The Performance Evaluation of 18650-Size Lithium-Ion Cells and Batteries for Future NASA Missions

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

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109

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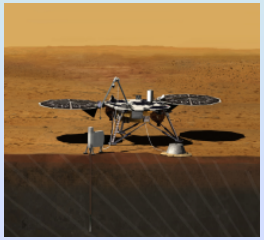
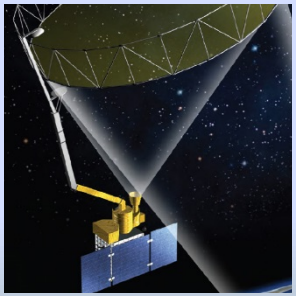
Outline

- Background
- Europa Clipper Mission
  - Cycle Life Performance Evaluation
  - Calendar Life Performance Evaluation
  - Impact of Radiation Exposure
  - Module Level Testing
- Mars Helicopter Technology Demonstration
  - High Power Cell Characterization
  - Module level testing
- Future Planned Missions to Icy Worlds
  - High Specific Energy Cells
  - Improved Low Temperature Capability
- Conclusions

Li-Ion Battery Technology for NASA Missions

- Large Capacity Cell Formats and Batteries
  - Attractive for Mars surface missions
  - Robust low temperature performance
  - Possess heritage on multiple missions
  - MER, MSL, Phoenix, and InSight,
  - Requires cell balancing electronics
- Small Cell Battery Designs Formats
  - Good cell to cell reproducibility
  - Modular designs
  - Does not require cell balancing electronics
  - Heritage on multiple NASA missions
    - Mars Express, Kepler, Aquarius, SMAP
  - Increasingly higher specific energy
- Small cell battery designs are becoming more increasingly attractive, due to the wide range of cell performance options, including very high specific energy and high power.





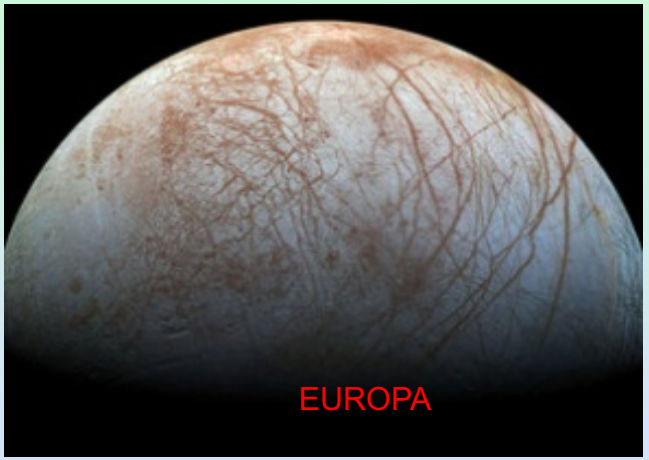
NASA's Planned Europa Mission

➢ Anticipated Launch Date: TBD (2020's)

- NASA's planned Europa mission would conduct a detailed reconnaissance of Jupiter's moon Europa and to 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) Interior Characterization of Europa using Magnetometry (ICEMAG)
3) Mapping Imaging Spectrometer for Europa (MISE)
4) Europa Imaging System (EIS)
5) Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON)
6) Europa Thermal Emission Imaging System (E-THEMIS)
7) Mass Spectrometer for Planetary Exploration/Europa (MASPEX)
8) Ultraviolet Spectrograph/Europa (UVS)
9) Surface Dust Mass Analyzer (SUDA)



Key Driving Battery Requirements

- Long life = 11 years (long cruise period)
- High radiation tolerance
- High specific energy
- Operating Temperature Range: 0° to +30°C
- The preliminary architecture for the Europa mission is to use a battery design consisting of high specific energy small 18650-size Li-ion cells, to capitalize on their internal safety functions, high capacity, and excellent cell-to-cell reproducibility.

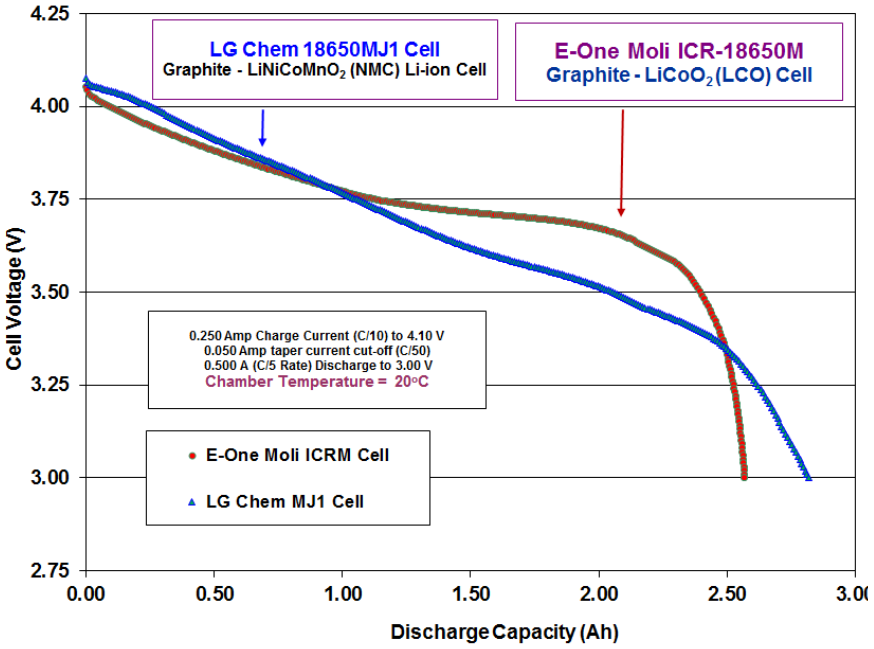
NASA's Planned Europa Mission: Lithium-Ion 18650 Cell Chemistry Assessment

- The Europa Mission has identified a number of small cell Li-ion options that are good candidates for the project, which provide high specific energy and good performance characteristics.
  - Molicel ICR-M 18650 Cells
  - Molicel ICR-J 18650 Cells
  - Panasonic NCR-A 18650 Cells
  - Panasonic NCR-B 18650 Cells
  - LG Chem MJ1 18650 Cells
- An in-house performance assessment program has been initiated to determine the viability for the Europa project, which includes the following:
  - Cycle life performance under various conditions
  - Storage life testing at the cell level (at 0°C and +25°C)
  - High temperature storage characterization (+30°C)
  - 8-Cell module 100% DOD cycle life testing at +20°C
  - 8-Cell module long term storage life testing at +0°C
  - Discharge and charge rate characterization testing
  - Radiation tolerance (subjected to ^{60}Co gamma rays)
- The LG Chem MJ1 and Moli ICRM cells have emerged as the most viable options for the Europa Clipper Mission.

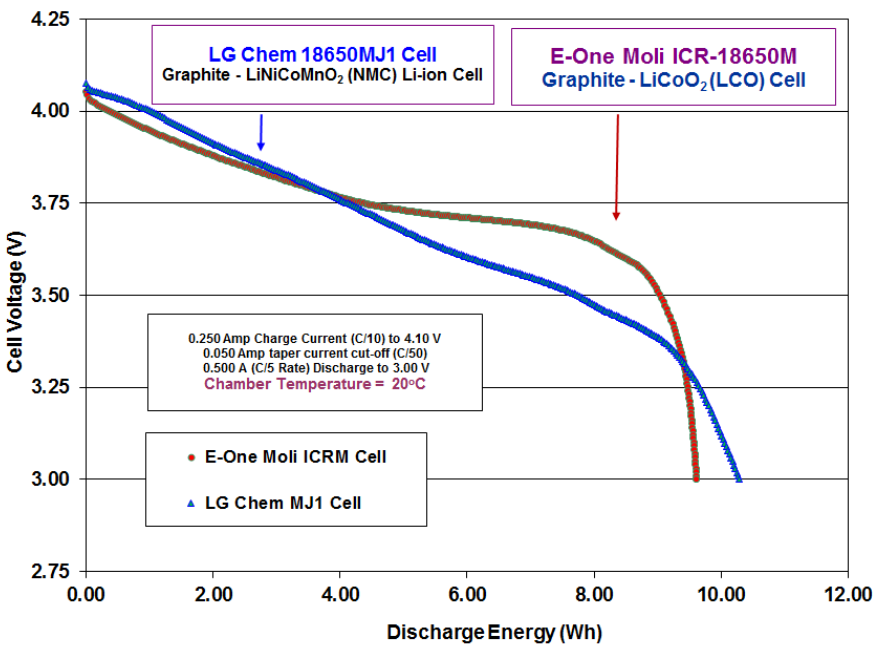
NASA's Planned Europa Mission: Lithium-Ion 18650 Cell Chemistry Assessment

❑ *Initial cell characteristics: Discharge capacity and energy at +20°C*

Initial Discharge Capacity (Ah) at 20°C



Watt Hours Delivered (Wh) at 20°C

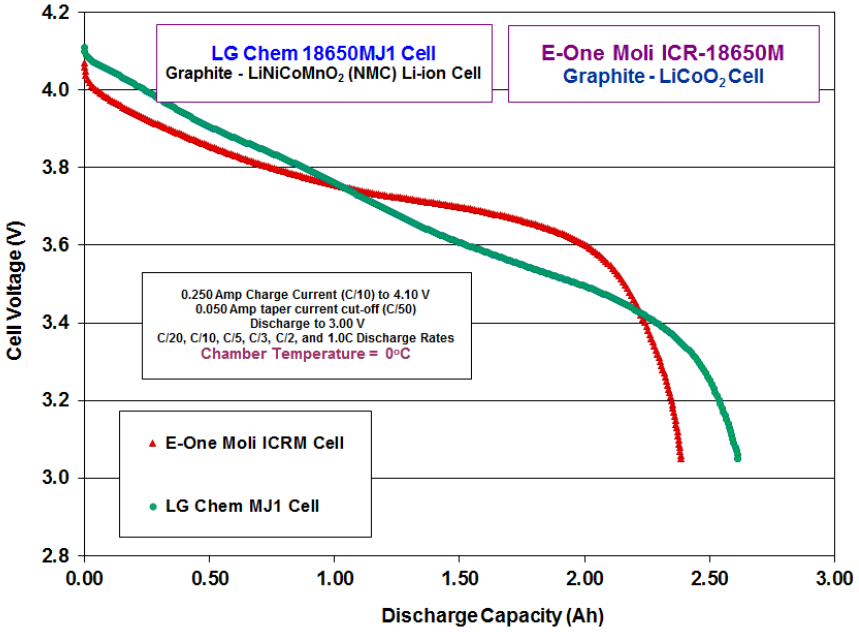


- Discharge capacity (Ah)(**A**) and discharge energy (Wh)(**B**) of LG Chem MJ1 and Moli ICR-M Li-Ion 18650-size cells at 20°C using C/5 charge and discharge rates over the voltage range of 3.0V to 4.10V.

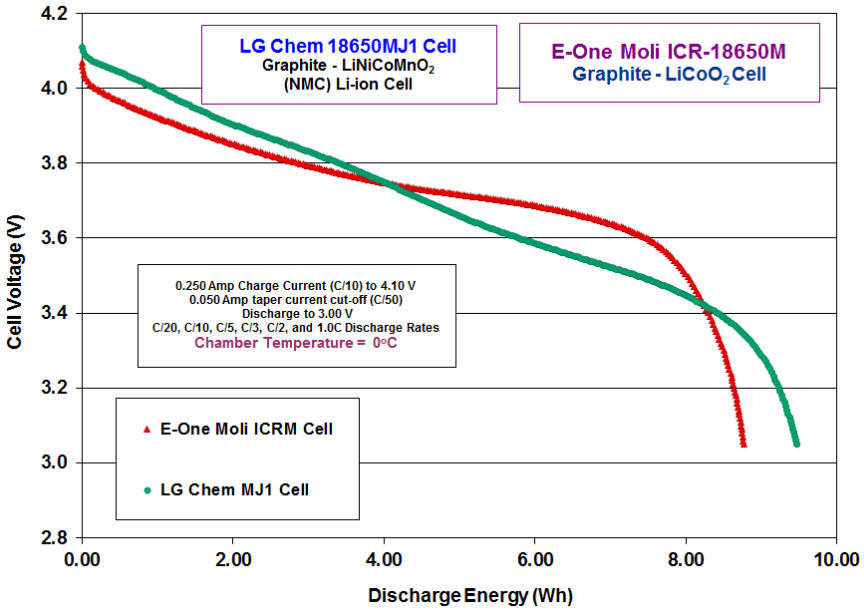
NASA's Planned Europa Mission: Lithium-Ion 18650 Cell Chemistry Assessment

❑ *Initial cell characteristics: Discharge capacity and energy at 0°C*

Initial Discharge Capacity (Ah) at 0°C



Watt Hours Delivered (Wh) at 0°C

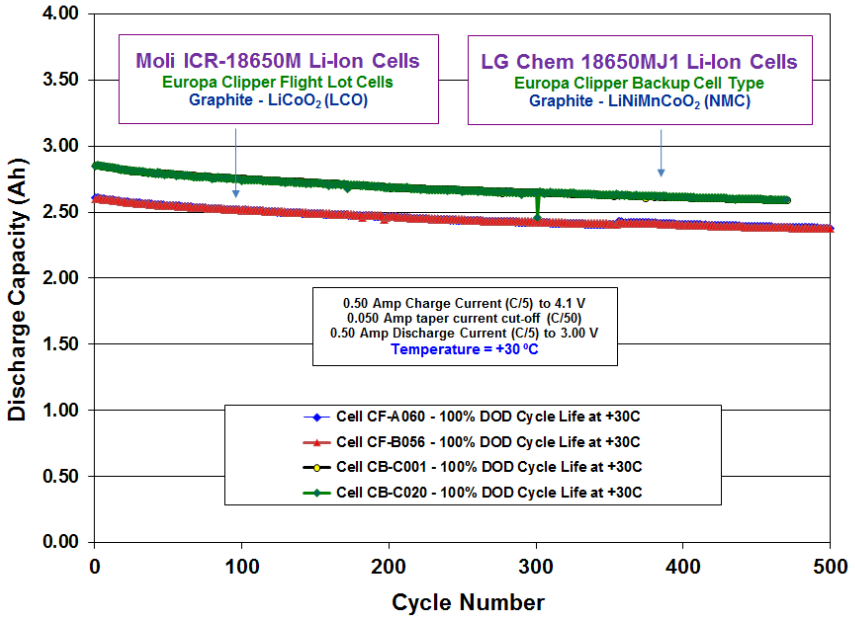


- Discharge capacity (Ah)(**A**) and discharge energy (Wh)(**B**) of LG Chem MJ1 and Moli ICR-M Li-Ion 18650-size cells at 0°C using C/5 charge and discharge rates over the voltage range of 3.0V to 4.10V.

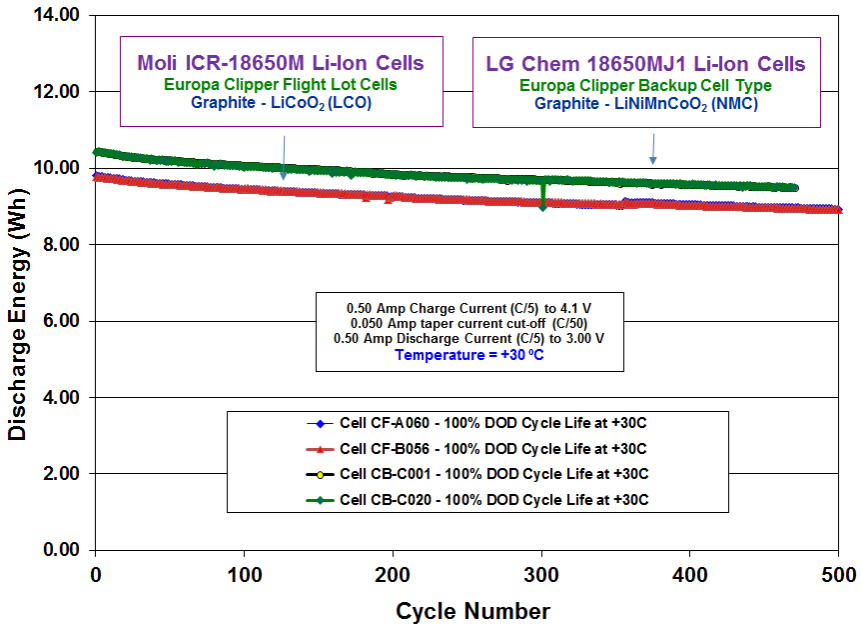
NASA's Planned Europa Mission:
Li-Ion Cell Level Testing: Cycle Life Performance

- ***Results of 100% DOD Cycle Life Testing +30°C***

Discharge Capacity (Ah) at 30°C



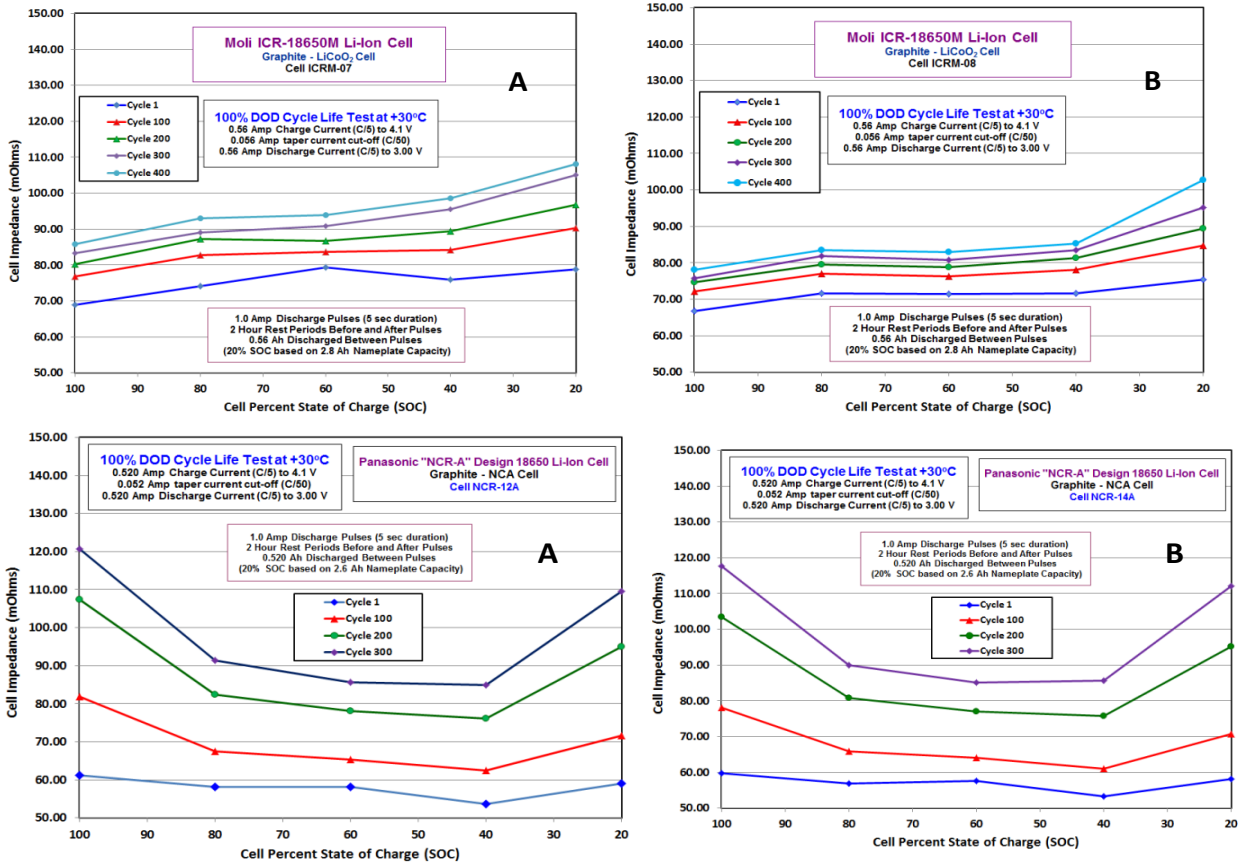
Discharge Energy (Wh) at 30°C



- Cycle life performance (100% Depth of Discharge) of LG Chem MJ1 and Moli ICR-M Li-Ion 18650-size cells at 30°C using C/5 charge and discharge rates over the voltage range of 3.0V to 4.10V, expressed in terms of the discharge capacity (Ah) (**A**) and discharge energy (Wh) (**B**).

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

- ***Results of 100% DOD Cycle Life Testing +30°C: Impedance Characteristics***

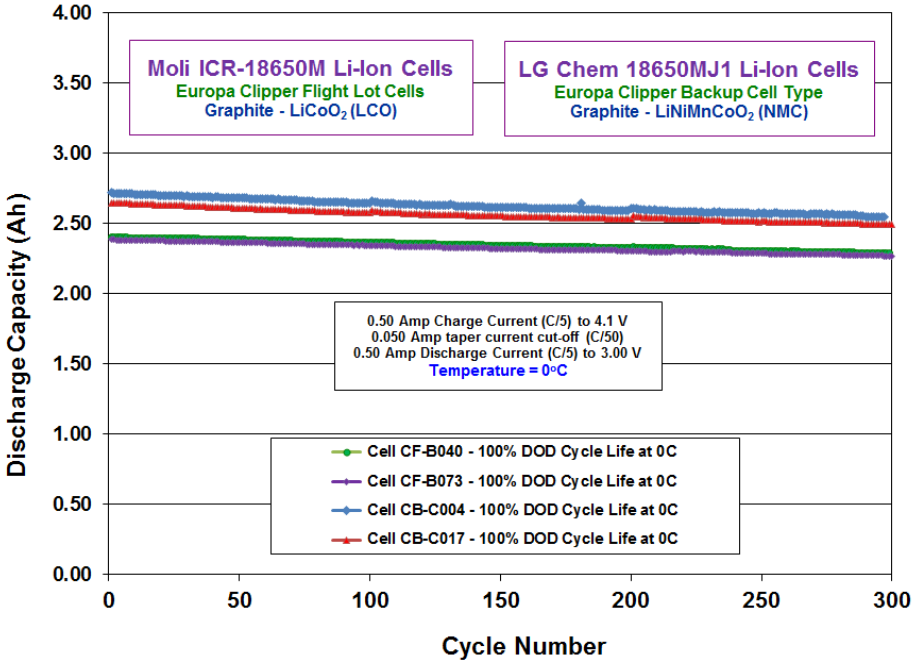


- E-One Moli cells displayed a lower amount of permanent capacity fade compared to Panasonic.

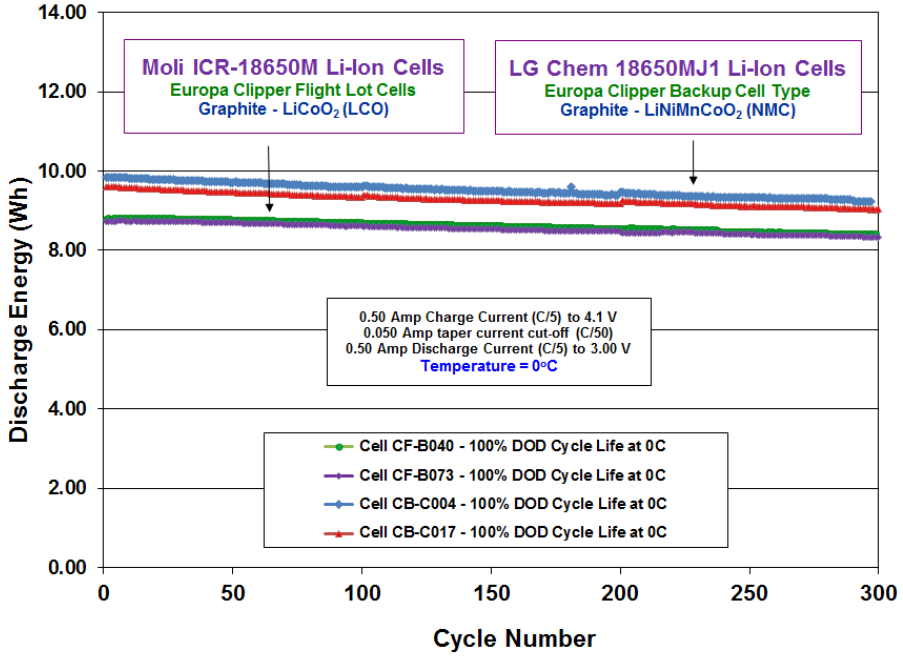
NASA's Planned Europa Mission:
Li-Ion Cell Level Testing: Cycle Life Performance

❑ *Results of 100% DOD Cycle Life Testing 0°C*

Discharge Capacity (Ah) at 0°C



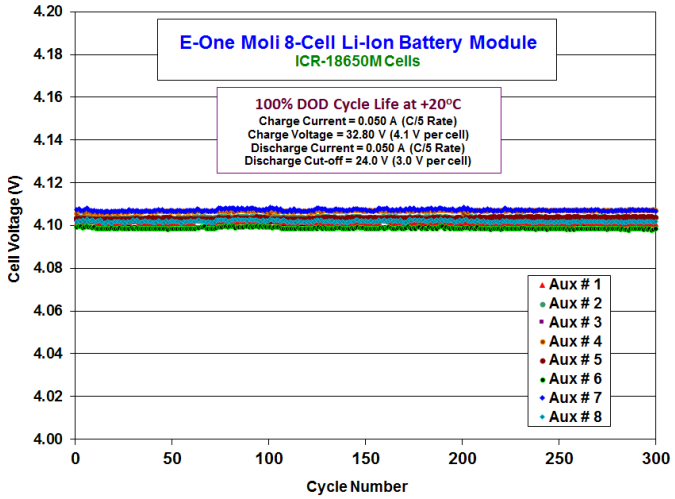
Discharge Energy (Wh) at 0°C

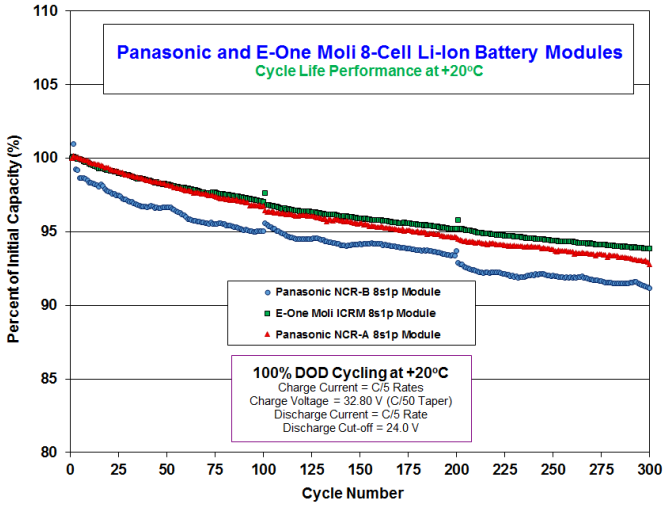


- Cycle life performance (100% Depth of Discharge) of LG Chem MJ1 and Moli ICR-M Li-Ion 18650-size cells at 0°C using C/5 charge and discharge rates over the voltage range of 3.0V to 4.10V, expressed in terms of the discharge capacity (Ah) (**A**) and discharge energy (Wh) (**B**).

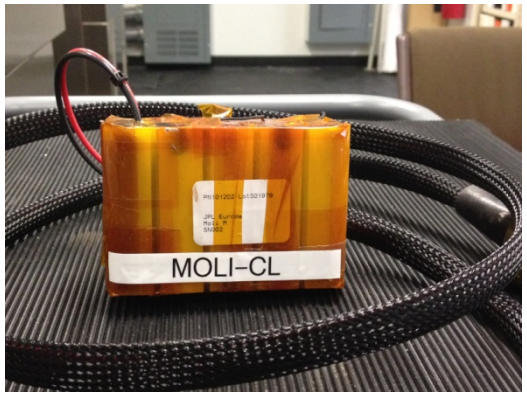
NASA's Planned Europa Mission:
Li-Ion Module Level Testing: Cycle Life Performance

- ***Summary of String Level Cycle Life Testing :***
  - Two different cell designs: (i) NCR-A, and (ii) Moli ICR-M (*NCR-B is completed*)
  - Modules fabricated by ABSL (8s1p modules)
  - Validate cell dispersion characteristics (up to 300 cycles)
  - Cycling performed at +20°C (100 % DOD, 24V to 32.80V)
    - A total of 300 cycles should be completed to establish dispersion characteristics
  - Strings characterized for capacity and impedance
    - At 20° and 0°C every 100 cycles
  - This testing has been completed on Panasonic NCR-B strings



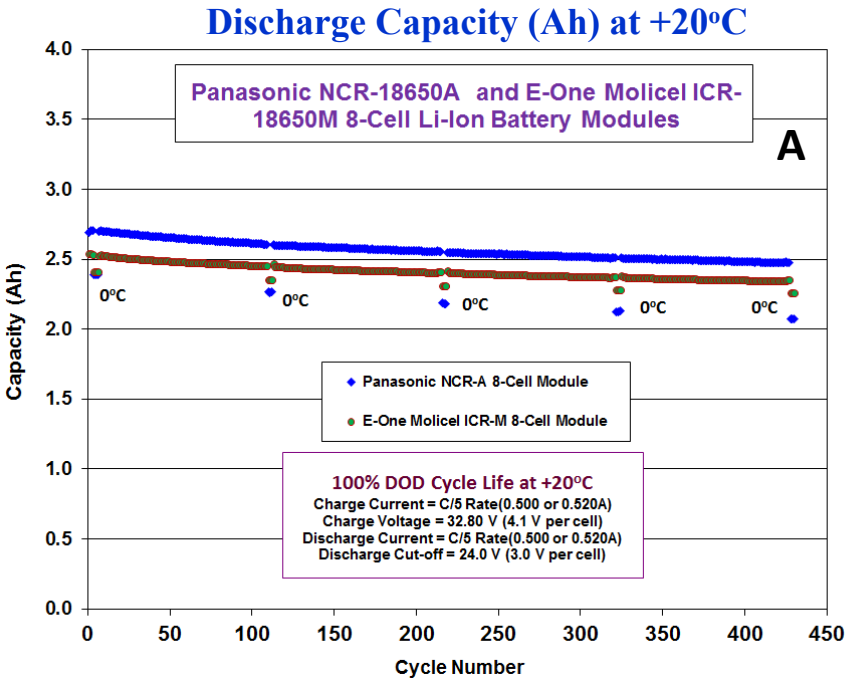


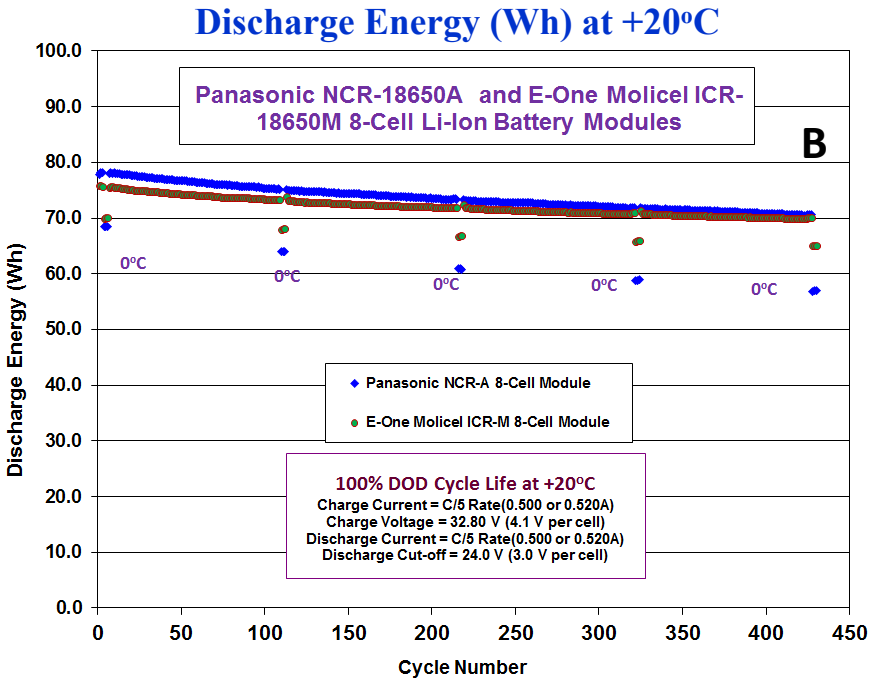
Minimal cell voltage dispersion observed on charge (EOCV) after completing 300 cycles (< 15 mV)



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

❑ *Results of 100% DOD Cycle Life Testing +20°C: 8-Cell Strings (8s1p)*



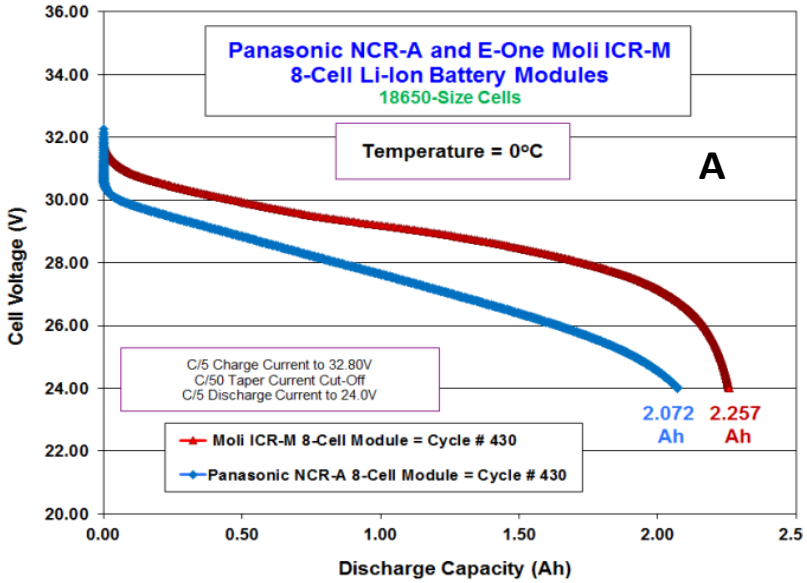


- Cycle life performance (100% Depth of Discharge) of Panasonic NCR-A and Moli ICR-M Li-Ion 8-cell strings at +20°C using C/5 charge and discharge rates over the voltage range of 24.0V to 32.80V, expressed in terms of the discharge capacity (Ah) (A) and discharge energy (Wh) (B).

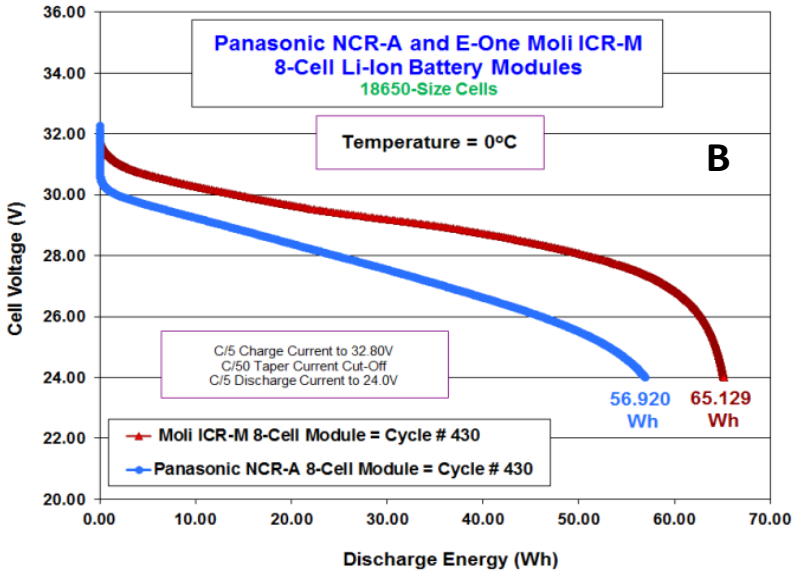
NASA's Planned Europa Mission:
Li-Ion Module Level Testing: Cycle Life Performance

- ***Results of 100% DOD Cycle Life Testing +20°C: 8-Cell Strings (8s1p)***

Discharge Capacity (Ah) at 0°C



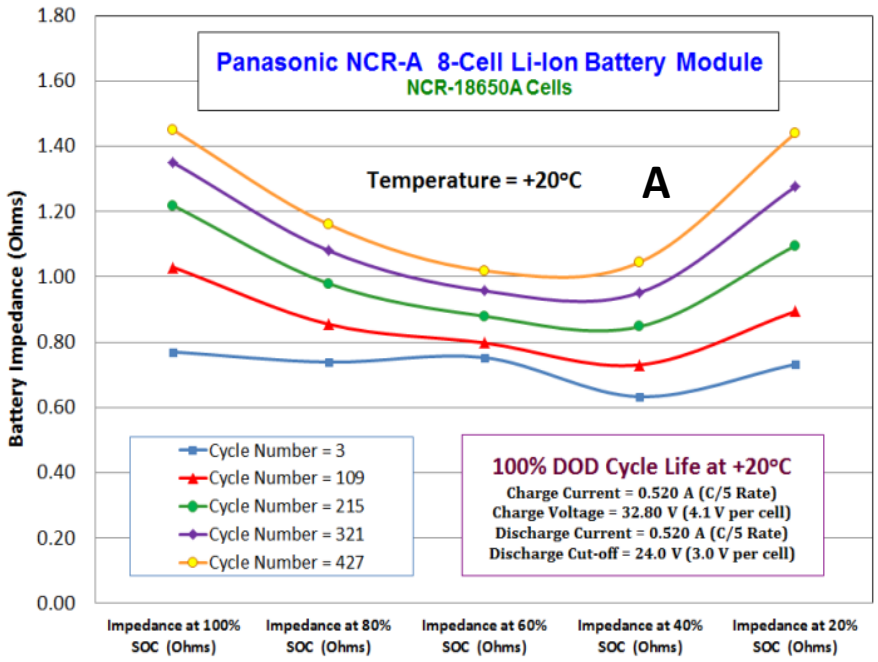
Discharge Energy (Wh) at 0°C

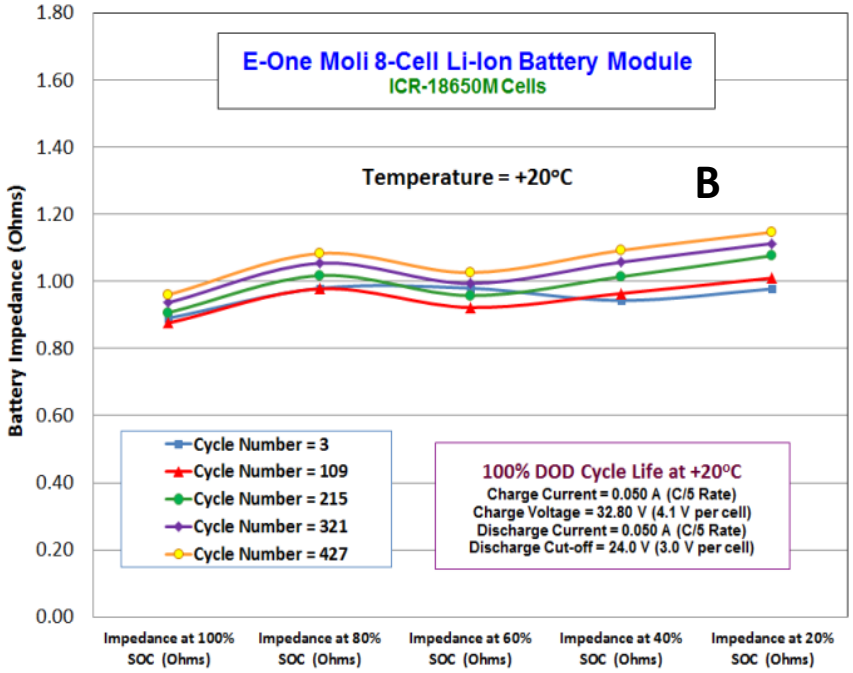


- The discharge curves of cycle #430 of Panasonic NCR-A and Moli ICR-M Li-Ion 8-cell strings at 0°C subjected to 100% cycle life testing at +20°C using C/5 charge and discharge rates over the voltage range of 24.0V to 32.80V, expressed in terms of the discharge capacity (Ah) (A) and discharge energy (Wh) (B).

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

- ***Results of 100% DOD Cycle Life Testing +20°C: 8-Cell Strings (8s1p)***
  - ***Current-Interrupt Impedance Results (1A discharge pulse for 5 seconds)***

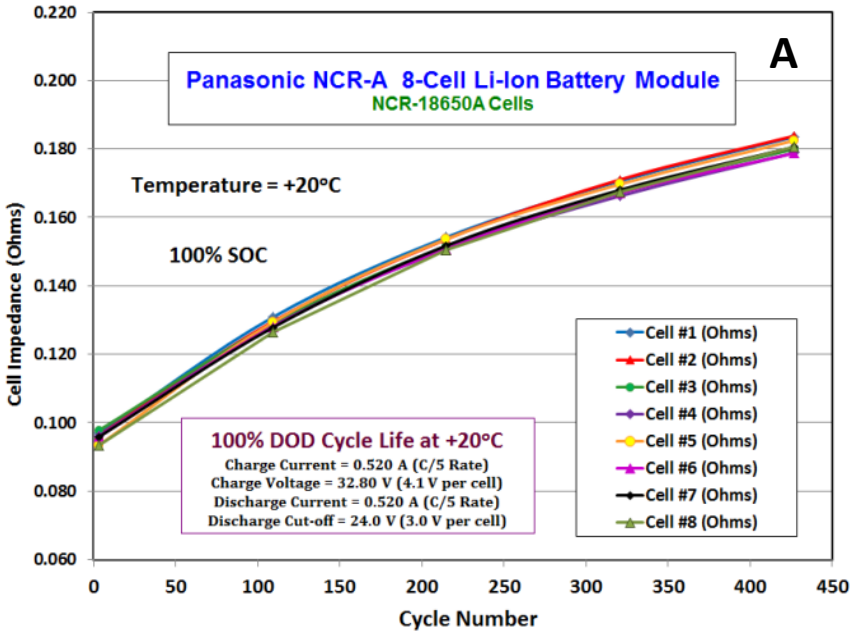


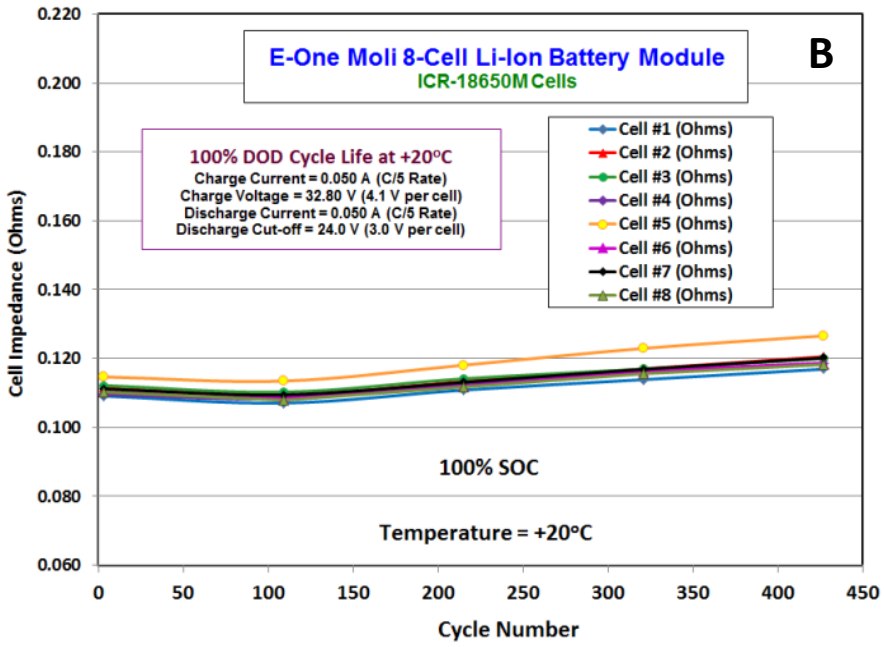


- The battery impedance characteristics at +20°C as a function of life of Panasonic NCR-A (**A**) and Moli ICR-M (**B**) Li-Ion 8-cell strings cycled at 100% DOD at +20°C using C/5 charge and discharge rates over the voltage range of 24.0V to 32.80V.

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

- ***Results of 100% DOD Cycle Life Testing +20°C: 8-Cell Strings (8s1p)***
  - ***Current-Interrupt Impedance Results at 20°C (1A discharge pulse for 5 seconds)***

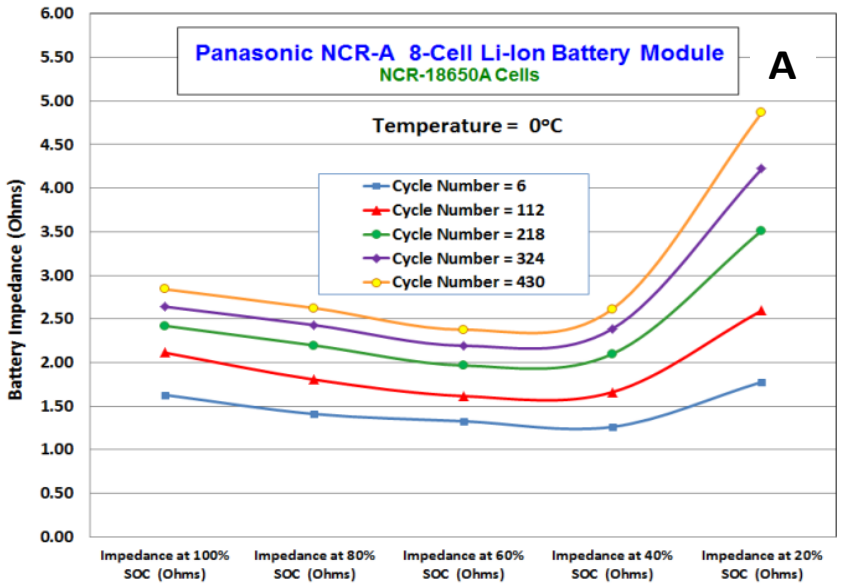


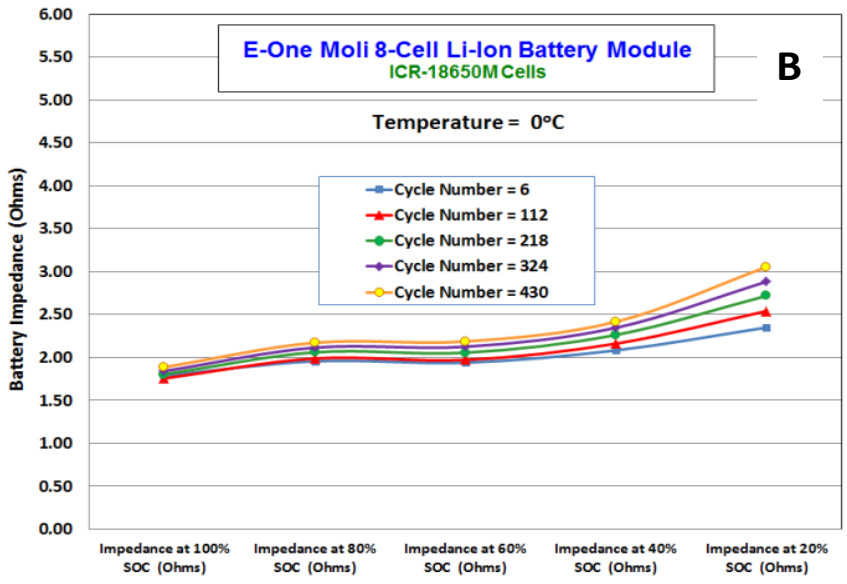


- The battery impedance characteristics of individual Panasonic NCR-A (**A**) and Moli ICR-M (**B**) cells in 8-cell strings at 100% SOC at +20°C as a function of life cycled at 100% DOD at +20°C using C/5 charge and discharge rates over the voltage range of 24.0V to 32.80V.

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

- ***Results of 100% DOD Cycle Life Testing +20°C: 8-Cell Strings (8s1p)***
  - ***Current-Interrupt Impedance Results at 0°C (1A discharge pulse for 5 seconds)***

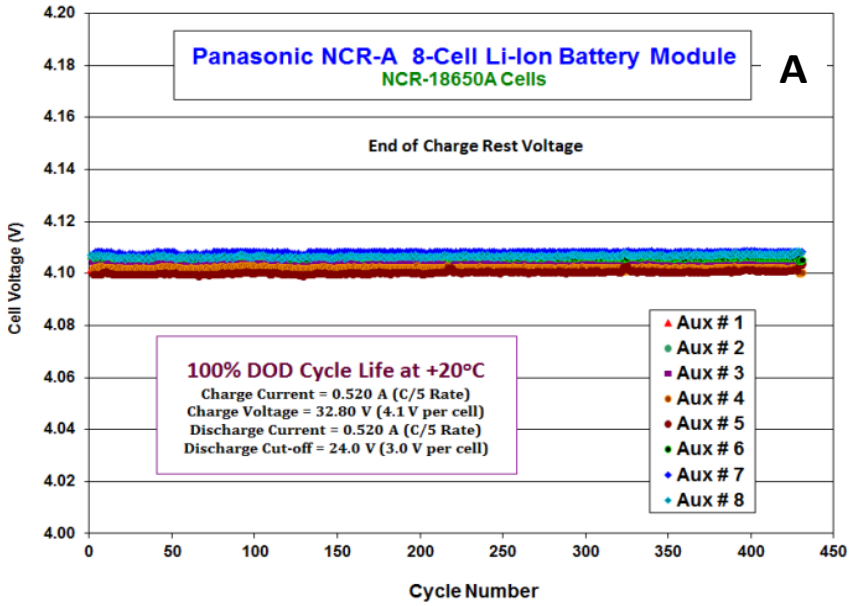


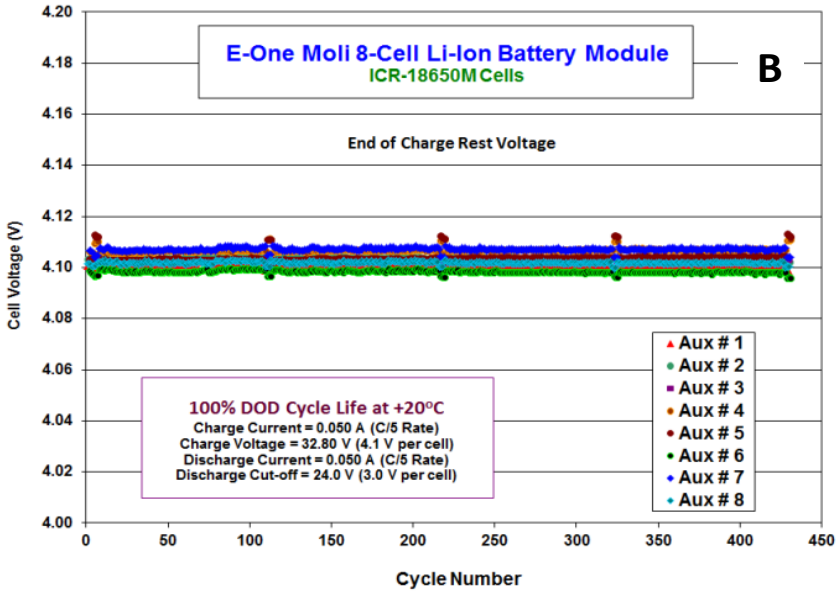


- The battery impedance characteristics at 0°C as a function of life of Panasonic NCR-A (**A**) and Moli ICR-M (**B**) Li-Ion 8-cell strings cycled at 100% DOD at +20°C using C/5 charge and discharge rates over the voltage range of 24.0V to 32.80V

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

- ***Results of 100% DOD Cycle Life Testing +20°C: 8-Cell Strings (8s1p)***
  - ***Cell voltage dispersion as a function of cycling***



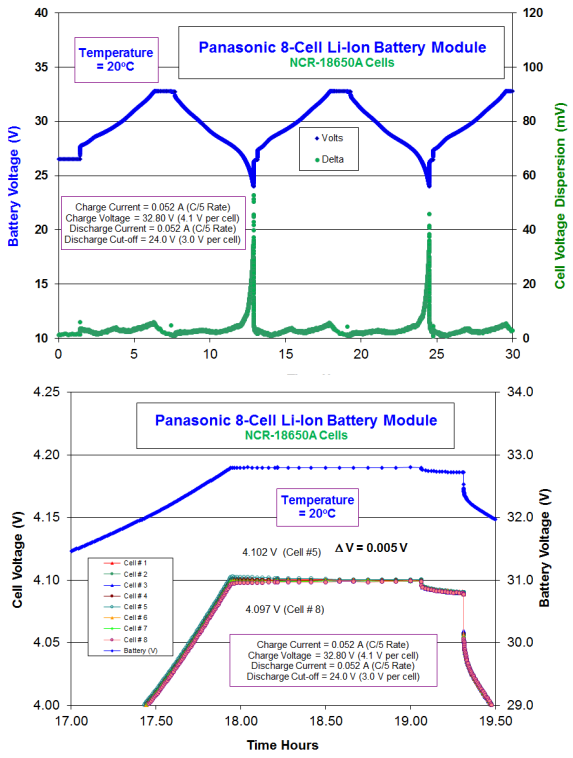


- The cell voltage dispersion at +20°C at rest after charge as a function of life of Panasonic NCR-A (**A**) and Moli ICR-M (**B**) Li-Ion 8-cell strings subjected to cycle life testing at 100% DOD at +20°C using C/5 charge and discharge rates over the voltage range of 24.0V to 32.80V.

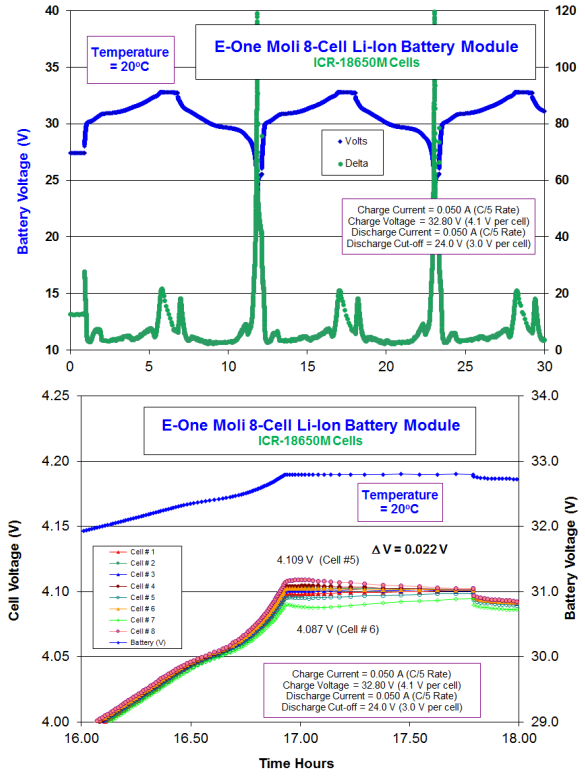
NASA's Planned Europa Mission:
Li-Ion Module Level Testing: Calendar Life Performance

- ***Summary of String Level, Long Term Storage Life Testing:***
  - **Three different module designs: (i) NCR-A, (ii) NCR-B, (iii) Moli ICR-M (Supplied by ABSL)**
  - **Validate cell dispersion characteristics; Modules do not contain pre-matched cells**
  - **Strings characterized for capacity and impedance (at 20° and 0°C) periodically**

Panasonic NCR-A Module



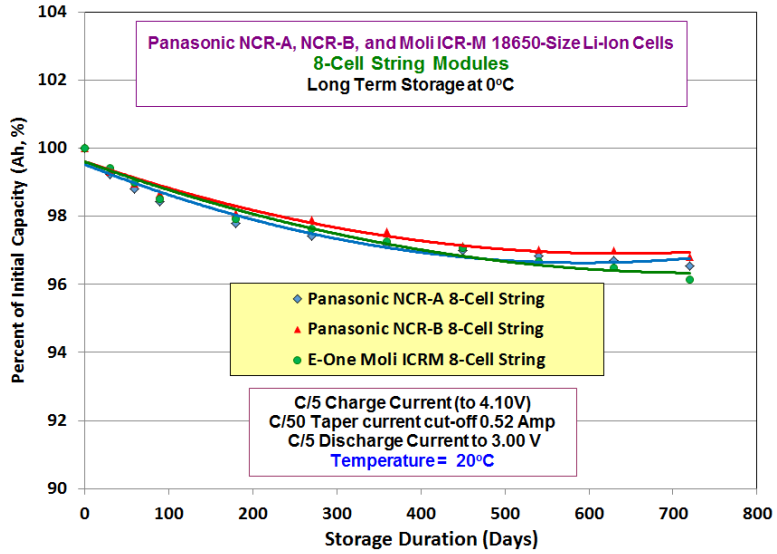
Moli ICR-M Module

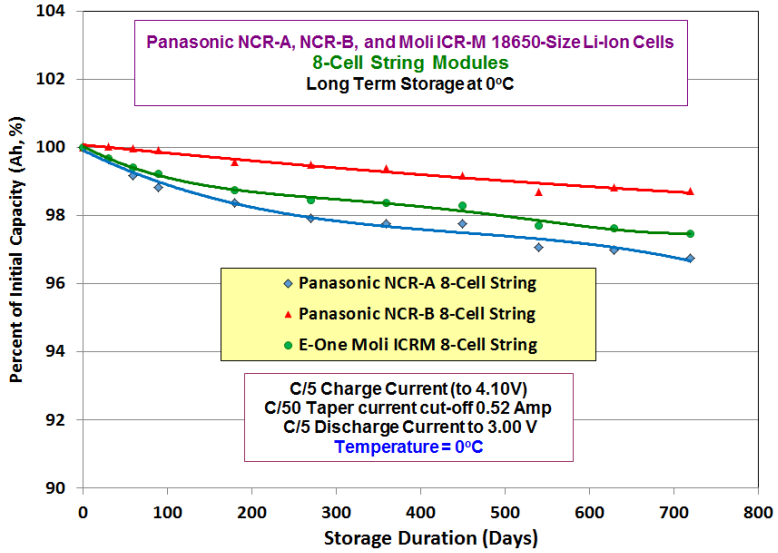


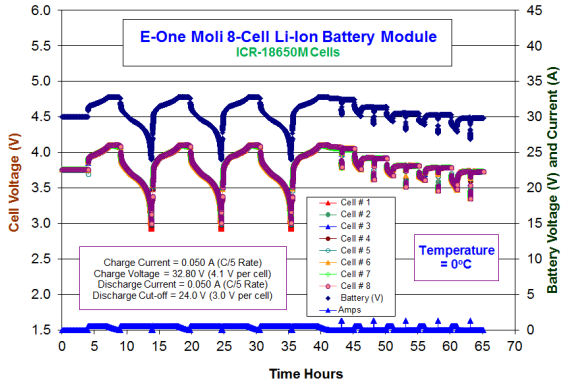
- All modules display little increase in voltage dispersion with storage and cycling.
- Maximum voltage dispersion is observed at the end of discharge.
- Cell voltage dispersion is being monitored and tracked with time.
- Modules have completed 24 months of storage on the bus at 0°C (at ~ 70% SOC).

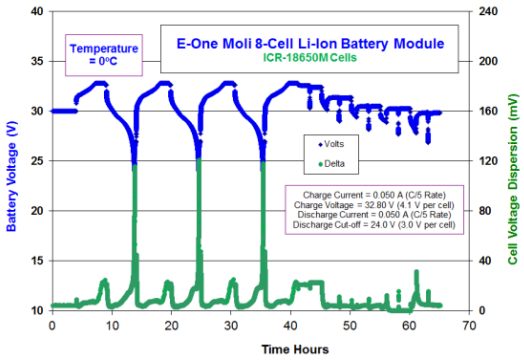
NASA's Planned Europa Mission:
Li-Ion Module Level Testing: Calendar Life Performance

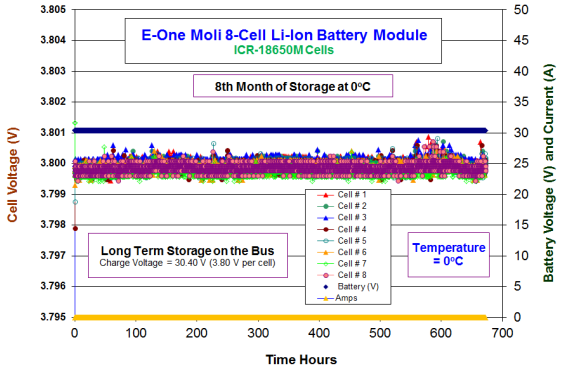
- ***Summary of String Level, Long Term Storage Life at 0°C:***







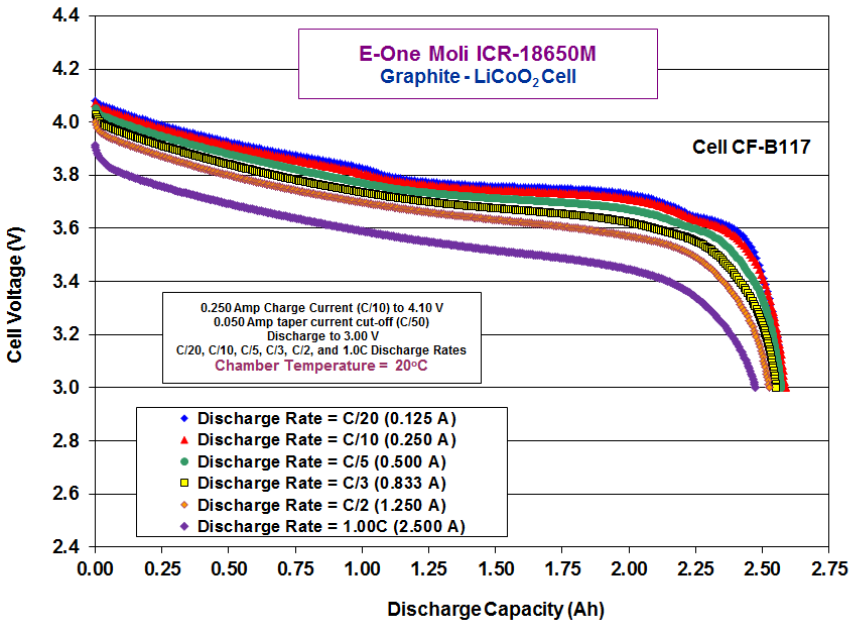




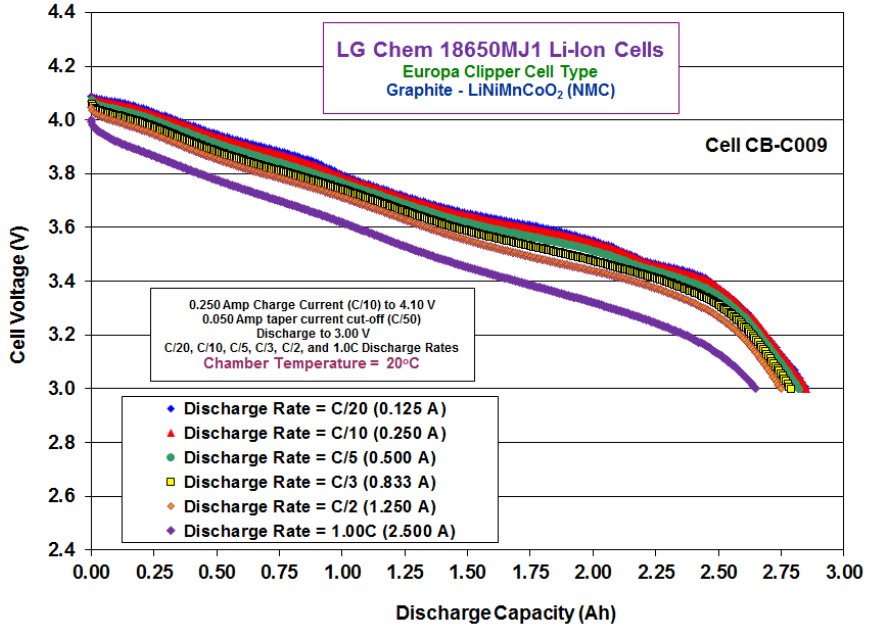
NASA's Planned Europa Mission:
Li-Ion Cell Level Testing: Discharge Rate Performance

- ***Summary of discharge rate testing at different temperatures (2.50V to 4.10V)***

Discharge Capacity (Ah) at 20°C



Discharge Capacity (Ah) at 20°C

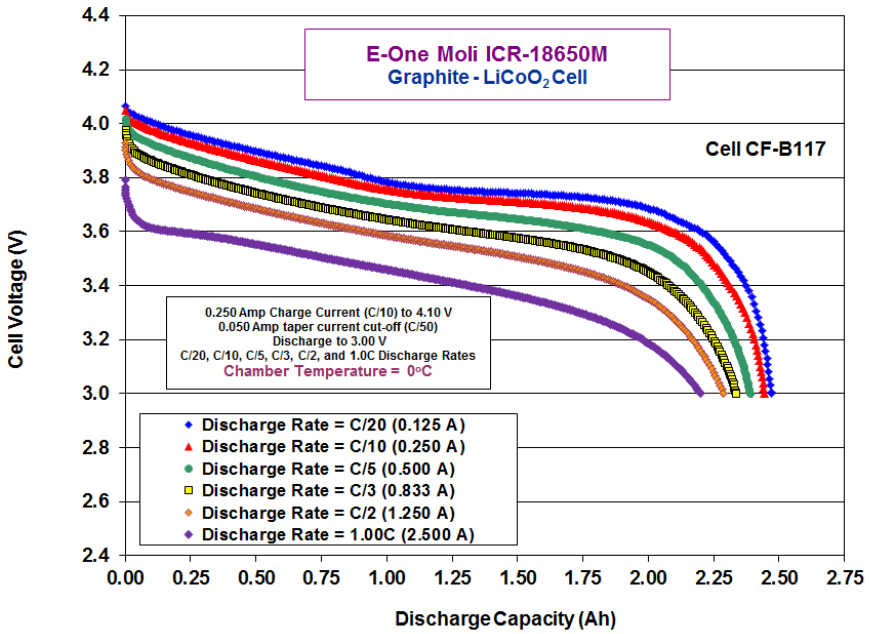


- Discharge Capacity (Ah) of E-One Molicel ICR-M cells and LG Chem cells at various discharge rates at 20°C. Cells were charged at the specified temperatures.

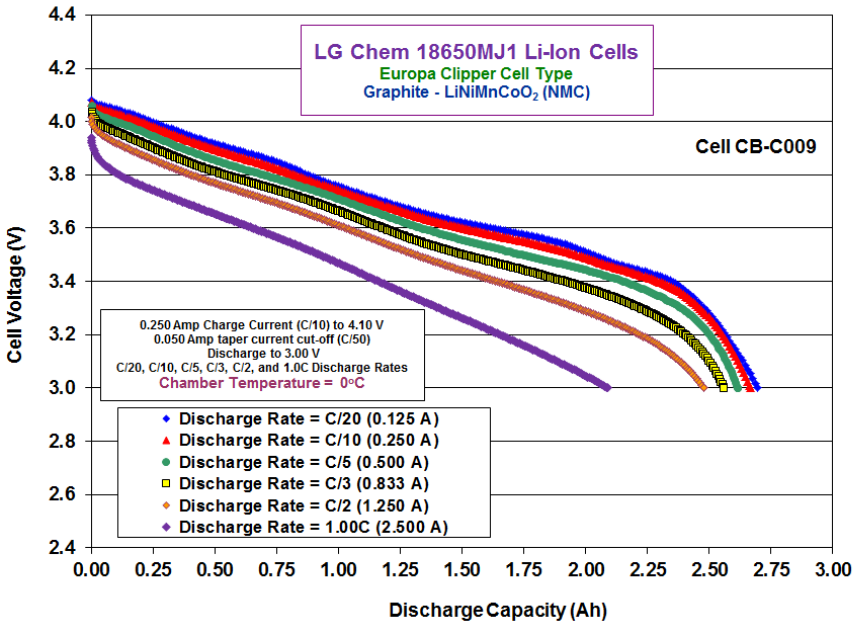
NASA's Planned Europa Mission:
Li-Ion Cell Level Testing: Discharge Rate Performance

- ***Summary of discharge rate testing at different temperatures (2.50V to 4.10V)***

Discharge Capacity (Ah) at 0°C



Discharge Capacity (Ah) at 0°C



- Discharge Capacity (Ah) of E-One Molicel ICR-M cells and LG Chem cells at various discharge rates at 0°C. Cells were charged at the specified temperatures.

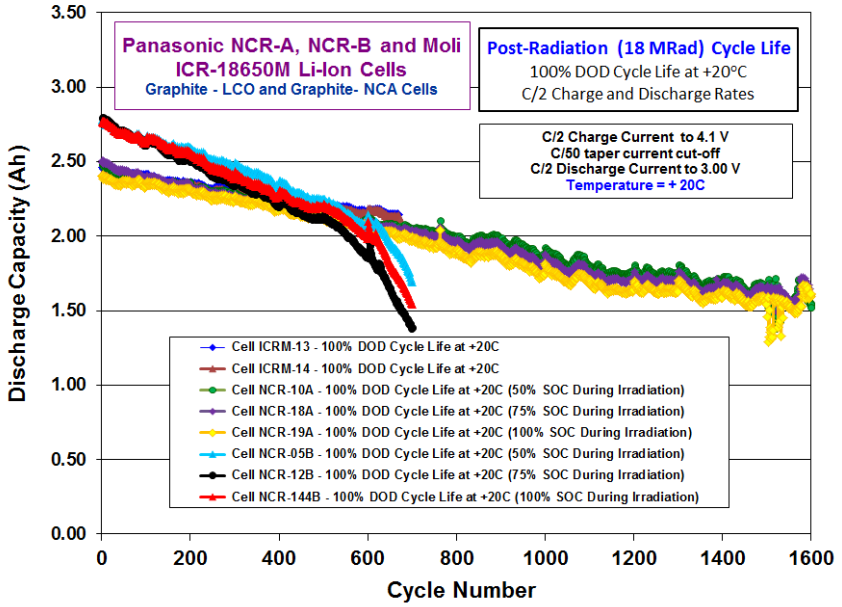
NASA's Planned Europa Mission:
Li-Ion Cell Level Testing: Radiation Tolerance

- ***Summary of discharge rate testing at different temperatures (2.50V to 4.20V)***

Impact of 18 Mrad of ^{60}Co γ-ray irradiation

	Moli ICR-M Cell (ICRM-13)						Moli ICR-M Cell (ICRM-14)					
	Ah	Percent of Initial (%)	Wh	Percent of Initial (%)	mOhms (80% SOC)	Percent Increse in Impedance (%)	Ah	Percent of Initial (%)	Wh	Percent of Initial (%)	mOhms (80% SOC)	Percent Increse in Impedance (%)
Initial Performance at +20°C	2.6100	100	9.8368	100	93.54	0.00	2.5031	100	9.4525	100	85.60	0.00
Performance at +20°C After 4 Mrad Radiation	2.6033	99.75	9.8135	99.76	92.93	-0.65	2.4682	98.60	9.3131	98.52	89.11	4.10
Performance at +20°C After 8 Mrad Radiation	2.5098	96.16	9.4708	96.28	97.20	3.92	2.4647	98.47	9.3046	98.43	89.57	4.63
Performance at +20°C After 18 Mrad Radiation	2.4935	95.54	9.4129	95.69	94.91	1.47	2.4555	98.10	9.2730	98.10	86.06	0.53
100% DOD Cycle Life Testing at +20°C (C/2 Rates) After 18 Mrad Radiation: Cycle #1	2.4576	94.16	8.9690	91.18			2.4218	96.75	8.8608	93.74		
100% DOD Cycle Life Testing at +20°C (C/2 Rates) After 18 Mrad Radiation: Cycle #100	2.4071	92.23	8.7928	89.39	92.47	-1.14	2.3781	95.00	8.7107	92.15	81.79	-4.46
100% DOD Cycle Life Testing at +20°C (C/2 Rates) After 18 Mrad Radiation: Cycle #200	2.3445	89.83	8.5424	86.84	97.20	3.92	2.3340	93.24	8.5412	90.36	86.06	0.53
100% DOD Cycle Life Testing at +20°C (C/2 Rates) After 18 Mrad Radiation: Cycle #300	2.2988	88.08	8.3552	84.94	100.56	7.50	2.2761	90.93	8.3136	87.95	88.50	3.39

Cycle life after 18 Mrad of ^{60}Co γ-ray irradiation



- Cycle life performance (100% Depth of Discharge) of Panasonic NCR-A, NCR-B and Moli ICR-M Li-Ion 18650-size cells at 20°C using C/2 charge and discharge rates over the voltage range of 3.0V to 4.10V, after being subjected to 18 Mrad radiation from a Co^{60} source.
- The E-One Moli ICR-M cells still provided over 90% of the initial capacity (33A) and over 8 Wh per cell (33B) after completing 400 cycles.

NASA's Planned Europa Mission:
Li-Ion Cell Level Testing:
Radiation Tolerance (Moli ICRM Cell vs LG Chem MJ1 Cell)

- **Impact of ^{60}Co γ-irradiation upon capacity and impedance:**
  - Minimal performance degradation of Moli ICRM cell and LG Chem cells after being exposed to radiation.
  - Less than 1% capacity loss observed after 20 Mrad with both types of cells when evaluated at 0°C.
  - We obtained 50 Moli ICRM cells for evaluation (25 cells exposed to 12 Mrad, and 25 cells exposed to 20 Mrad).
  - We obtained 10 LG Chem cells for evaluation (5 exposed to 12 Mrad, and 5 exposed to 20 Mrad).
  - ABSL/Sandia has irradiated an additional 100 LG Chem cell (20 Mrad) for evaluation (40 go to JPL).

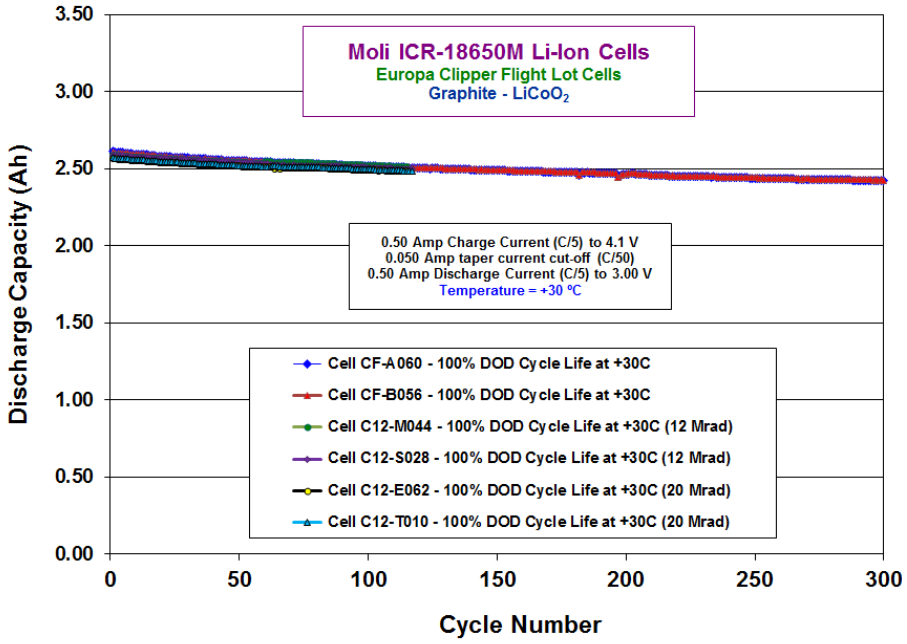
	E-One Moli ICRM Cells				
	Non-Irradiated Flight Batch Cells (50 Cells)	Cells Exposed to 12 Mrad Irradiation (25 Cells)	Percent Capacity Loss (%)	Cells Exposed to 20 Mrad Irradiation (25 Cells)	Percent Capacity Loss (%)
Average Capacity at 20°C	2.6196	2.5833	1.39	2.5734	1.76
Average Impedance at 20°C (80% SOC)	74.40	75.78	1.85	75.31	1.23
Average Capacity at 0°C	2.3811	2.3605	0.86	2.3607	0.86
Average Impedance at 0°C (80% SOC)	178.44	177.68	-0.43	174.17	-2.39

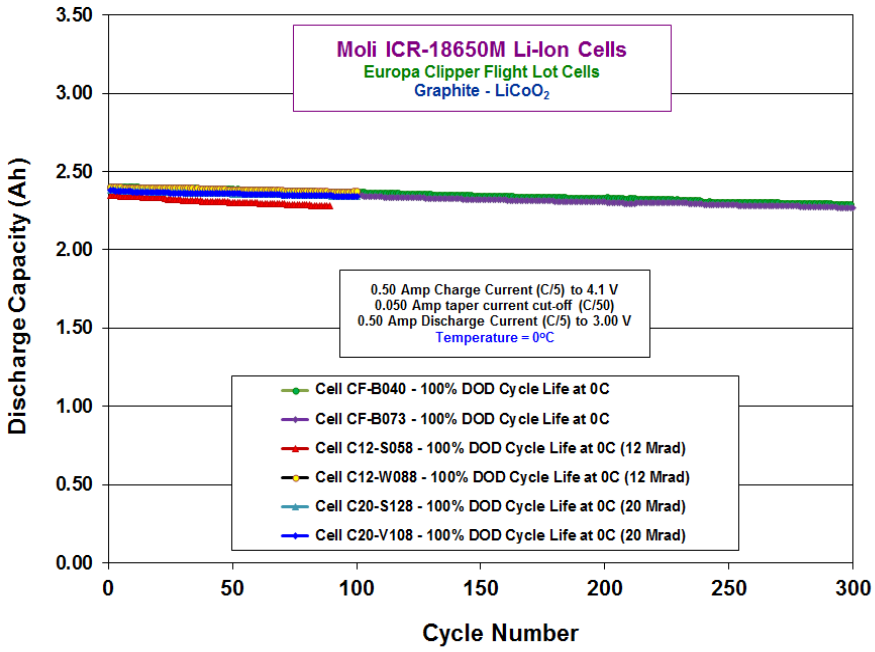
	LG Chem MJ1 Cells				
	Non-Irradiated Batch Cells (50 Cells)	Cells Exposed to 12 Mrad Irradiation (5 Cells)	Percent Capacity Loss *or* Impedance Increase (%)	Cells Exposed to 20 Mrad Irradiation (5 Cells)	Percent Capacity Loss (%)
Average Capacity at 20°C	2.8526	2.8475	0.18	2.8412	0.40
Average Impedance at 20°C (80% SOC)	41.46	42.69	2.97	43.03	3.79
Average Capacity at 0°C	2.6011	2.5986	0.10	2.5846	0.63
Average Impedance at 0°C (80% SOC)	71.22	73.67	3.44	75.75	6.36

- Both cell types display good tolerance to radiation
- The LG Chem cell displays less than 1% capacity loss after 20 Mrad of radiation.

NASA's Planned Europa Mission:
Li-Ion Cell Level Testing:
Radiation Tolerance (Moli ICRM Cell vs LG Chem MJ1 Cell)

- **Impact of ^{60}Co γ-irradiation upon capacity and impedance:**
  - Minimal performance impact of irradiation upon cycle life performance observed with Moli ICRM cells.
  - Comparable performance obtained at +30°C and 0°C after 12-20 Mrad exposure.
  - Testing of LG Chem MJ1 cells is underway.
  - String level testing of both chemistry is planned as well.





Mars Helicopter Planned Technology Development

Expand Exploration using Aerial Mobility

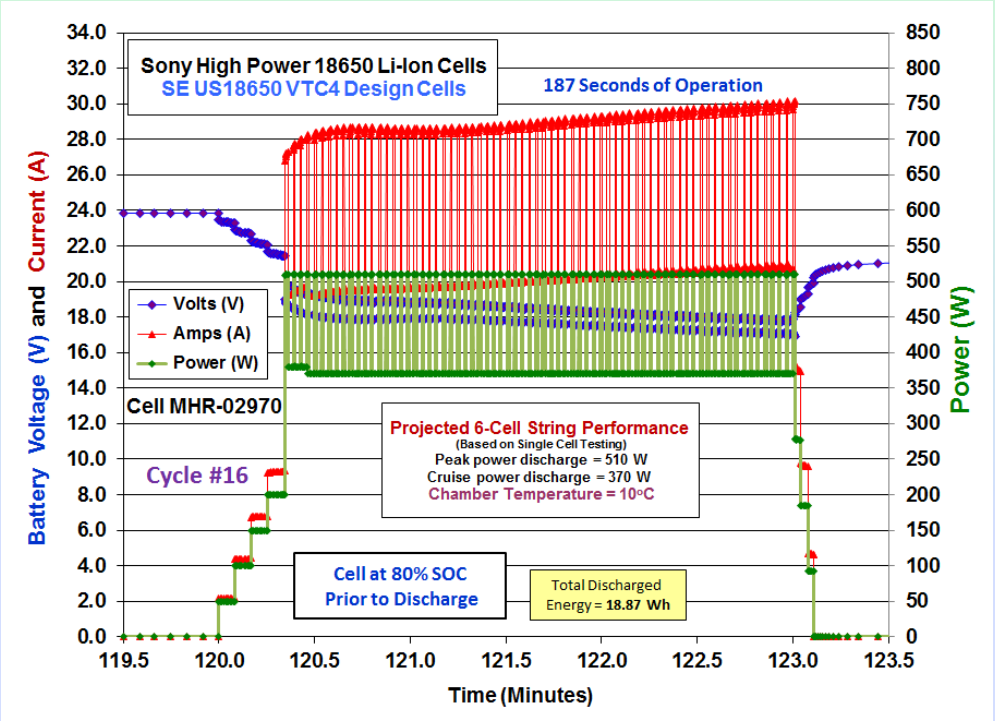
- Capable of flight in thin Mars atmosphere (10 millibar or ~1% of Earth)
- “Co-axial” Helicopter
- Blades 1.2-meter tip-to-tip
- Mass 1.8 Kg
- Solar powered - up to one 90-second flight per day
- Flight Range up to 300 m
- Heights up to 10 m
- Autonomous flight & landing
- Able to survive cold Martian nights

Description of Current Planned Li-Ion Battery for Mars Helicopter Leonardo Technology Demonstration

- Description of Current Baseline Li-Ion Battery for MHL:
  - Baseline 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 = - 10°C to 25°C
  - Non-Operational Allowable Flight Temperature (AFT) Range = - 10°C to 45°C
    - Temperature range applies to cruise period
    - Cells will be maintained at a low SOC during cruise (20-50% SOC)

Performance of Sony SE US18650 VTC4 Li-ion Cells
High Power Test: 10°C, 187 Seconds, 80% SOC, 72 Pulses

- Temp = 10°C
- SOC = 80%
- 72 x 510W pulses
- 151 Second flight
- 187 Seconds total operational time

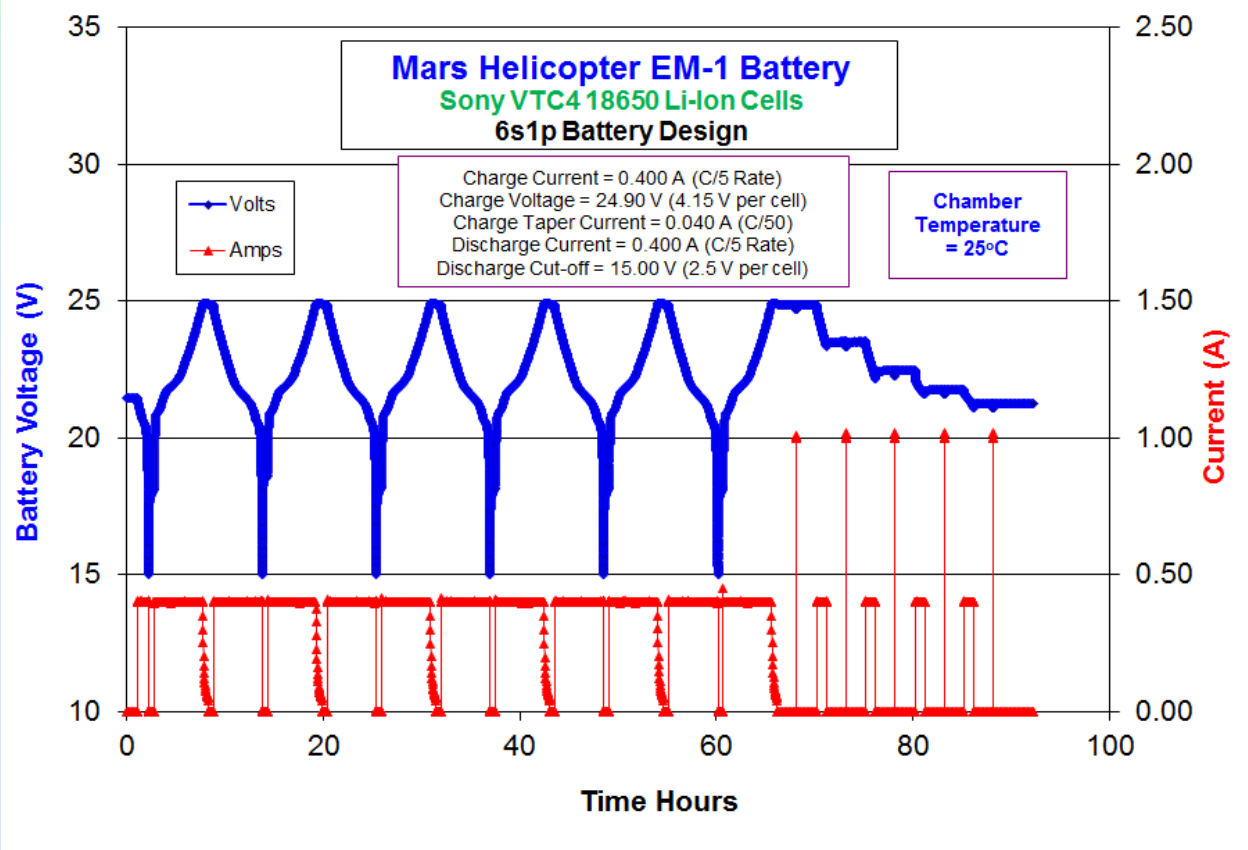


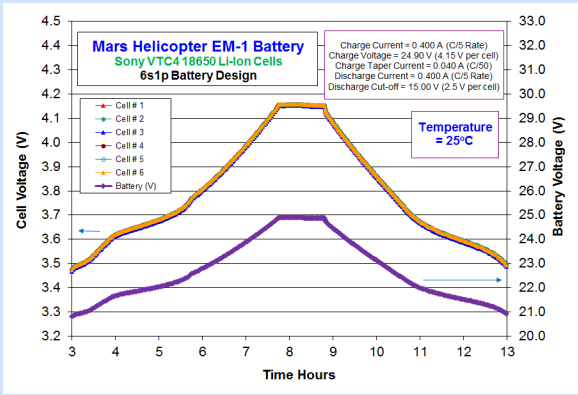
- The Sony VTC4 cell design is capable of supporting 187 seconds of high power operation under an aggressive load profile, corresponding to 510W peak and 370W nominal power levels at the string level
- Initial Cell Temperature = 10°C
- **Maximum cell discharge current observed = 30.159A**
- **Minimum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

More recent testing has demonstrated that the battery can support 510W peak and 370W nominal power loads at +10°C. (Initial SOC = 80).

Summary of MHS Li-Ion EM-1 Technology Demonstration
Battery Acceptance Testing

- **(A) Capacity and Impedance Characterization Measurement at + 25°C**



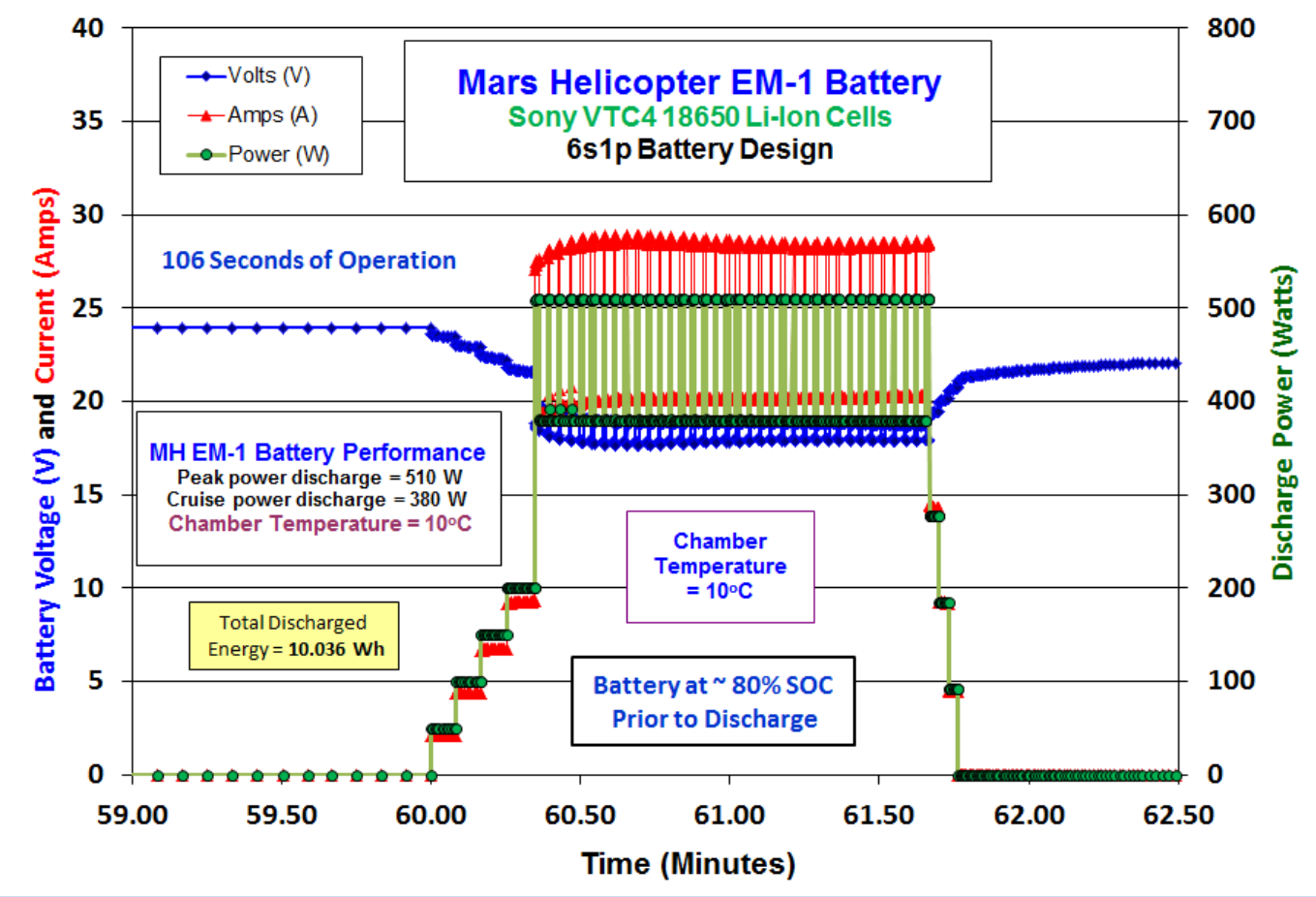


- Minimal cell voltage dispersion observed amongst the cells of the 6-cell string.

Battery level performance demonstrated to correlate well with individual cell testing.

MHL Li-Ion EM-1 Battery High Power Profile Test

Mars Helicopter 6s1p Battery High Power Test (510W Peak)



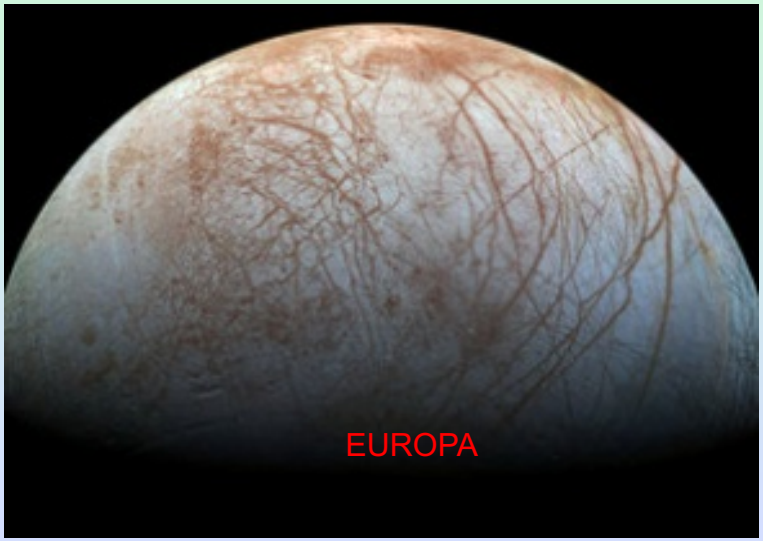
Prototype battery demonstrate to support peak power demands.

Background: Mission Concept Needs

Potential Future Ocean Worlds Power System Needs

- **Power: ~ 100 W**
- **Voltage ~ 28 V**
- **Operational Life on Surface: 7-14 days**

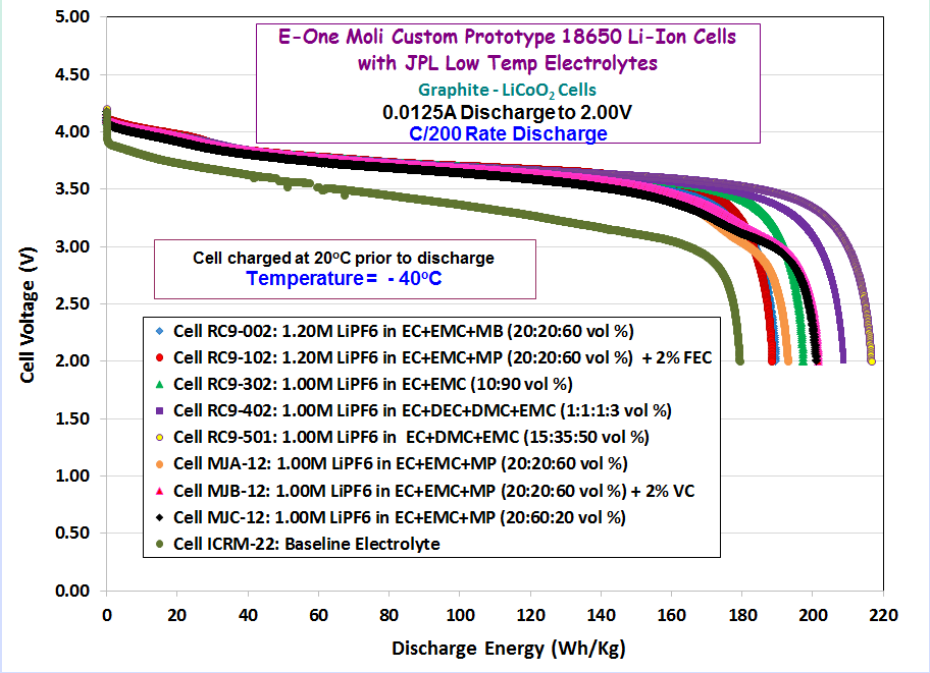
  (2 - 4 Europa days)
- **Mission Survivability/Shelf Life: 15 years**
- **Operating Temperature: - 60°C to 40°C**
- **Radiation Tolerance: > 2-4 Mrad**
- **Planetary Protection: Required**



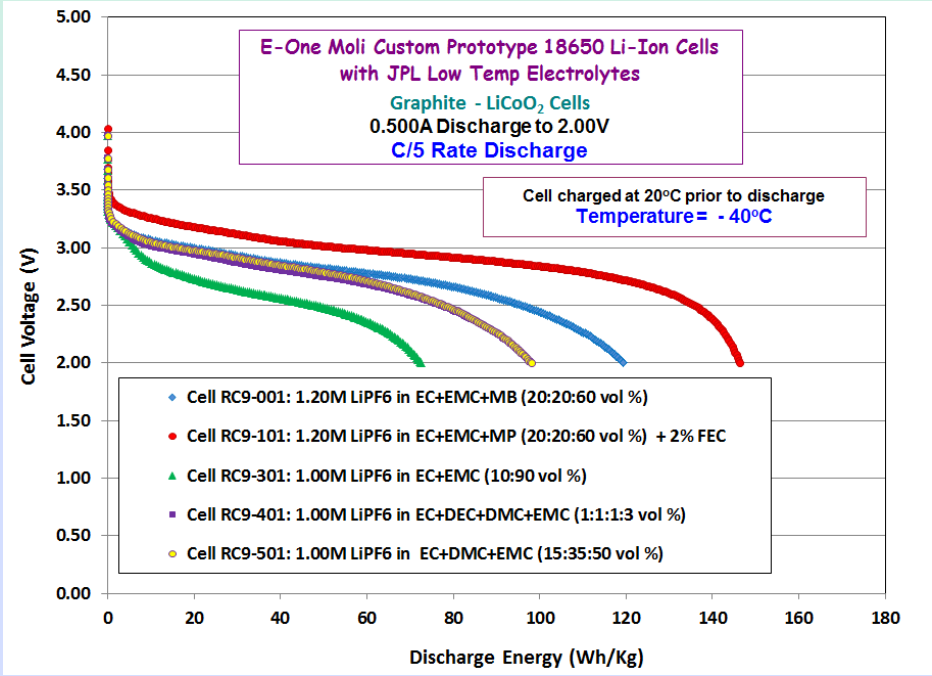
- **A potential future mission to Europa, or other Ocean World, could benefit significantly from a low temperature rechargeable battery with full operational capability when coupled with solar arrays, enabling a means to meet a 14 day requirement:**
  - If RHU's or RTG's were not selected to provide heat, low temperature batteries would be desired
  - Improved low temperature performance **(down to -60°C)** would reduce thermal power loads
  - Results in lower power sub-system and thermal power sub-system mass
  - Extended mission durations are possible (> 14 days)

Performance of E-One Moli Custom Prototype 18650 Cells at Room Temperature: Characteristization at - 40°C (C/200 Discharge to 2.0V)

C/200 Discharge



C/5 Discharge

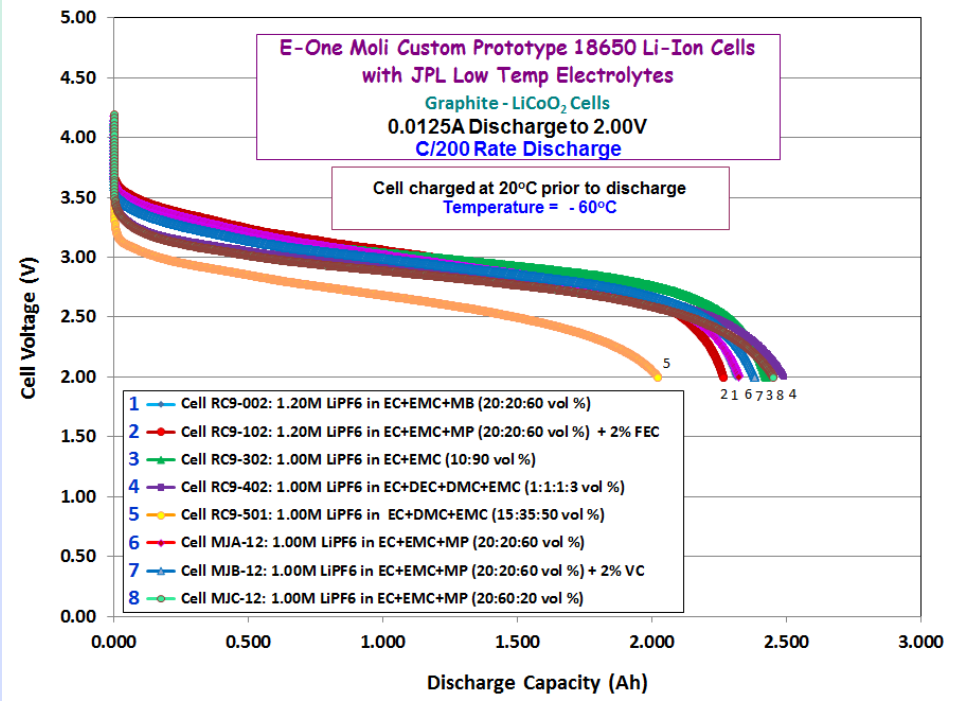


- With charging at room temperature, excellent specific energy can be observed at low rate (C/200) at -40°C.
- Over 200 Wh/kg was observed for many electrolyte variations.
- At these low rates, the all carbonate-based electrolyte systems provided the highest specific energy.

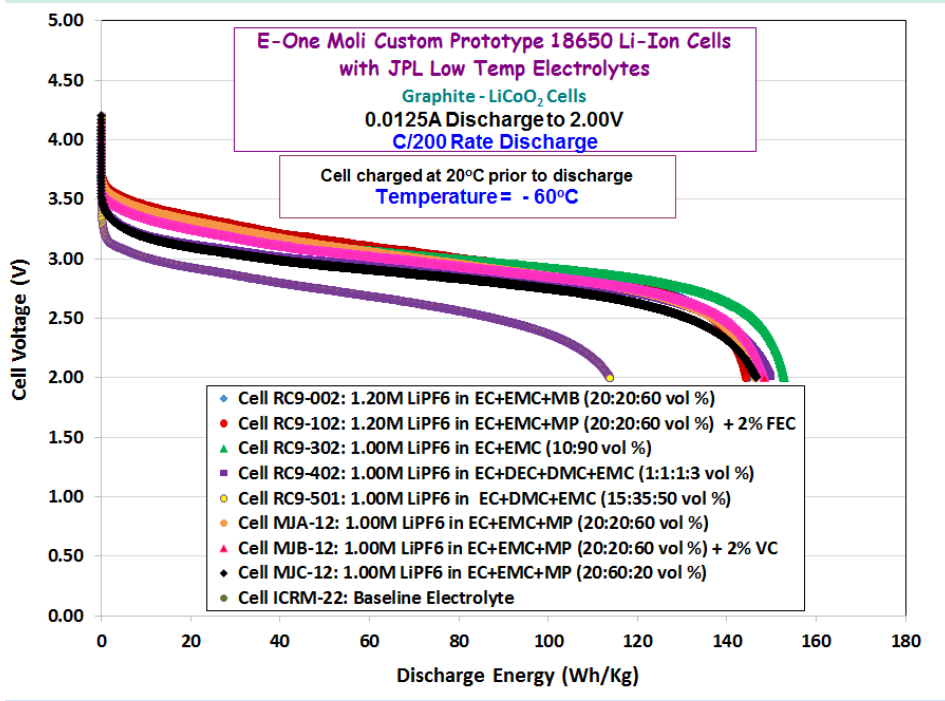
M. C. Smart, F. C. Krause, J. –P. Jones, L. D. Whitcanack, B. V. Ratnakumar, E. J. Brandon, and M. Shoesmith, "Low Temperature Electrolytes in High Specific Energy 18650 Li-Ion Cells for Future NASA Missions", 2016 Prime Pacific Rim Meeting on Electrochemical and Solid-State Science, Honolulu, HI, October 2-7, 2016.

Performance of E-One Moli Custom Prototype 18650 Cells at Room Temperature: Characteristization at - 60°C (C/200 Discharge to 2.0V)

Discharge Capacity (Ah)



Discharge Energy (Wh/Kg)



- With charging at room temperature, excellent specific energy can be observed at low rate (C/200) at -60°C .
- Over 150 Wh/kg was observed for many electrolyte variations.

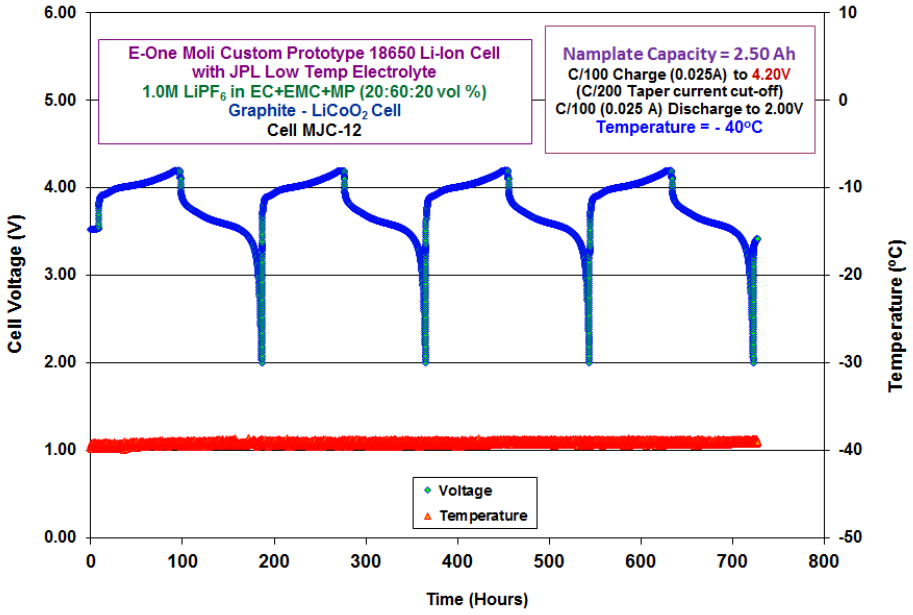
M. C. Smart, F. C. Krause, J. –P. Jones, L. D. Whitcanack, B. V. Ratnakumar, E. J. Brandon, and M. Shoesmith, "Low Temperature Electrolytes in High Specific Energy 18650 Li-Ion Cells for Future NASA Missions", 2016 Prime Pacific Rim Meeting on Electrochemical and Solid-State Science, Honolulu, HI, October 2-7, 2016.

Performance of E-One Moli Custom Prototype 18650 Cells

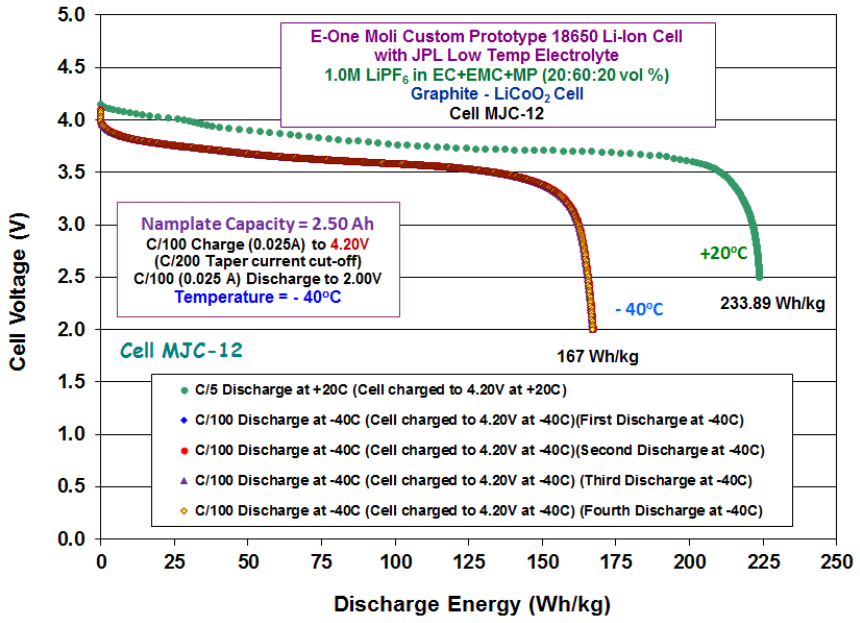
Charge and Discharge at -40°C (C/100 Rates))(Charge Voltage = 4.20V)

JPL Electrolyte "C" = 1.0M $LiPF_6$ in EC+EMC+MP (20:60:20 vol %) [InSight Electrolyte]

Continuous cycling at -40°C (4.20V Charge)



Specific Energy (Wh/kg) at -40°C



- Excellent specific energy at -40°C observed using a low rate charge and discharge (C/100) (i.e., 167 Wh/kg).
- No lithium plating observed when charging to 4.20V at -40°C using low rate charge.

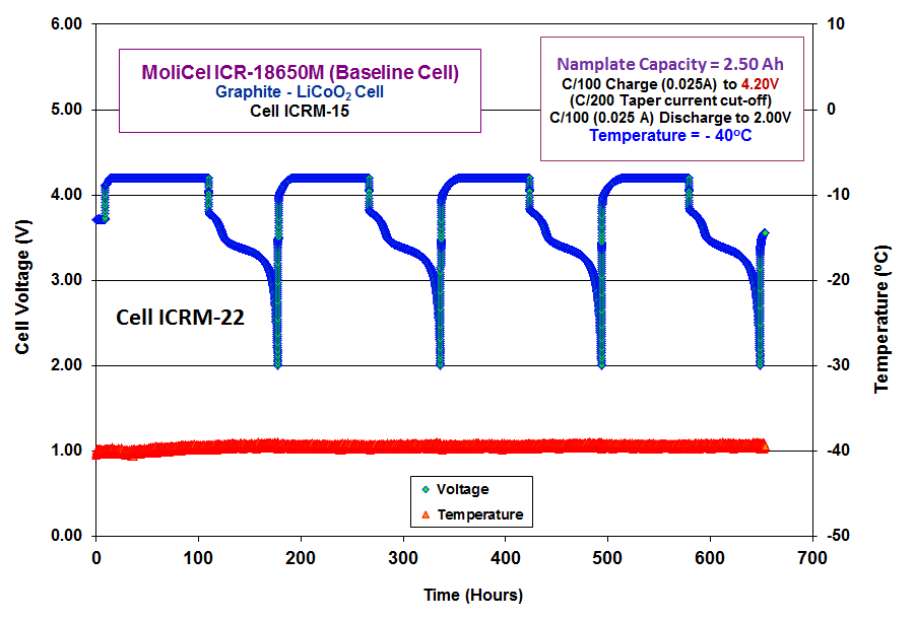
- **The custom E-One Moli cells with JPL electrolytes display improved cycling performance at -40°C compared to the baseline. A number custom JPL electrolytes have been demonstrated to meet programmatic target of >100 Wh/kg (both charge and discharge at -40°C).**

Performance of E-One Moli Custom Prototype 18650 Cells

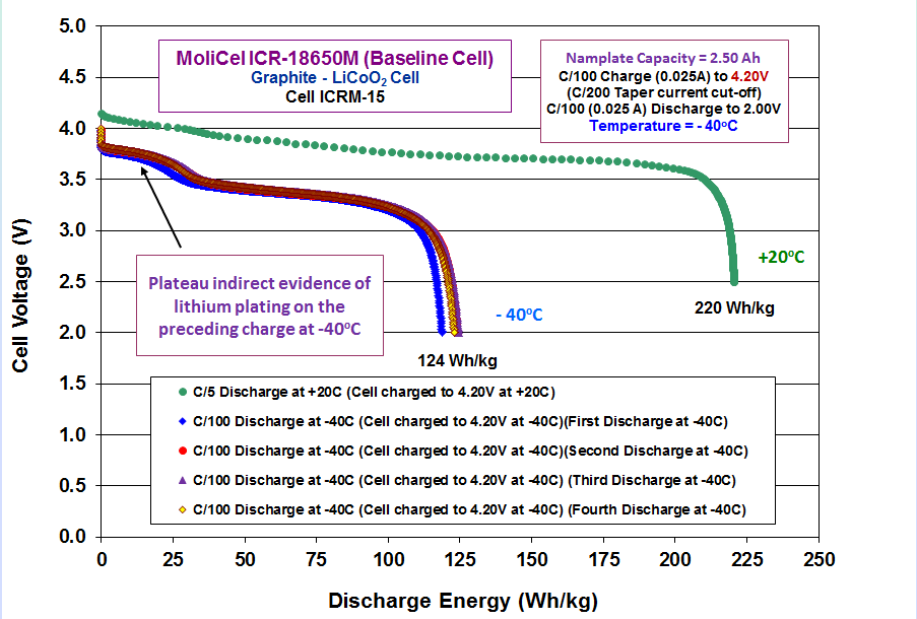
Charge and Discharge at -40°C (C/100 Rates))(Charge Voltage = 4.20V)

Baseline Commercial Off-the-Shelf Cell (COTS)

Continuous cycling at -40°C (4.20V Charge)



Specific Energy (Wh/kg) at -40°C

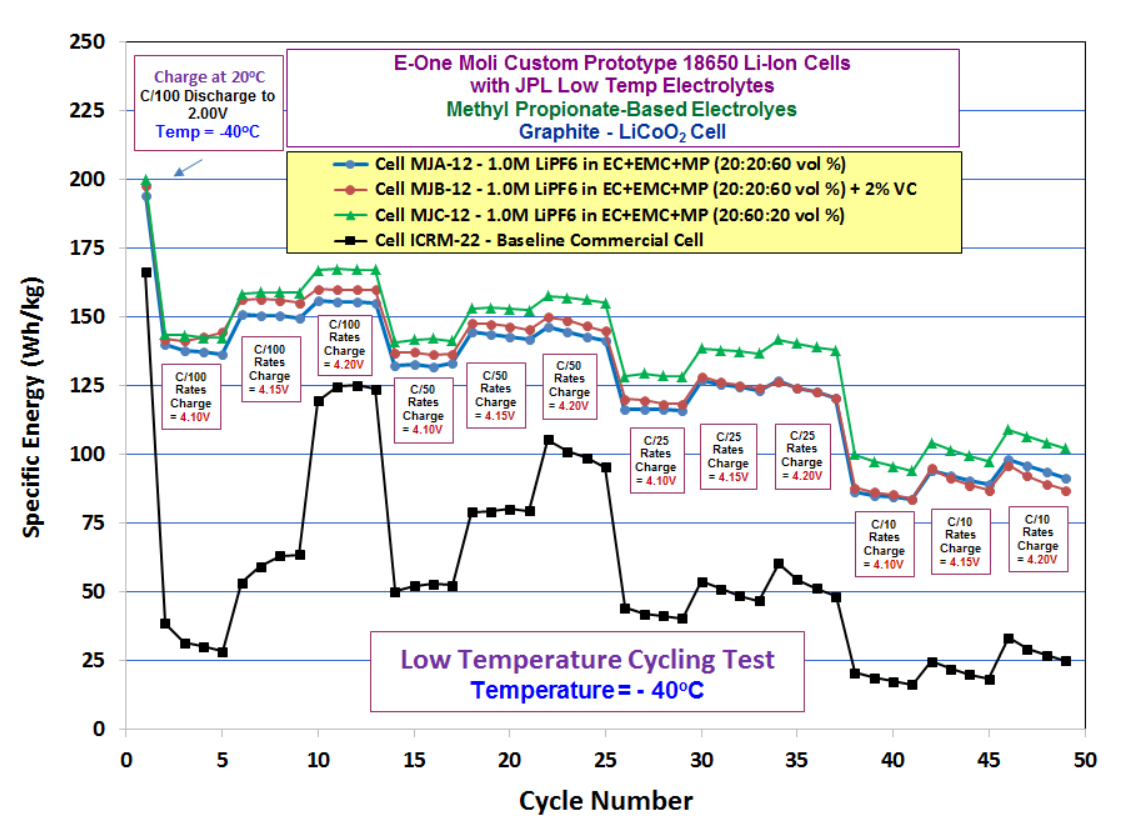


- Although good specific energy at -40°C is observed with the baseline commercial cell when charging to 4.20V at -40 (C/100) (i.e., > 124Wh/kg), there is evidence of lithium plating which leads to cell degradation.

- The custom E-One Moli prototype cells with JPL electrolytes display improved cycling performance at -40°C compared to the baseline. A number of cells containing JPL electrolytes have been demonstrated to meet programmatic target of >100 Wh/kg (both charge and discharge at -40°C).

Performance of E-One Moli Custom Prototype 18650 Cells

Continuous cycling at -40°C: Effect of charge voltage and charge rate

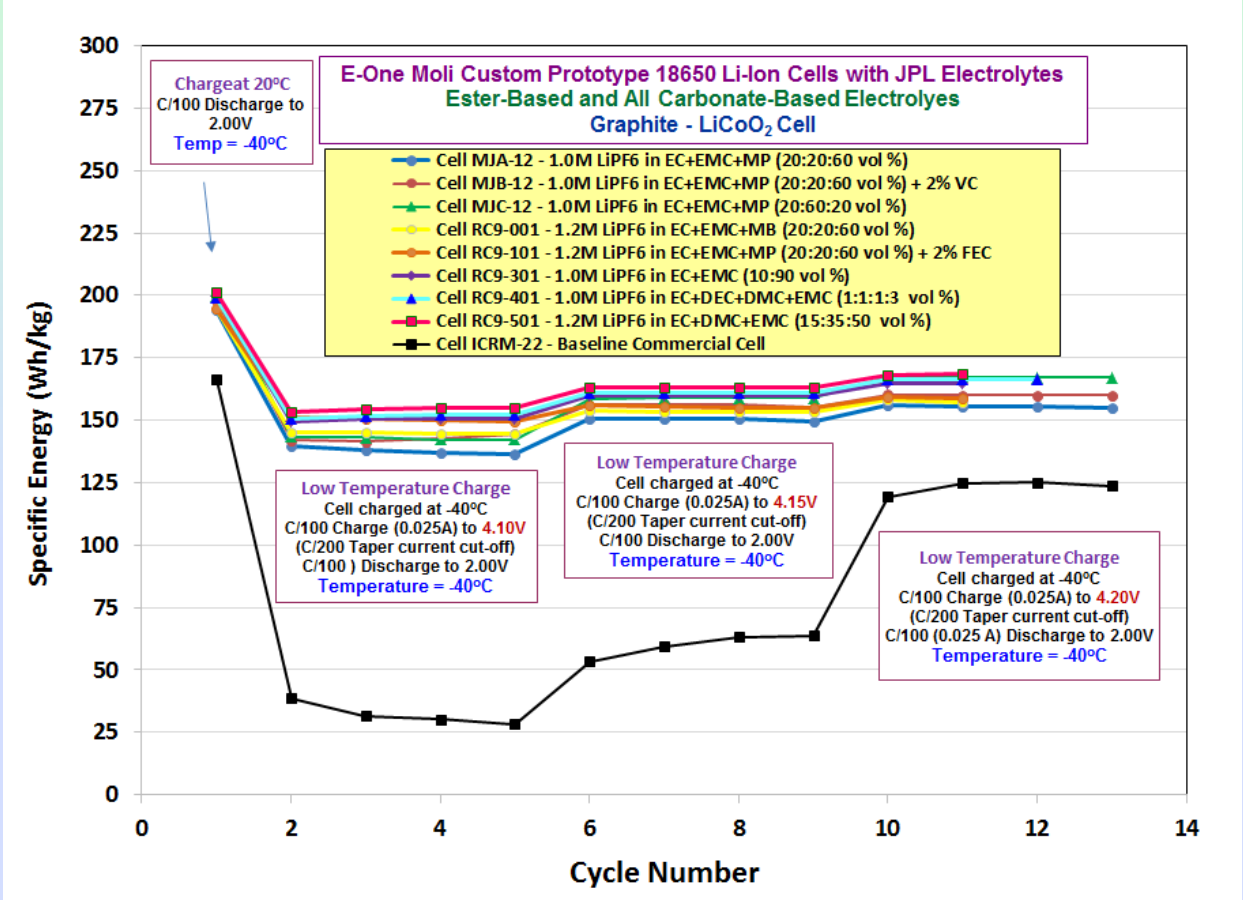


- Excellent specific energy at -40°C observed using a low rate charge and discharge (C/100) (i.e., > 167 Wh/kg).
- At higher charge rates and charge voltage, there may be some lithium plating occurring, which may account for the higher capacity fade observed.

- The custom E-One Moli prototype cells with JPL electrolytes display improved cycling performance at -40°C compared to the baseline. A number of cells containing JPL electrolytes have been demonstrated to meet programmatic target of >100 Wh/kg (both charge and discharge at -40°C).

Performance of E-One Moli Custom Prototype 18650 Cells

Continuous cycling at -40°C: Effect of charge voltage and charge rate



- Excellent specific energy at -40°C observed using a low rate charge and discharge (C/100) (i.e., > 167 Wh/kg).
- Cells containing all-carbonate-based electrolytes appear to display very stable performance and high specific energy when cycled at low rates.

M. C. Smart, F. C. Krause, J. –P. Jones, L. D. Whitcanack, B. V. Ratnakumar, E. J. Brandon, and M. Shoesmith, "Low Temperature Electrolytes in High Specific Energy 18650 Li-Ion Cells for Future NASA Missions", 2016 Prime Pacific Rim Meeting on Electrochemical and Solid-State Science, Honolulu, HI, October 2-7, 2016.

Summary and Conclusions

- **Planned Europa Mission :**
  - When cells were when subjected to 100% DOD cycling at +30°C and at 0°C, and successfully the E-One Moli ICR-M cell and the LG Chem MJ1 cells displayed good life characteristics.
  - When subjected to 100% DOD cycling at 0°C, the E-One Moli ICR-M cells displayed the most stable performance and delivered the highest capacity after completing 300 cycles.
  - The E-One Moli ICR-M and the LG Chem MJ1 cells displayed excellent discharge rate capability over a range of temperatures, exceeding mission requirements.
  - Both the LG Chem MJ1 and the E-One Moli ICR-M have been demonstrated to have excellent resilience to radiation.
  - The LG Chem MJ1 and the E-One Moli ICR-M cell have been identified as being the most viable options for the Europa Clipper mission, based upon a number of performance characteristics.
- **Planned Mars Helicopter Technology Demonstration:**
  - Sony VTC4 cells have been demonstrated to have excellent power capability, being able to support 30A discharge currents, while still providing good specific energy.
  - Prototype 6-cell modules have been demonstrated to support the high power requirements (510W peak and 360W continuous), enabling flight.
- **Potential Future Ocean Worlds Applications:**
  - Custom Moli 18650 cells with JPL electrolytes display improved cycling performance at -40°C compared to the baseline. A number of cells containing JPL electrolytes have been demonstrated to deliver >150 Wh/kg (both charge and discharge at -40°C).
  - At - 60°C, over 150 Wh/kg was delivered with many permutations at low rate.

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) and supported by the Europa Clipper Mission and the Mars Helicopter Technology Demonstration.

ABSL Space Products

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E-One Moli Energy

Mark Shoesmith