li-ion Battery
  - COTS Sony VTC4 18650 cells demonstrated to have excellent power capability
  - EM and FM modules demonstrated to support 510W peak and 370 W continuous loads
  - On Mars, Ingenuity has completed over 24 flights and flown over 5 km
    - Minimal battery degradation observed
    - Minimal cell to cell voltage dispersion (< 10mV)
    - Ingenuity has operated for over a year after separation from the rover.

Acknowledgments

The work described here was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA).