# The Performance Evaluation of High Specific Energy 18650-Size Lithium-Ion Cells for the Planned Europa Clipper Mission

M. C. Smart, F. C. Krause, A. Lawrence,
B. V. Ratnakumar, A. Ulloa-Severino, and R. C. Ewell

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

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# Outline

- *Background*
- *Over-view of Test Plan*
- *Cycle Life Performance Evaluation*
  - *Cell level testing at +30°C, 0°C, and -20°C*
  - *Module level testing at +20°C*
- *Calendar Life Performance Evaluation*
  - *Short duration cell level testing at high temperature*
  - *Long duration cell level testing at 0°C and +20°C*
  - *Long duration module level testing at +20°C*
- *Discharge Rate Performance Evaluation*
- *Assessment of Radiation Tolerance*
- *Conclusions*

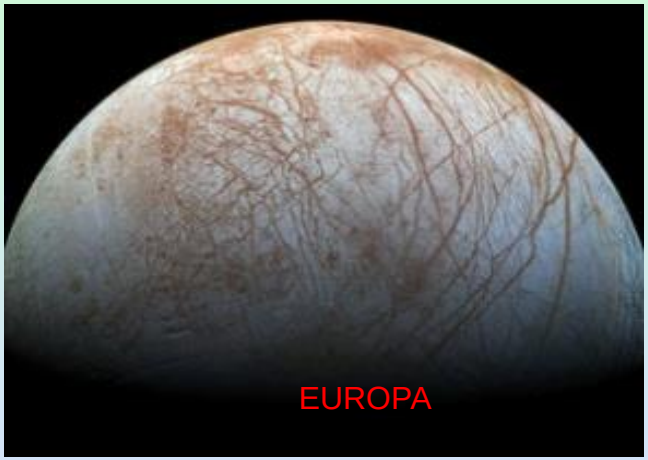
# NASA's Planned Europa Mission

- **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

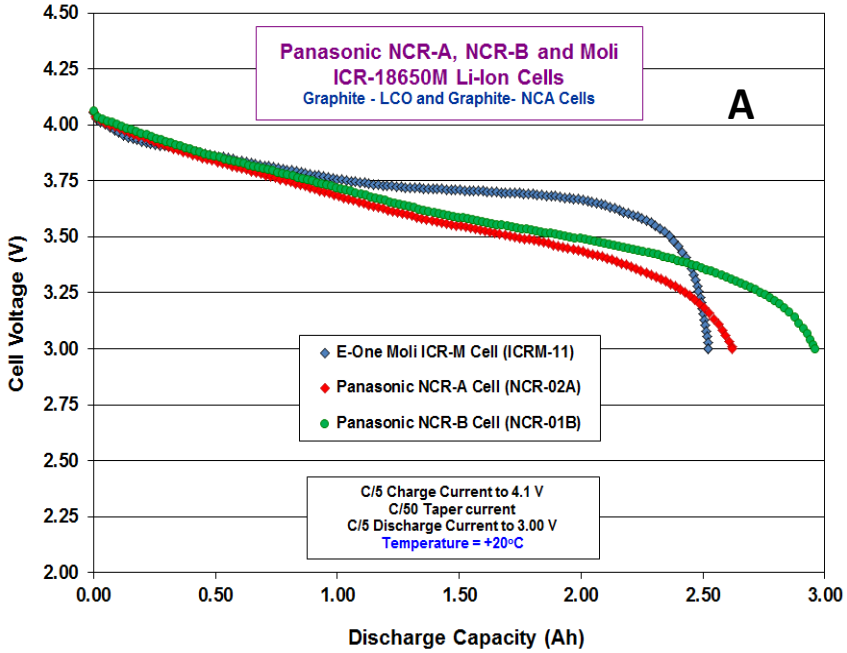
- **The Europa Mission has identified a number of viable small cell Li-ion options that are good candidates for the project, which provide high specific energy and good performance characteristics.**
  - **Molicel ICR-M 18650 Cells**
  - **Molicel ICR-J 18650 Cells**
  - **Panasonic NCR-A 18650 Cells**
  - **Panasonic NCR-B 18650 Cells**

- **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$^{o}$C and +25$^{o}$C)**
  - **High temperature storage characterization (+30$^{o}$C)**
  - **8-Cell module 100% DOD cycle life testing at +20$^{o}$C**
  - **8-Cell module long term storage life testing at +0$^{o}$C**
  - **Discharge and charge rate characterization testing**
  - **Radiation tolerance (subjected to $^{60}$Co gamma rays)**

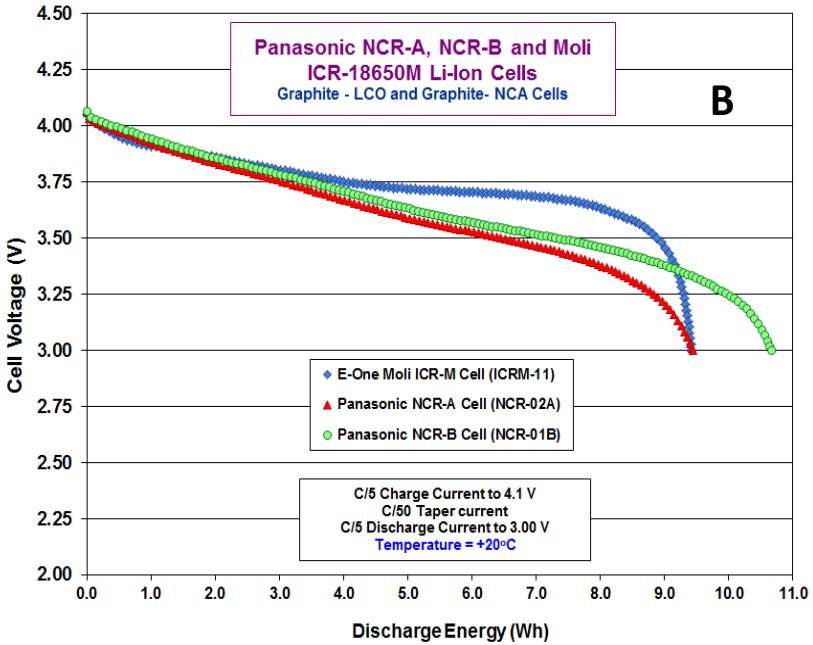
# NASA's Planned Europa Mission: Lithium-Ion 18650 Cell Chemistry Assessment

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

**Initial Discharge Capacity (Ah) at 20°C**




**Watt Hours Delivered (Wh) at 20°C**

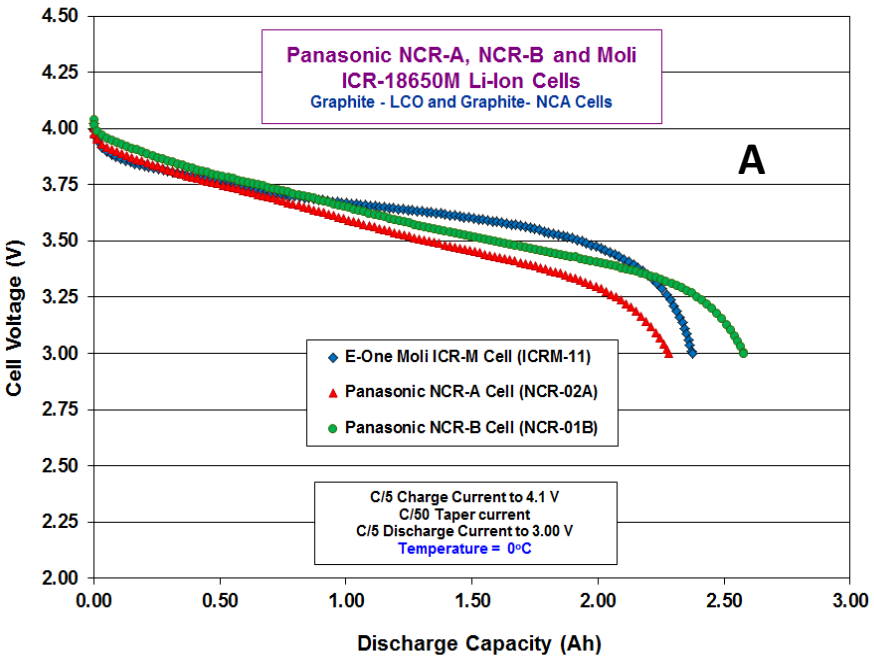



- Discharge capacity (Ah)(**A**) and discharge energy (Wh)(**B**) of Panasonic NCR-A, NCR-B and Moli ICR-M Li-Ion 18650-size cells at 20°C using C/5 charge and discharge rates over the voltage range of 3.0V to 4.10V.

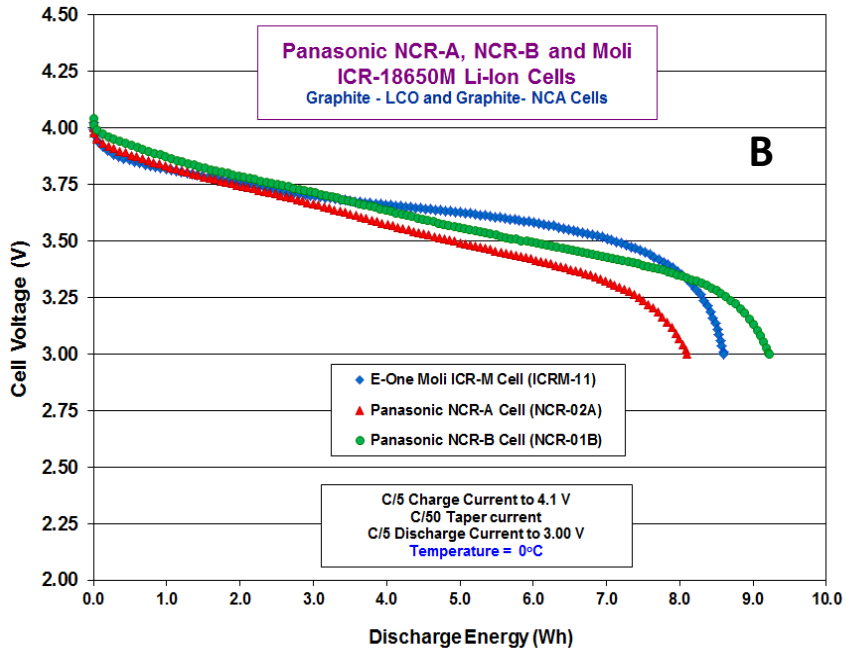
# NASA's Planned Europa Mission: Lithium-Ion 18650 Cell Chemistry Assessment

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

**Initial Discharge Capacity (Ah) at 0°C**




**Watt Hours Delivered (Wh) at 0°C**

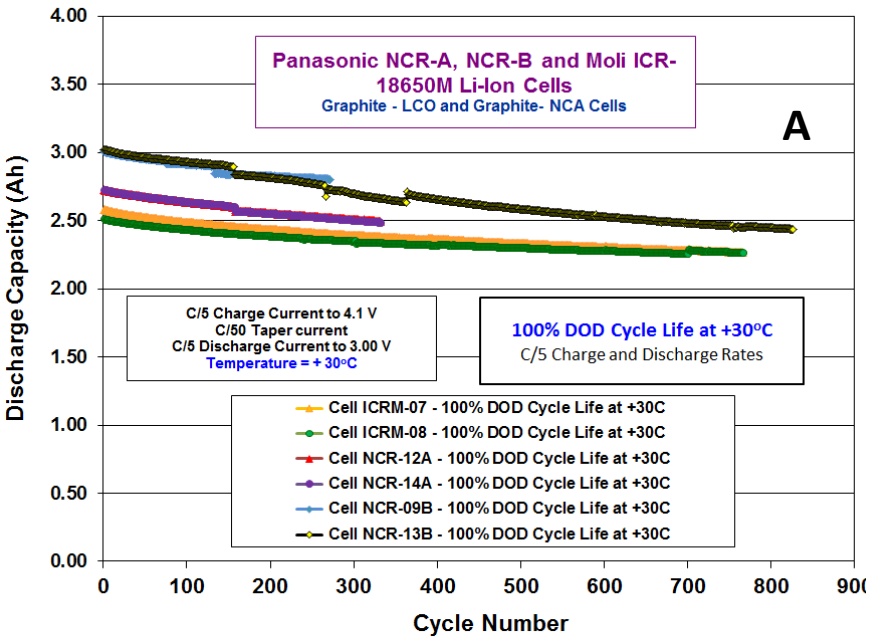



- Discharge capacity (Ah)(**A**) and discharge energy (Wh)(**B**) of Panasonic NCR-A, NCR-B and Moli ICR-M Li-Ion 18650-size cells at 0°C using C/5 charge and discharge rates over the voltage range of 3.0V to 4.10V.

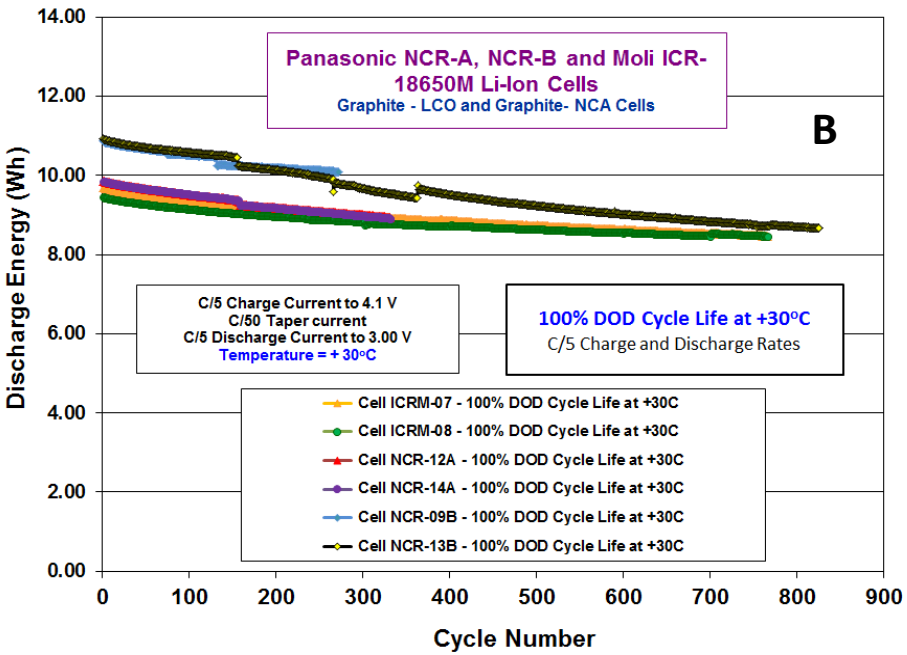
# NASA's Planned Europa Mission:
## Li-Ion Cell Level Testing: Cycle Life Performance

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

**Discharge Capacity (Ah) at 30°C**



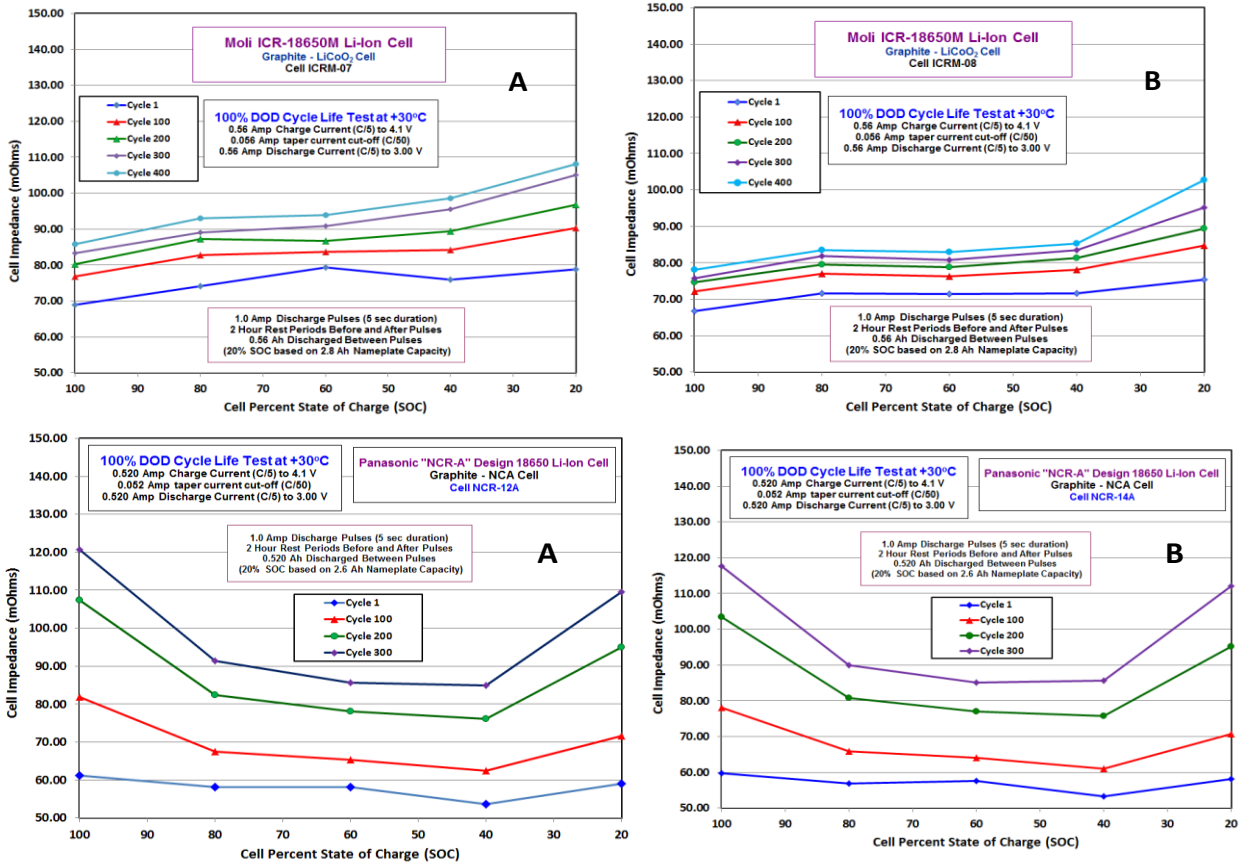

**Discharge Energy (Wh) at 30°C**




- Cycle life performance (100% Depth of Discharge) of Panasonic NCR-A, NCR-B 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

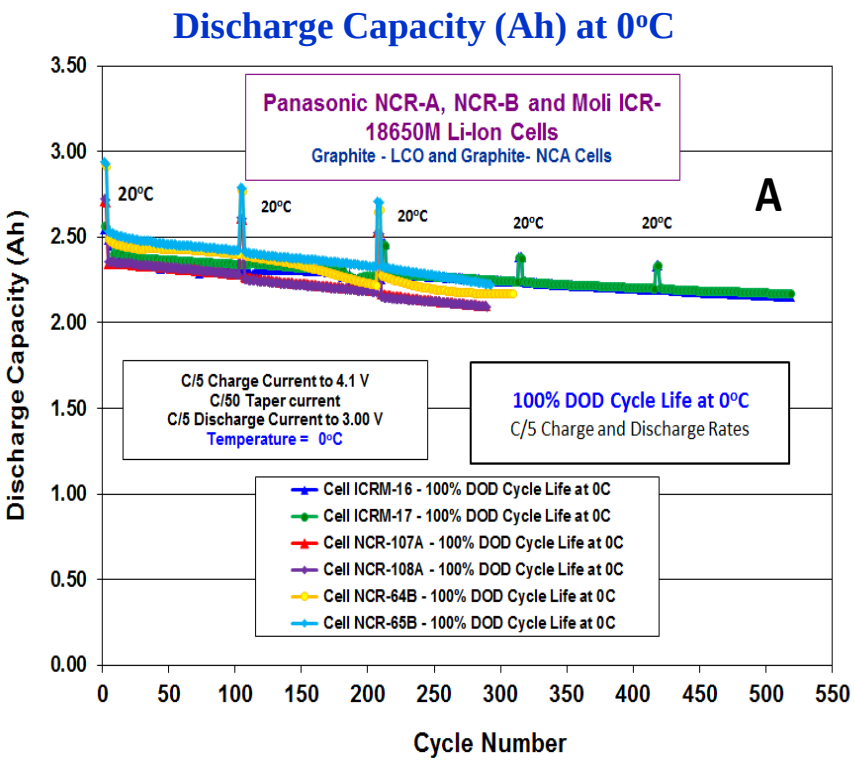
- ***Results of 100% DOD Cycle Life Testing +30°C: Impedance Characteristics***

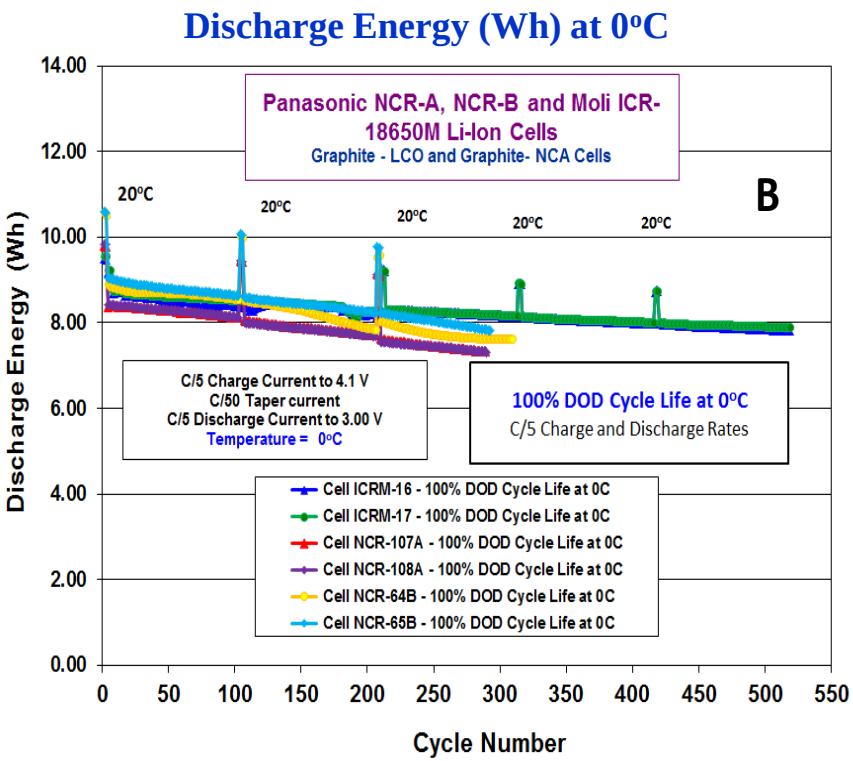



- E-One Moli cells have displayed the least amount of permanent capacity fade.

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

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



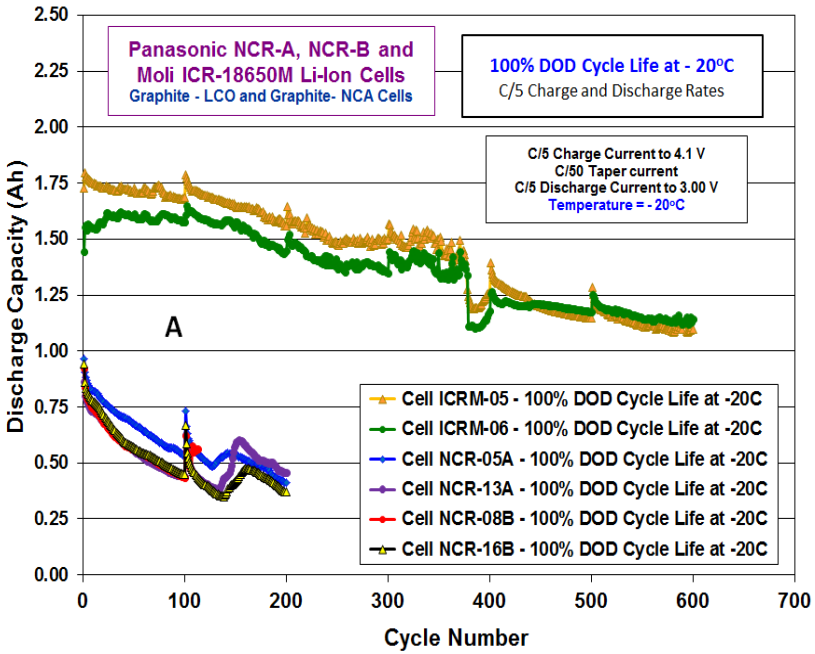




- Cycle life performance (100% Depth of Discharge) of Panasonic NCR-A, NCR-B and Moli ICR-M Li-Ion 18650-size cells at 0°C using C/5 charge and discharge rates over the voltage range of 3.0V to 4.10V, expressed in terms of the discharge capacity (Ah) (**A**) and discharge energy (Wh) (**B**).

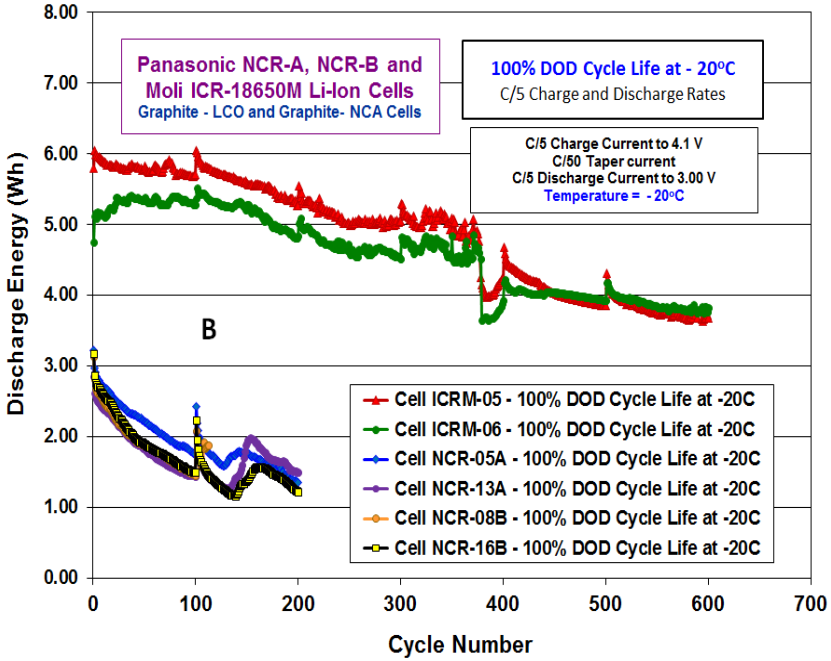
# NASA's Planned Europa Mission:
## Li-Ion Cell Level Testing: Cycle Life Performance

- ***Results of 100% DOD Cycle Life Testing - 20°C***

**Discharge Capacity (Ah) at - 20°C**



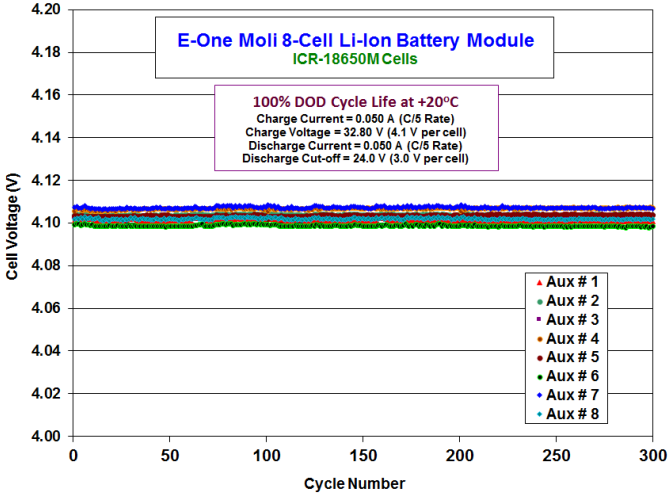

**Discharge Energy (Wh) at - 20°C**

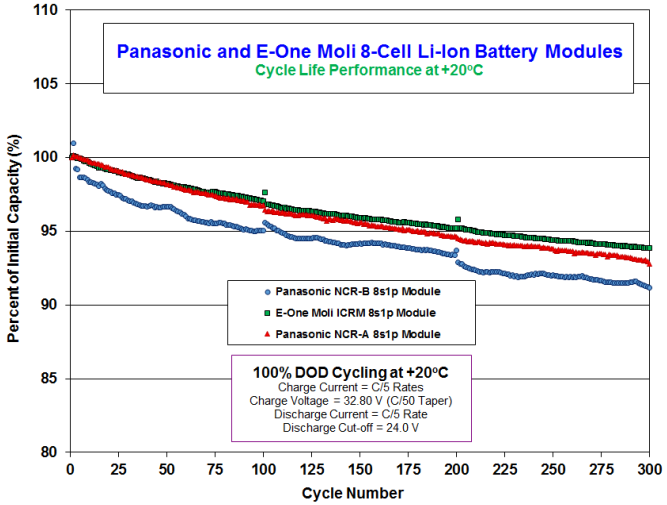



- Cycle life performance (100% Depth of Discharge) of Panasonic NCR-A, NCR-B and Moli ICR-M Li-Ion 18650-size cells at - 20°C using C/5 charge and discharge rates over the voltage range of 3.0V to 4.10V, expressed in terms of the discharge capacity (Ah) (**A**) and discharge energy (Wh) (**B**).
- The E-One Moli ICR-M cells are much more tolerant to charging at low temperatures, and are less prone to experience lithium plating degradation.

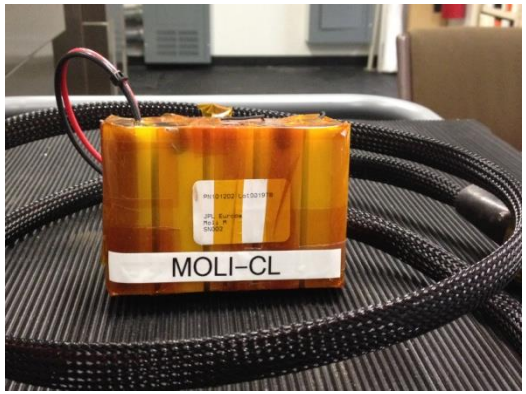
# NASA's Planned Europa Mission:
## Li-Ion Module Level Testing: Cycle Life Performance

- ***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 +20ºC (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 20º and 0ºC every 100 cycles**
  - **This testing has been completed on Panasonic NCR-B strings**



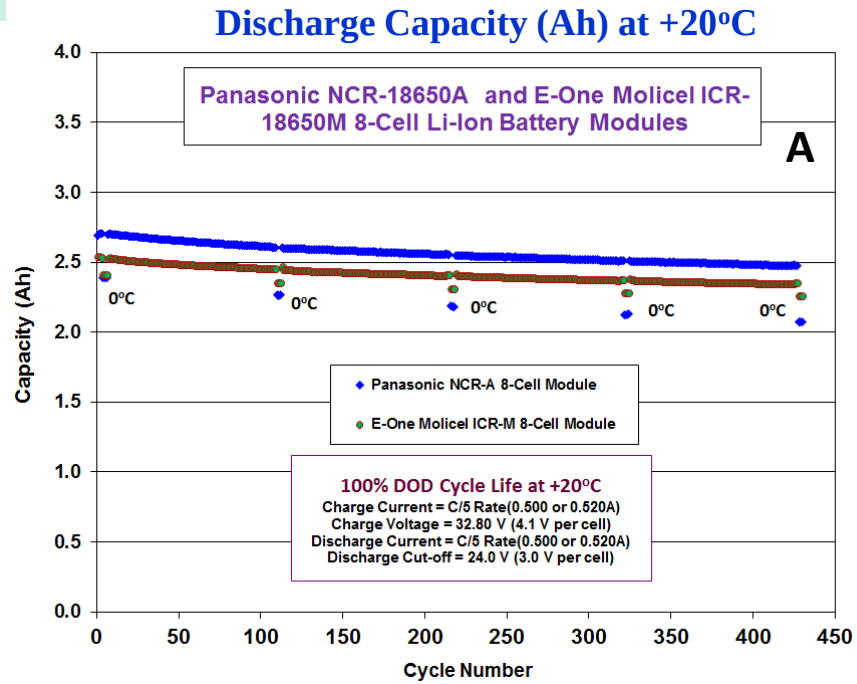



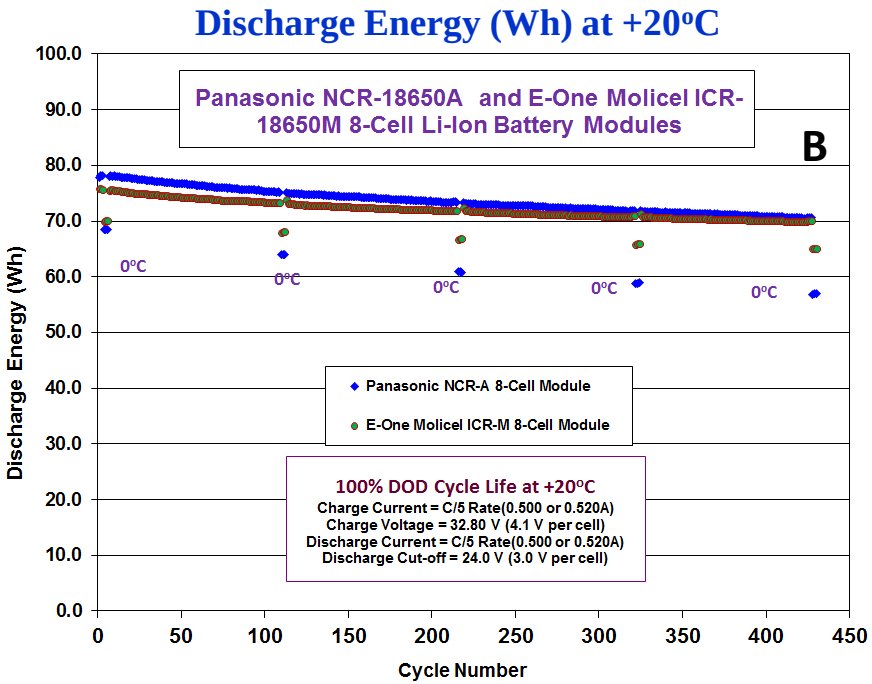

*Minimal cell voltage dispersion observed on charge (EOCV) after completing 300 cycles (< 15 mV)*



# 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)*



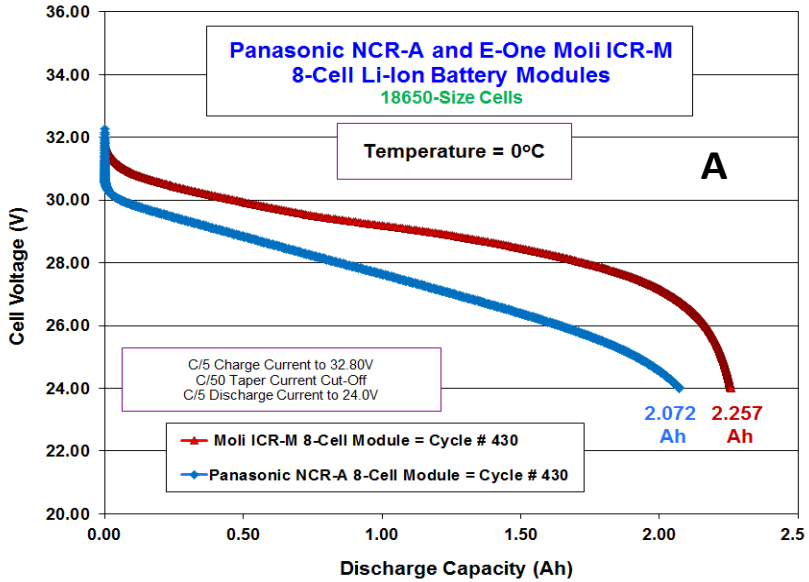




- Cycle life performance (100% Depth of Discharge) of Panasonic NCR-A and Moli ICR-M Li-Ion 8-cell strings at +20°C using C/5 charge and discharge rates over the voltage range of 24.0V to 32.80V, expressed in terms of the discharge capacity (Ah) (A) and discharge energy (Wh) (B).

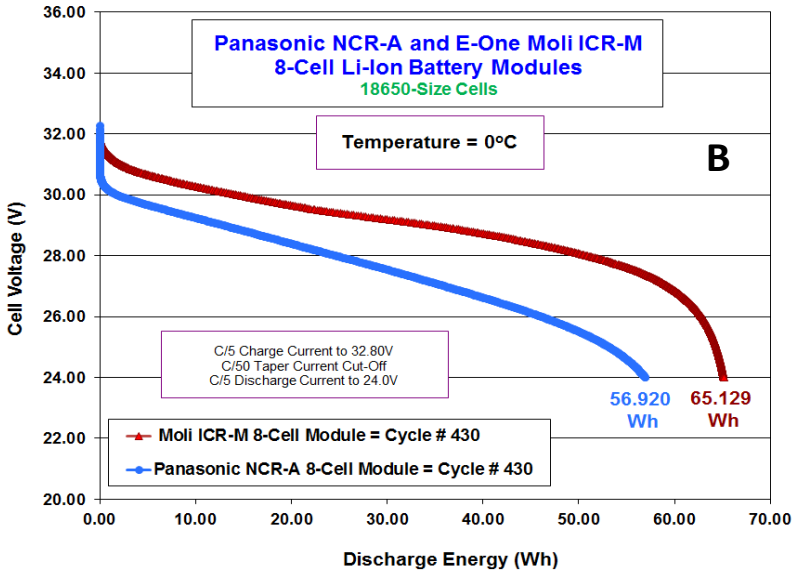
# NASA's Planned Europa Mission:
## Li-Ion Module Level Testing: Cycle Life Performance

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

**Discharge Capacity (Ah) at +20°C**



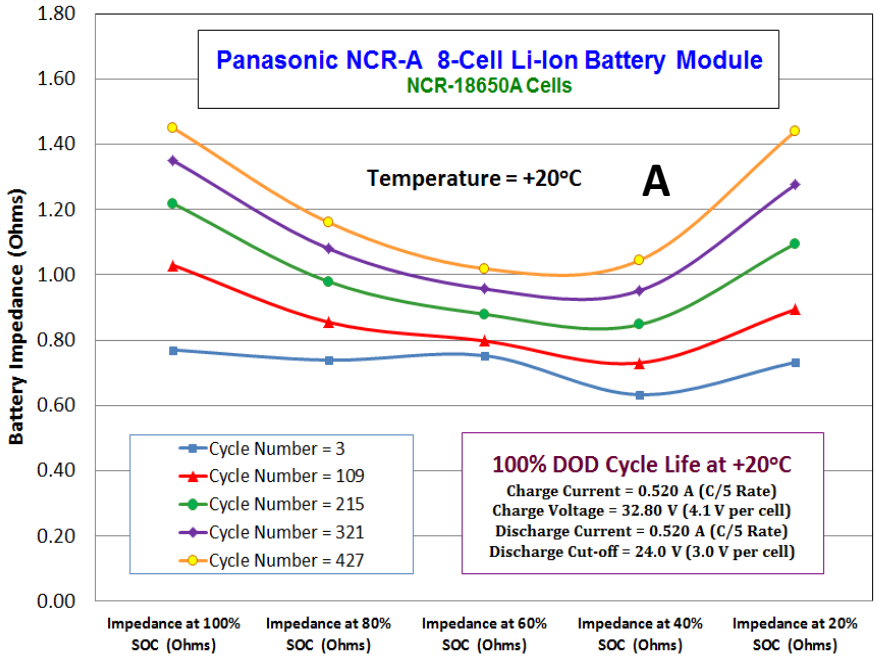

**Discharge Energy (Wh) at +20°C**

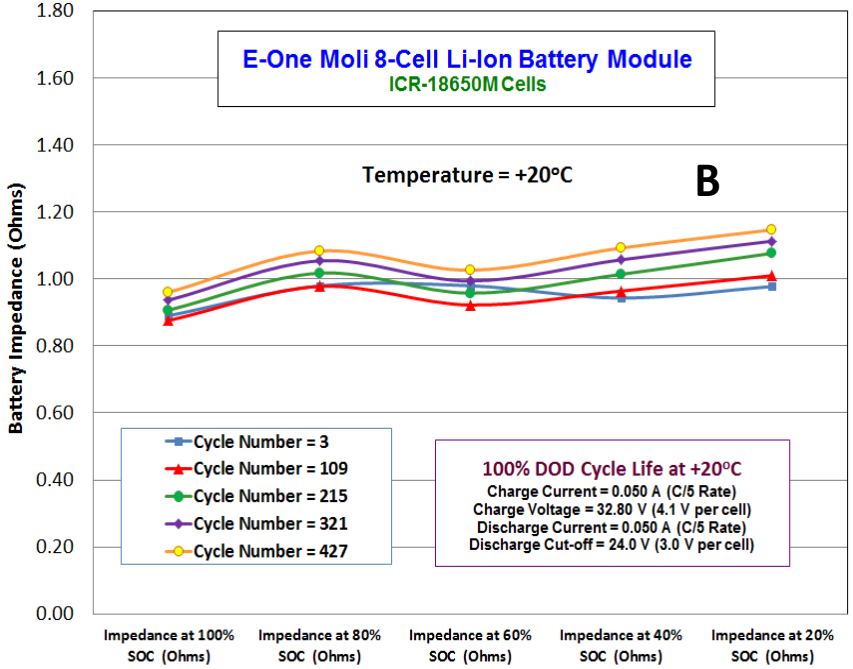



- The discharge curves of cycle #430 of Panasonic NCR-A and Moli ICR-M Li-Ion 8-cell strings at 0°C subjected to 100% cycle life testing at +20°C using C/5 charge and discharge rates over the voltage range of 24.0V to 32.80V, expressed in terms of the discharge capacity (Ah) (A) and discharge energy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

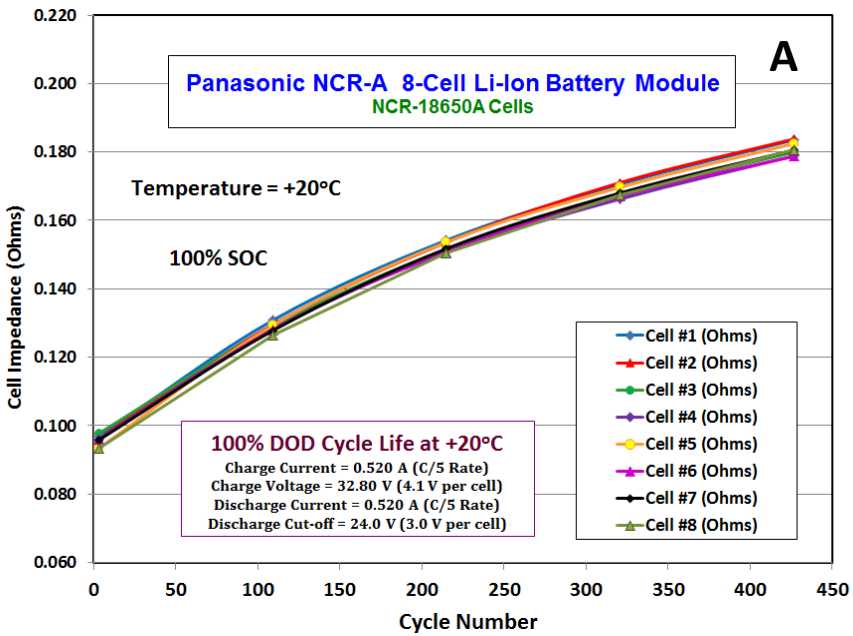


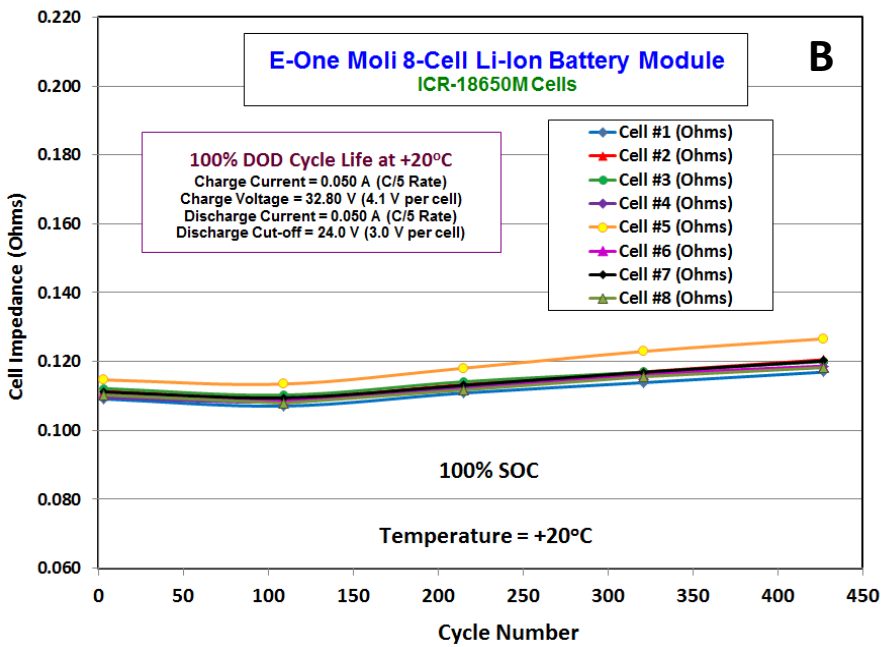




- The battery impedance characteristics at +20°C as a function of life of Panasonic NCR-A (**A**) and Moli ICR-M (**B**) Li-Ion 8-cell strings cycled at 100% DOD at +20°C using C/5 charge and discharge rates over the voltage range of 24.0V to 32.80V.

# 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)***

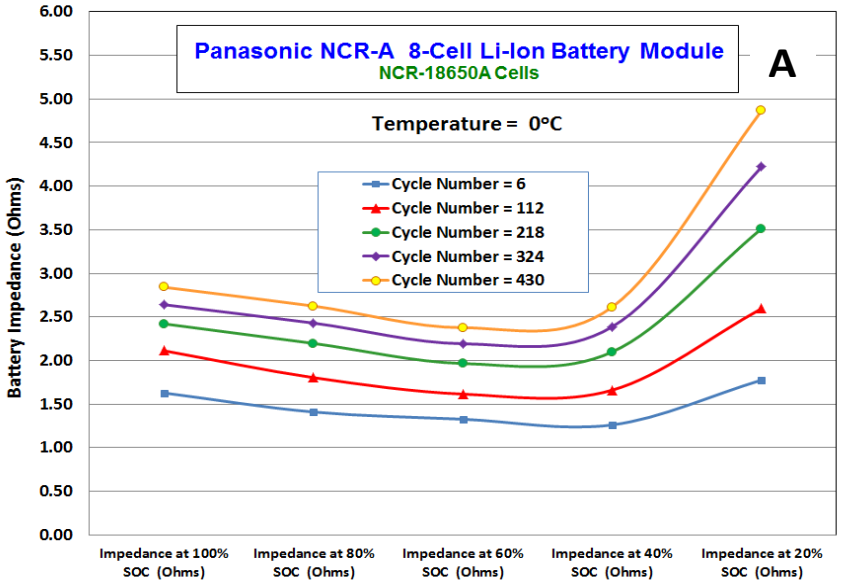


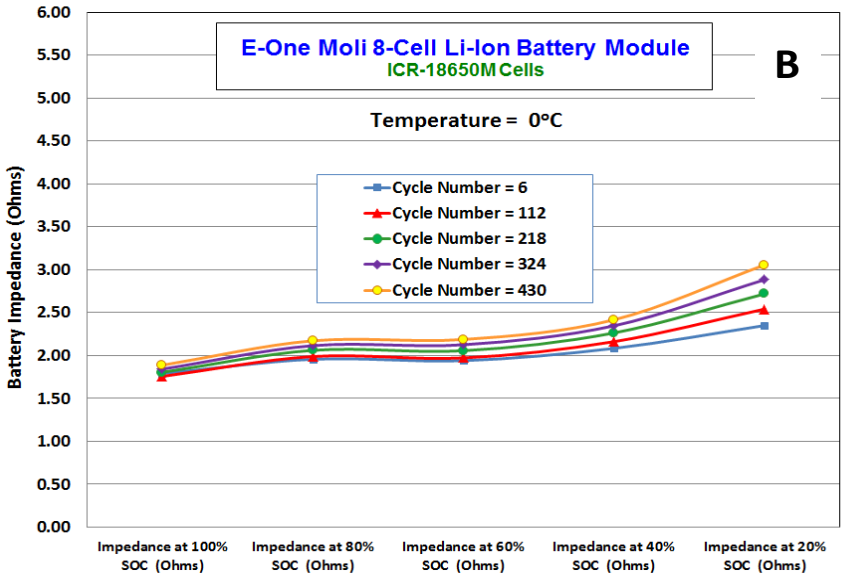




- The battery impedance characteristics of individual Panasonic NCR-A (**A**) and Moli ICR-M (**B**) cells in 8-cell strings at 100% SOC at +20°C as a function of life cycled at 100% DOD at +20°C using C/5 charge and discharge rates over the voltage range of 24.0V to 32.80V.

# 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)***

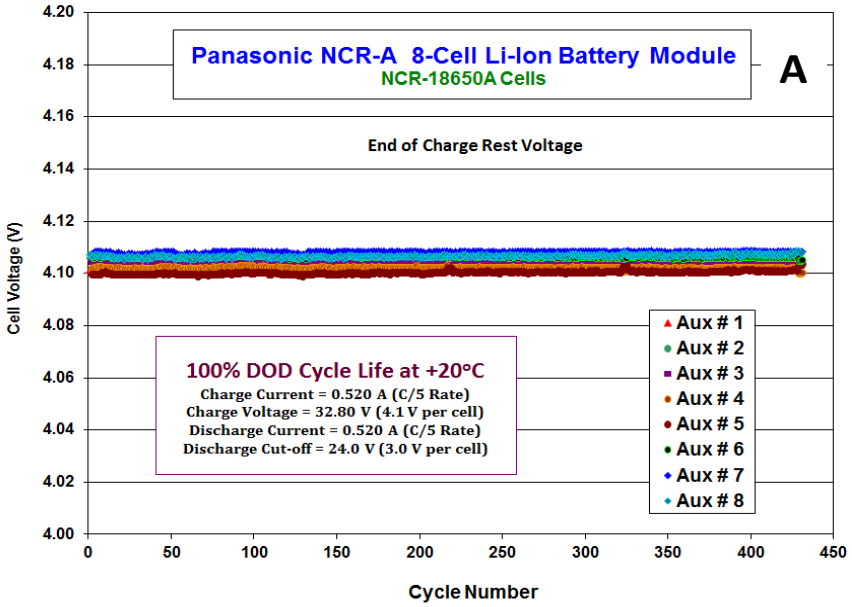


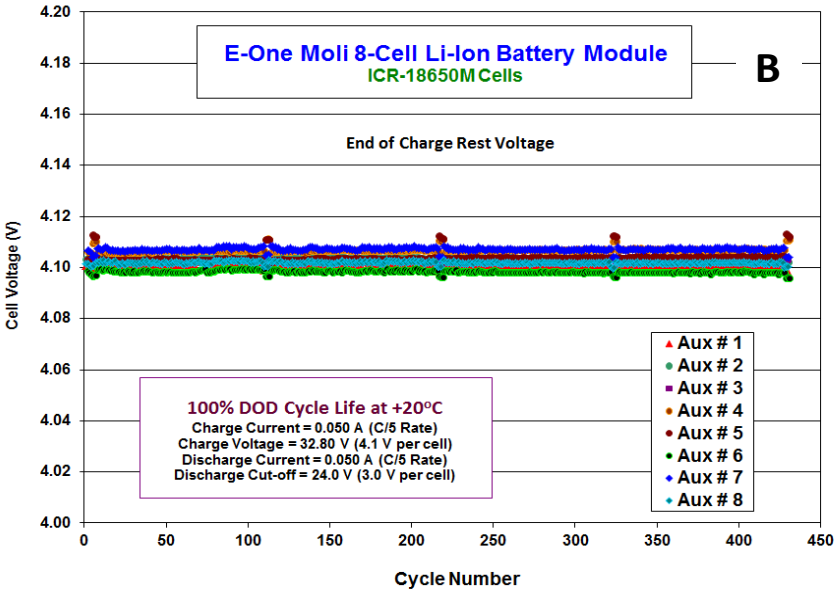




- The battery impedance characteristics at 0°C as a function of life of Panasonic NCR-A (**A**) and Moli ICR-M (**B**) Li-Ion 8-cell strings cycled at 100% DOD at +20°C using C/5 charge and discharge rates over the voltage range of 24.0V to 32.80V

# 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***

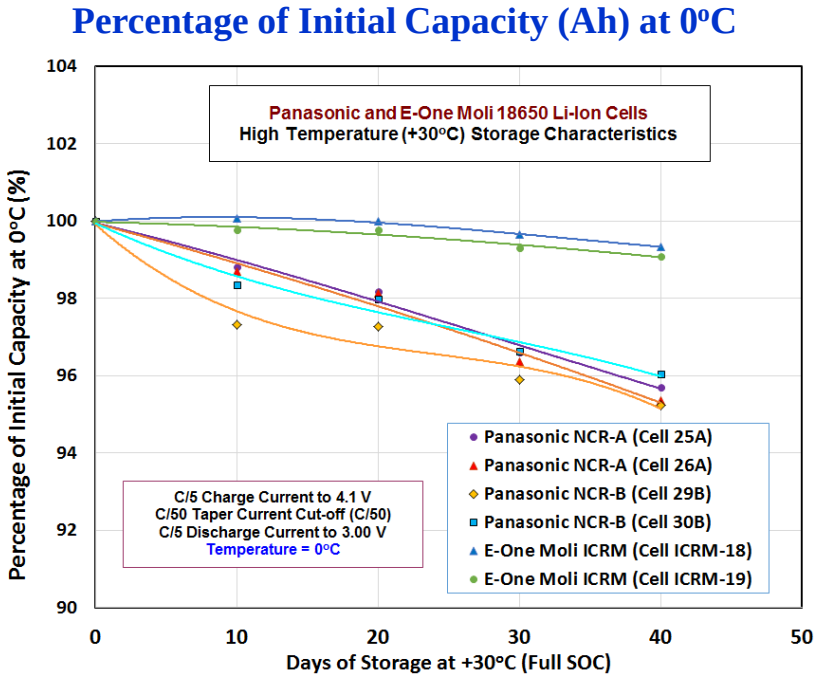


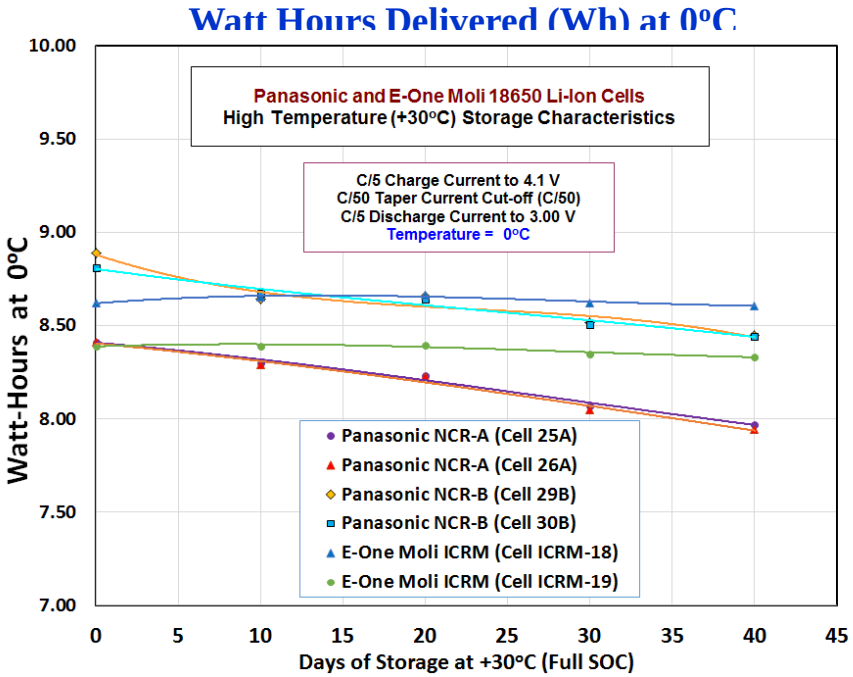




- The cell voltage dispersion at +20°C at rest after charge as a function of life of Panasonic NCR-A (**A**) and Moli ICR-M (**B**) Li-Ion 8-cell strings subjected to cycle life testing at 100% DOD at +20°C using C/5 charge and discharge rates over the voltage range of 24.0V to 32.80V.

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

- ***High temperature storage at +30°C: characterization at +0°C***



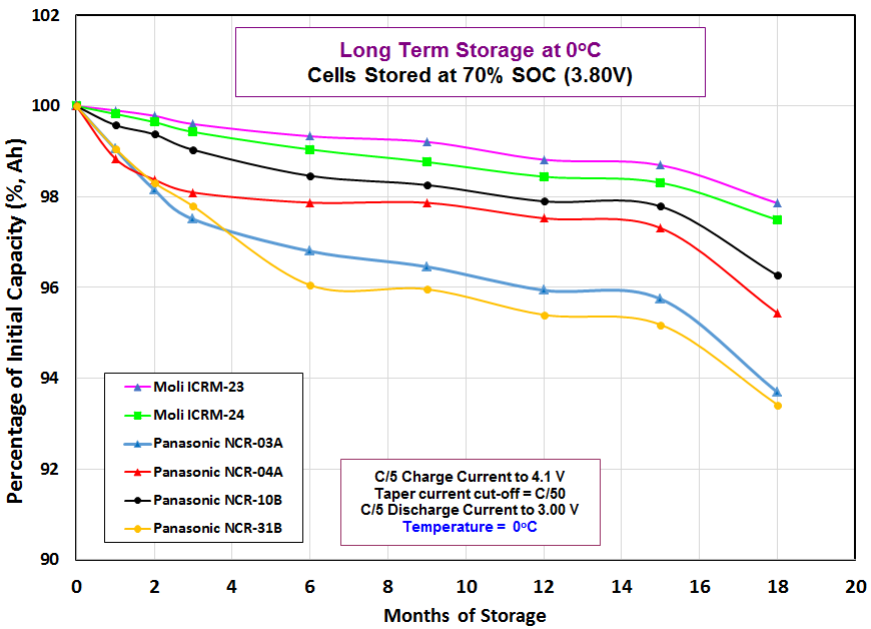




- E-One Moli cells have displayed the least amount of permanent capacity fade.
- **Cells subjected to 40 days of storage at +30°C** (cells fully charged)
- After completing 40 days of high temperature exposure, the following results were observed in terms of average increasing impedance (compared at 80% SOC): E-One Molicel ICR-M cells (1.6 % loss) < Panasonic NCR-B cells (7.7% loss) > Panasonic NCR-A cells (17.5% increase).

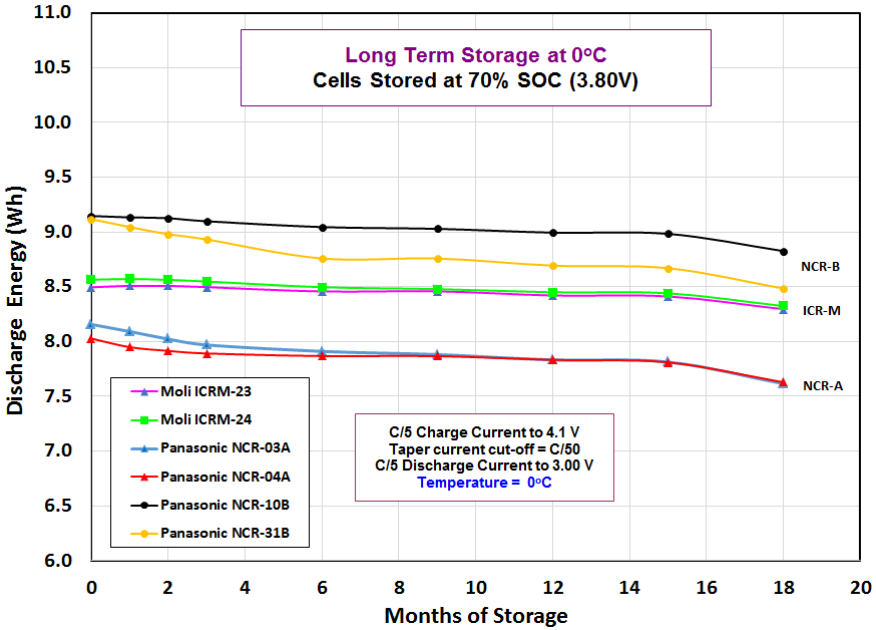
# NASA's Planned Europa Mission:
## Li-Ion Cell Level Testing: Calendar Life Performance

- ***Summary of cell high temperature storage results: characterization at +0°C***

**Percentage of Initial Capacity (Ah) at 0°C**




**Watt Hours Delivered (Wh) at 0°C**

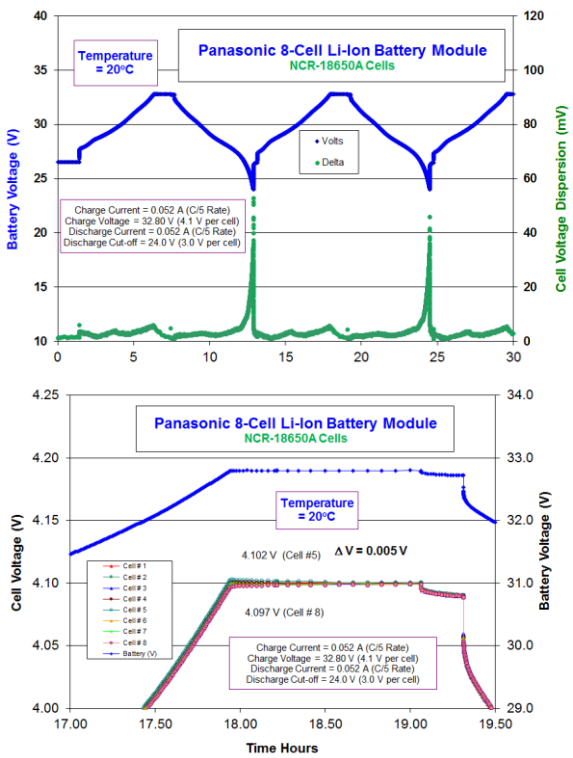



- The percentage of initial discharge capacity (%, Ah) (**A**) and discharge energy (Wh) (**B**) at 0°C observed with Panasonic NCR-A, Panasonic NCR-B, and E-One Molicel ICR-M cells observed during long term storage at 0°C. Cells were stored at ~ 70% SOC on the bus, corresponding to 3.80V.

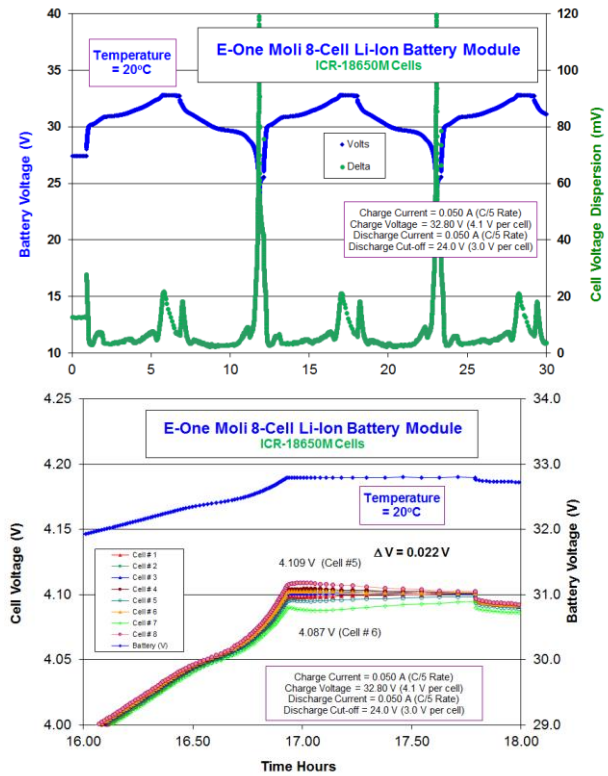
# NASA's Planned Europa Mission:
## Li-Ion Module Level Testing: Calendar Life Performance

- ***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 contained pre-matched cells**
  - **Strings characterized for capacity and impedance (at 20° and 0°C) periodically**

Panasonic NCR-A Module



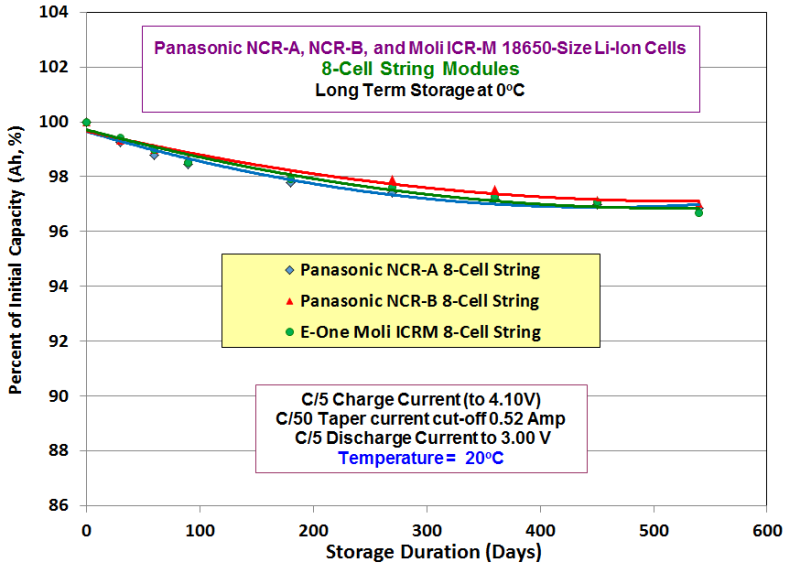

Moli ICR-M Module

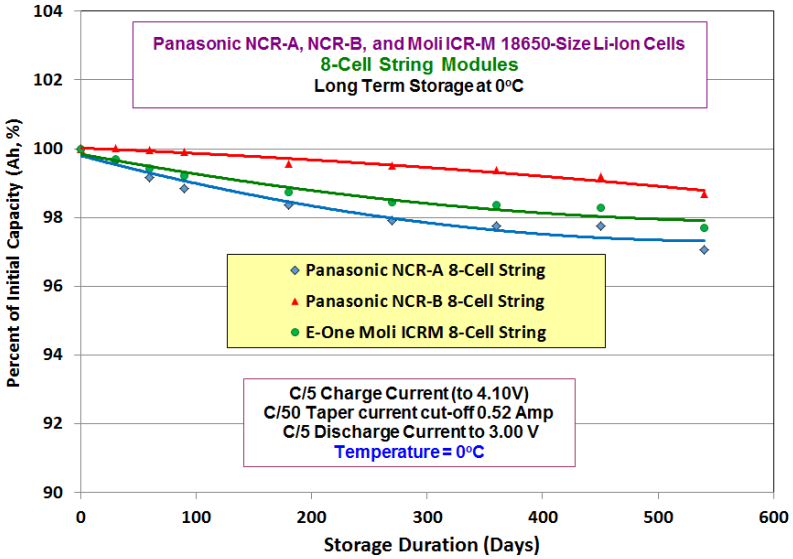


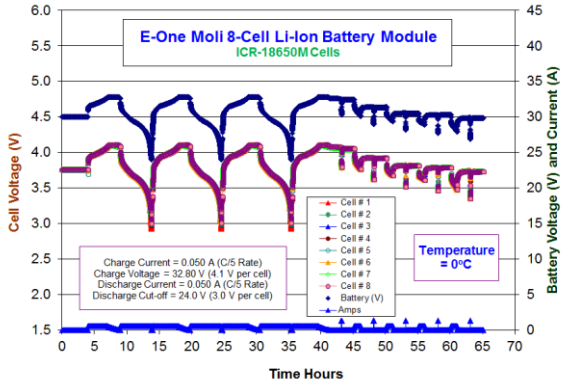

- All modules display little increase in voltage dispersion with storage and cycling.
- Maximum voltage dispersion is observed at the end of discharge.
- Cell voltage dispersion is being monitored and tracked with time.
- Modules have completed 18 months of storage on the bus at 0°C (at ~ 70% SOC).

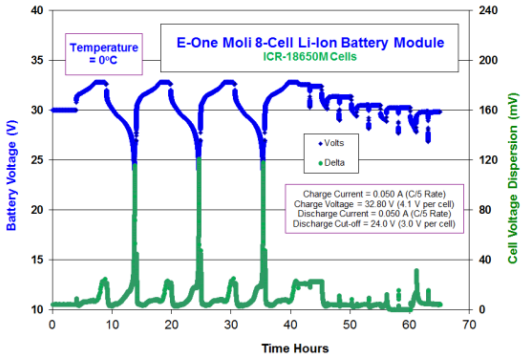
# NASA's Planned Europa Mission:
## Li-Ion Module Level Testing: Calendar Life Performance

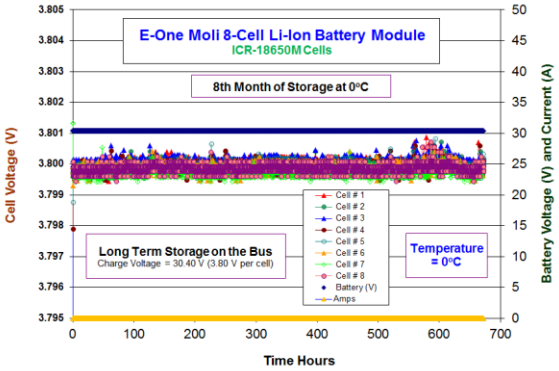
- ***Summary of String Level, Long Term Storage Life at 0°C:***



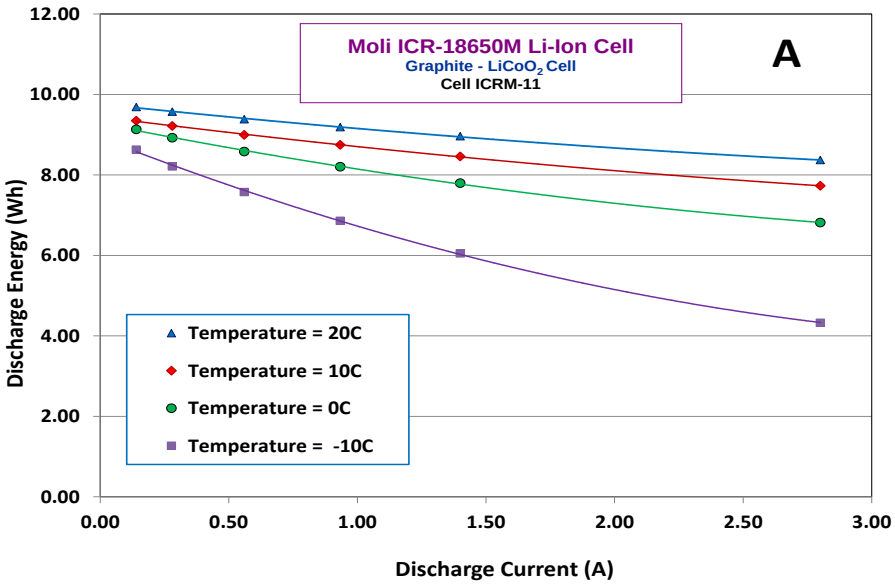



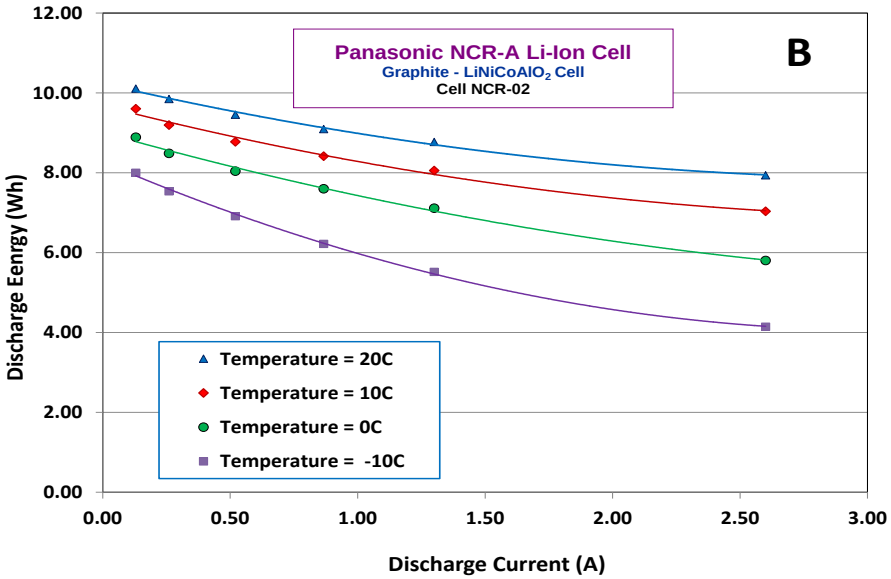
# NASA's Planned Europa Mission:
## Li-Ion Cell Level Testing: Discharge Rate Performance

- ***Summary of discharge rate testing at different temperatures (3.00V to 4.10V)***

**E-One Moli ICR-M Cell**




**Panasonic NCR-A Cell**

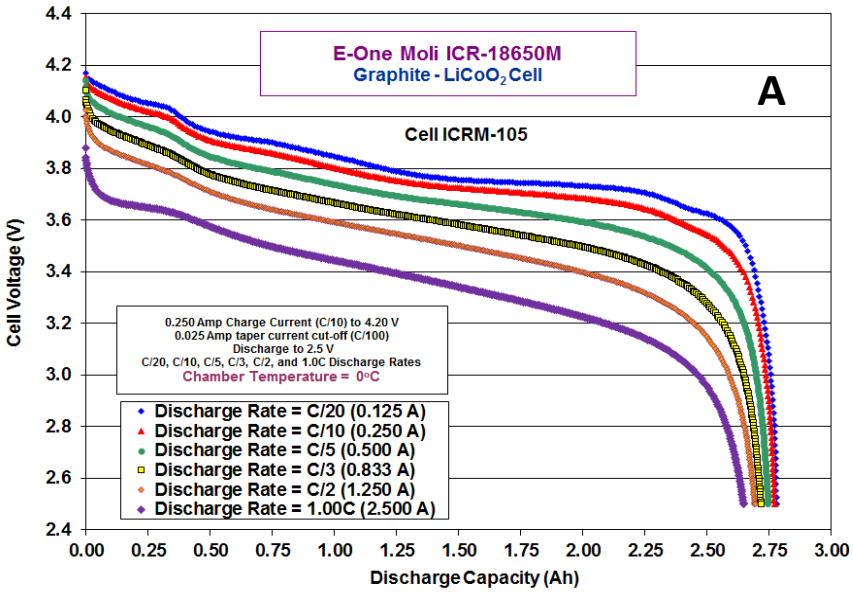



- Discharge energy (Wh) of E-One Molicel ICR-M cells and Panasonic NCR-A cells at various temperatures and discharge rates. Cells were charged at the specified temperatures.

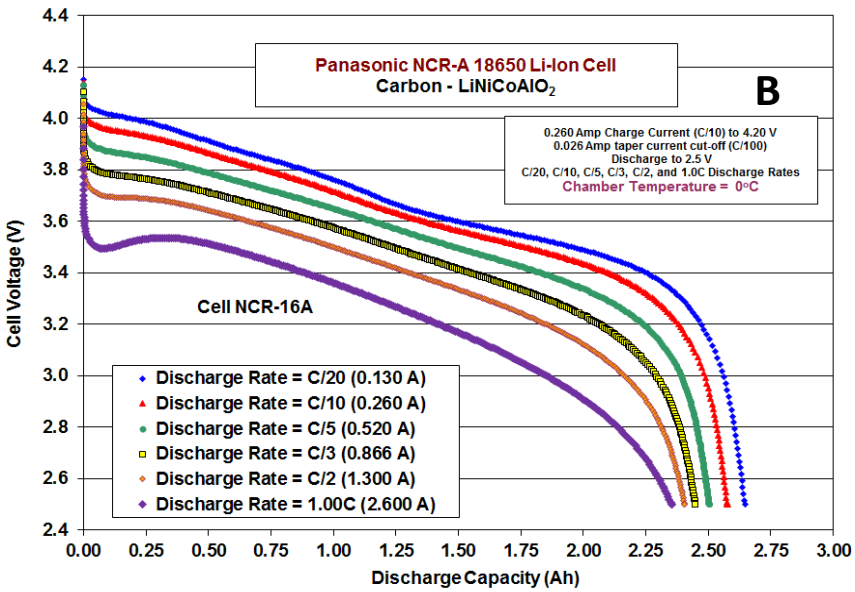
# NASA's Planned Europa Mission:
## Li-Ion Cell Level Testing: Discharge Rate Performance

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

**Percentage of Initial Capacity (Ah) at 0°C**




**Watt Hours Delivered (Wh) at 0°C**




- Discharge energy (Wh) of E-One Molicel ICR-M cells and Panasonic NCR-A cells at various temperatures and discharge rates. Cells were charged at the specified temperatures.

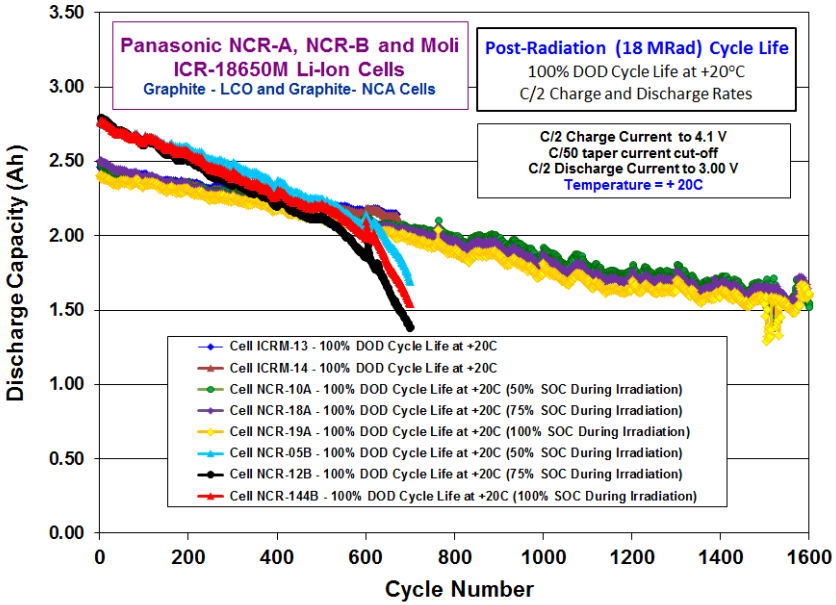
# NASA's Planned Europa Mission:
## Li-Ion Cell Level Testing: Radiation Tolerance

- ***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.

# Summary and Conclusions

- **Planned Europa Mission :**
  - All cells performed well when subjected to 100% DOD cycling at +30°C and successfully competed > 300 cycles, with the E-One Moli ICR-M cell and the Panasonic NCR-A displaying the least amount of capacity fade.
  - 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.
  - Superior performance was obtained with the E-One Moli ICR-M cells when subjected to 100% DOD cycling at -20°C, with over 3 times the capacity delivered by the Panasonic cells after completing 100 cycles.
  - The E-One Moli ICR-M cells are much more tolerant to charging at low temperatures, and are less prone to experience lithium plating degradation.
  - The E-One Moli ICR-M 8-cell module displayed higher discharge energy at 0°C, especially at after completing 400 cycles, and displayed much lower impedance growth.
  - After completing 40 days of high temperature exposure, E-One Moli ICR-M cells displayed the least amount of capacity loss and impedance growth as a result of storage.
  - The following results were observed in terms of average increasing capacity loss at 0°C after being stored for one year at 0°C: > E-One Moli ICR-M cells (1.37 % loss) < Panasonic NCR-B cells (3.23% loss) < Panasonic NCR-A cells (3.35% loss).
  - The E-One Moli ICR-M cells displayed better discharge rate capability compared to the Panasonic NCR-A cells, especially at lower temperature and higher discharge rates.
  - The E-One Moli ICR-M cell was identified as being the most attractive option for the Europa Clipper mission, based upon a number of performance characteristics.

# Acknowledgments

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ABSL Space Products

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Lyndsey Bienvenu
Joe Troutman
Roger Carlone
Kevin Schrantz