Performance of Commercial High Energy and High Power Li-Ion Cells in Jovian Missions Encountering High Radiation Environments

Ratnakumar Bugga, Charlie Krause, Keith Billings, John Paul Ruiz,
Erik Brandon, Eric Darcy,* and Chris Iannello**
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA
* Johnson Space Center, Houston, Texas
** NASA Kennedy Space Center, Florida

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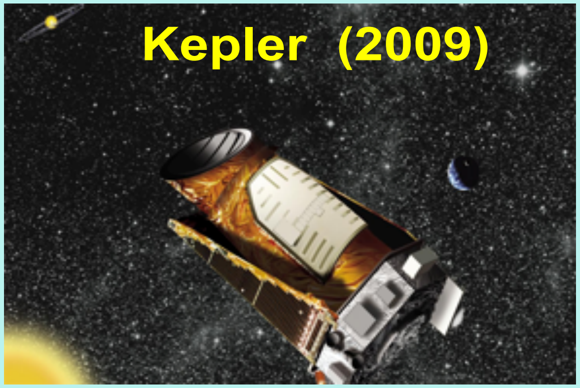
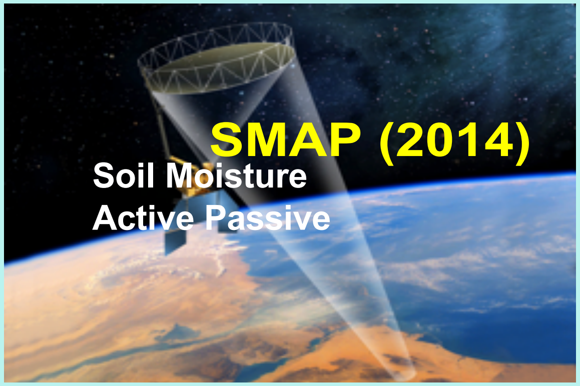
Background and Relevance

- NASA (JSC –Darcy et al) is developing thermal propagation-resistant high power/voltage batteries, demonstrating in 2 kWh battery module operating at 3C, with a specific energy >160 Wh/kg and > 200 Wh/l.
  - JPL is performing a comprehensive performance assessment of various high energy/high power 18650 Li-ion chemistries
- JPL is planning for an Europa surface mission (Lander), the Icy moon of Jupiter, with the goal of detecting biosignatures in the icy crust
  - Lander would be powered by a high energy primary battery (Li-CF_X),
  - Carrier (Cruise Stage): Li-ion battery
  - Descent Stage element
    - High power Li-ion cells instead of conventional of thermal batteries
- Applications: Planetary helicopters, Planetary Ascent vehicles Unmanned aerial vehicles, Hybrid power systems
- Future planetary missions (e.g., Europa Clipper, Artemis)

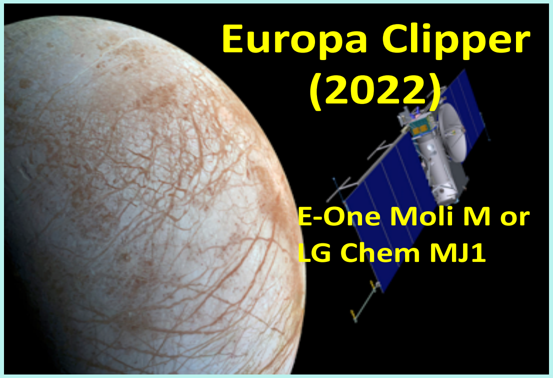
Planetary Missions with COTS Li-Ion Cells

Previous Missions (Sony HC cells)





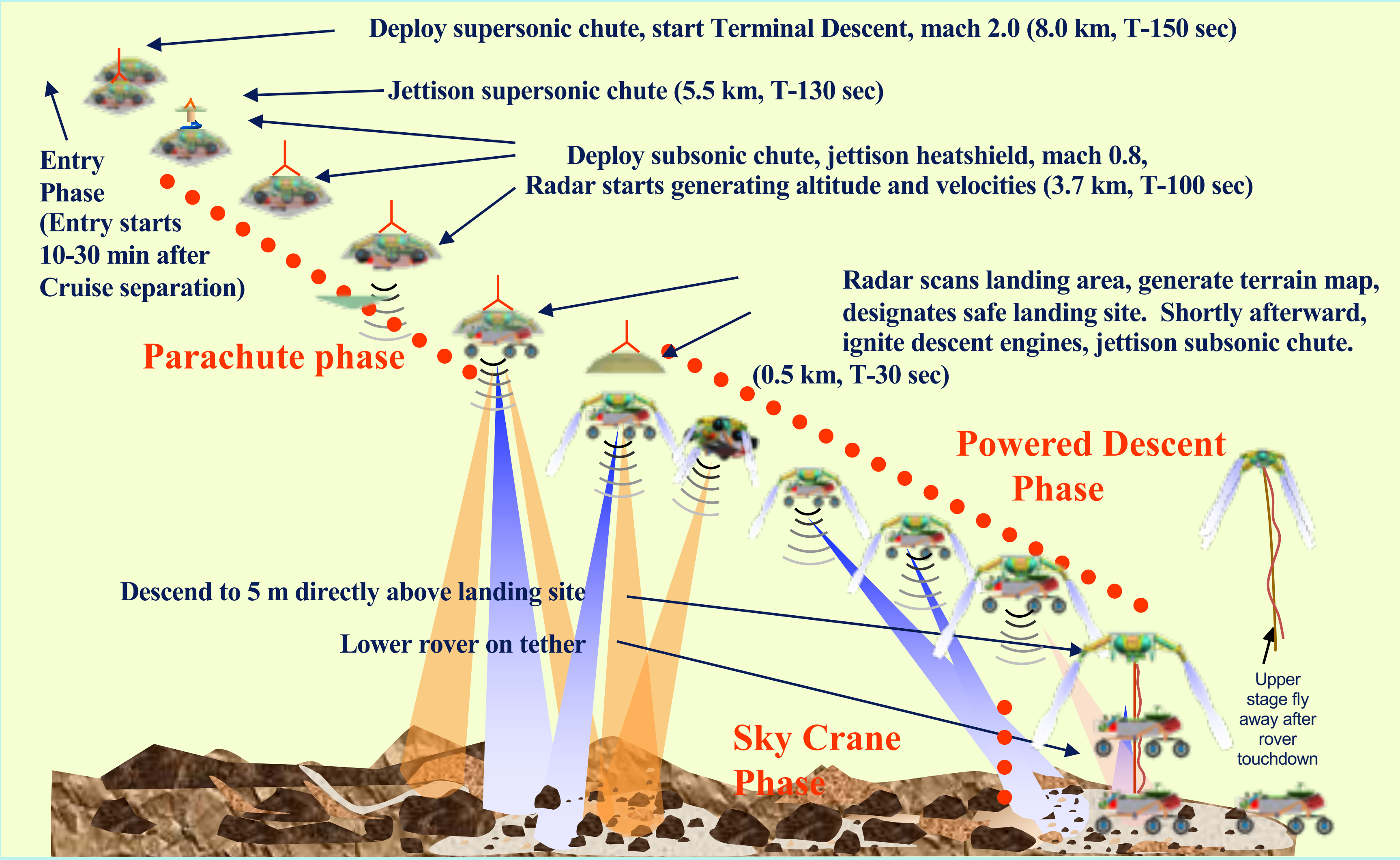
Upcoming Missions



- Mars Express is the longest operating mission with COTS Li-ion batteries.
- ABSL/ Enersys developed robust batteries of different sizes (8SXP) with Sony HC or HCM with $LiCoO_2$ cathode. This technology has become obsolete

- LG Chem MJ1 Cells to be used in the upcoming missions
  - Europa Clipper,
  - Crewed Lunar Exploration (Artemis and Orion)

Entry, Descent, and Landing (EDL) Sequence



- Thermal batteries (Li-FeS_2), which are typically used to support the pyro-events, provide high power densities, but not high specific energies (50 Wh/kg). Besides, their functionality is difficult assess before use.

High Energy and High Power COTS LI-Ion Cells

- **18650 Cells cells being evaluated (259- 276 Wh/kg and 704-735 Wh/l)**

Batch 1 cells	Batch 2 cells
LG M36	LG M36
LG MJ1	LG MJ1
Panasonic BJ	Panasonic/Sanyo GA,
Samsung 35E	Samsung 35E
Sony VC7	Samsung 36G

Performance Characteristics

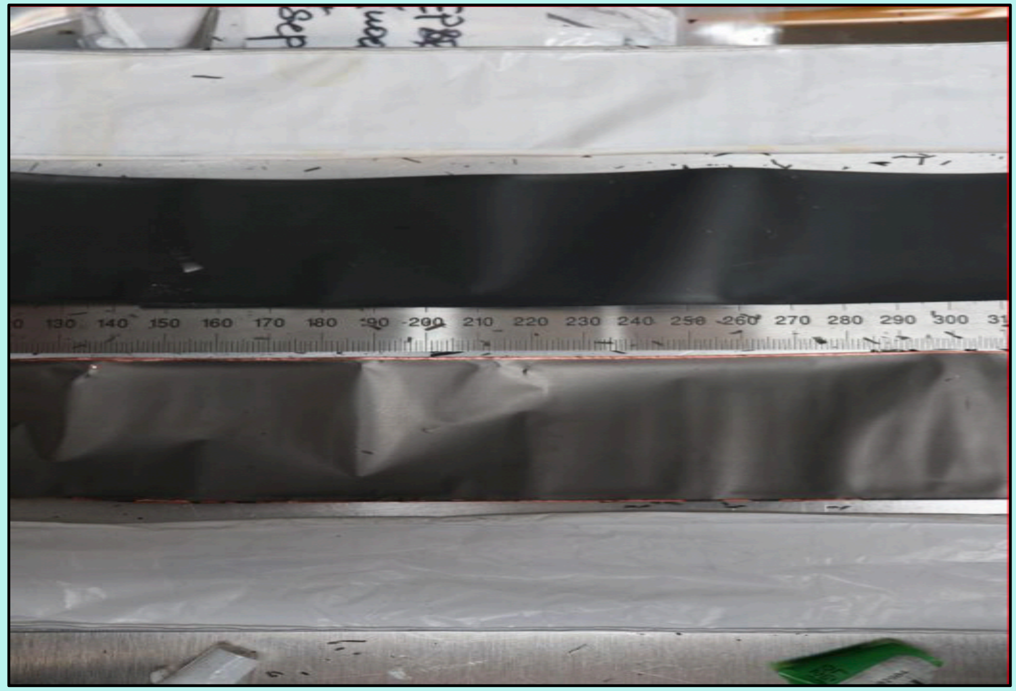
Characteristic	LG MJ1	Samsung 35E	Panasonic GA	Sony VC7
Capacity at C/10 at RT, Ah	3.41	3.49	3.34	3.5
Energy, Wh	12.46	12.7	12.16	12.72
DC Internal Resistance, mOhm	33	35	33	31
Mass, g	46.9	46	47	47.4
Specific Energy, Wh/kg	266	276	259	269
Energy Density, Wh/l	720	733	704	735

Voltage range: 4.2 to 2.5 V

- **Types of Tests**
  - Initial Characterization
  - Rate characterization at different temperatures
  - EIS (Electrochemical Impedance) during cycling and radiation
  - Cycle life testing at different temperatures
  - Radiation exposure to 18 Mrad (gamma radiation using Cobalt-60 source) and Post radiation cycling and rate characterization
  - Tear-down analyses
  - Charge rate characterization

DPA of High Energy and High Power Li-Ion Cells

- Cells dissected in the discharged state and components characterized
- Safety feature identification (CID, vents)
- Can specifications (wall thickness)
- Chemical analysis (XRD, NMR, EDX) of electrodes and electrolytes



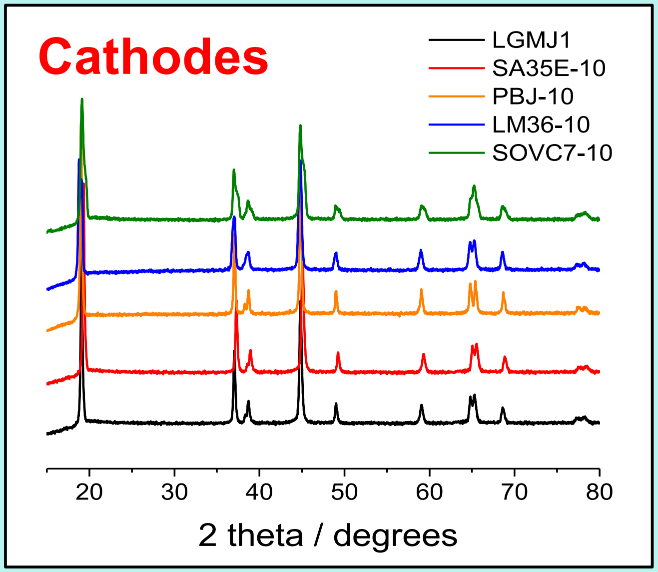
- High power designs have thinner and longer electrodes, as expected

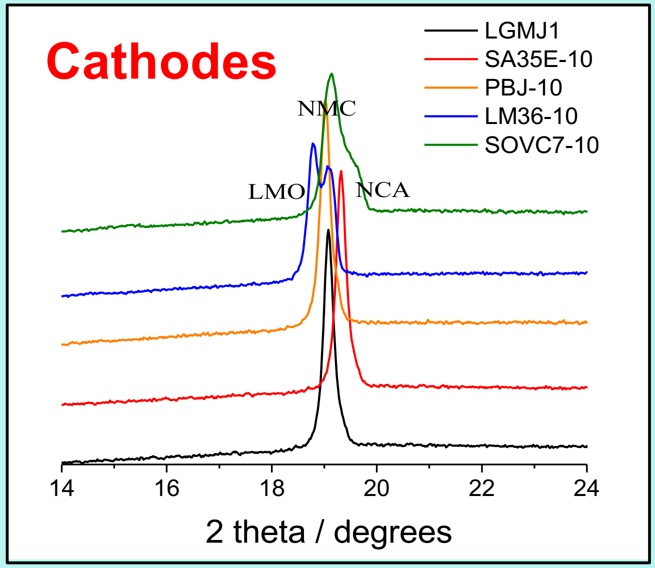
Cell	Anode L (mm)	Anode W (mm)	Anode thick. (mm)	Cathode L (mm)	Cathode W (mm)	Cathode thick. (mm)	Separator thick. (mm)	Can thick. (mm)
Sanyo GA	622	58	0.18	611	58	0.15	0.018	0.15
Samsung 30Q	943	58	0.11	900	58	0.10	0.018	0.15
Samsung 35E	603	60		616	58		0.015	
Samsung 36G	622	60		568	59		0.013	0.20
LG HG2	961	59	0.10	917	58	0.10	0.013	0.18
LG M36	653	60	0.18	606	60	0.16	0.020	
LG MJ1	660	60	0.17	610	59	0.16	0.015	0.19
Panasonic BJ	603	60	0.20	584	55	0.15	0.018	
Sony VC7	603	60		616	59		0.018	0.19

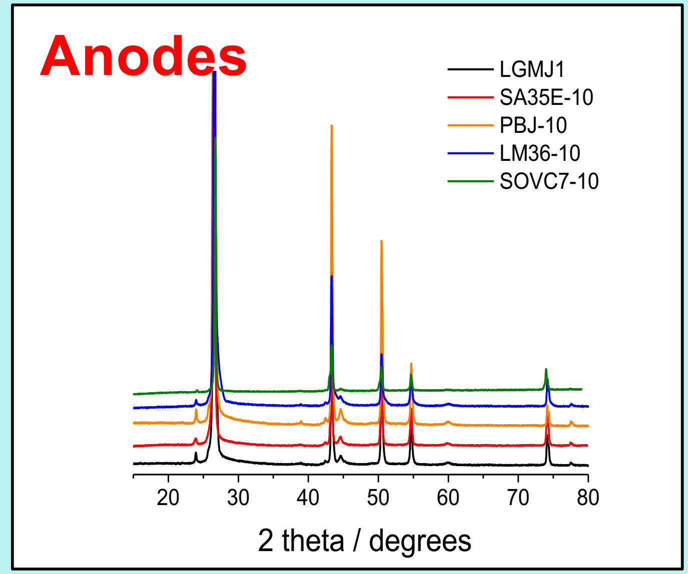
DPA of Li-Ion Cells - Cathodes

Diffraction typical for $LiMO_2$ layered structure (e.g. NMC, NCA)

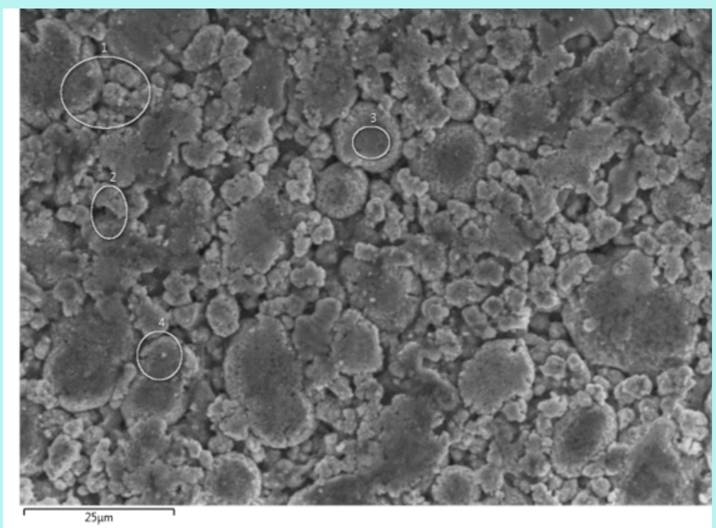
(111)/(001) peak shows variations

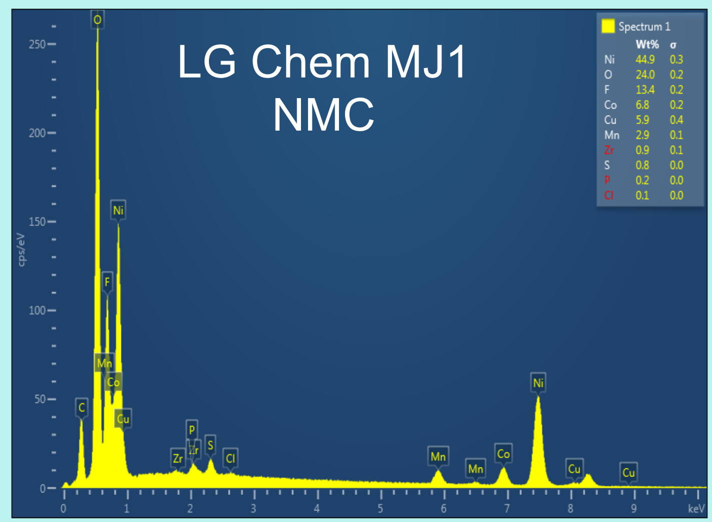






- NCA: Lithium Nickel Cobalt Aluminum Oxide ($LiNi_{0.8}Co_{0.15}Al_{0.05}$)
- LMO: Lithium Manganese Spinel Oxide ($LiMn_2O_4$)
- NMC: Lithium Nickel Manganese Cobalt Oxide ($LiNi_{1-x-y}Mn_xCo_yO_2$)





Chemistry of Li-Ion Cells- Summary

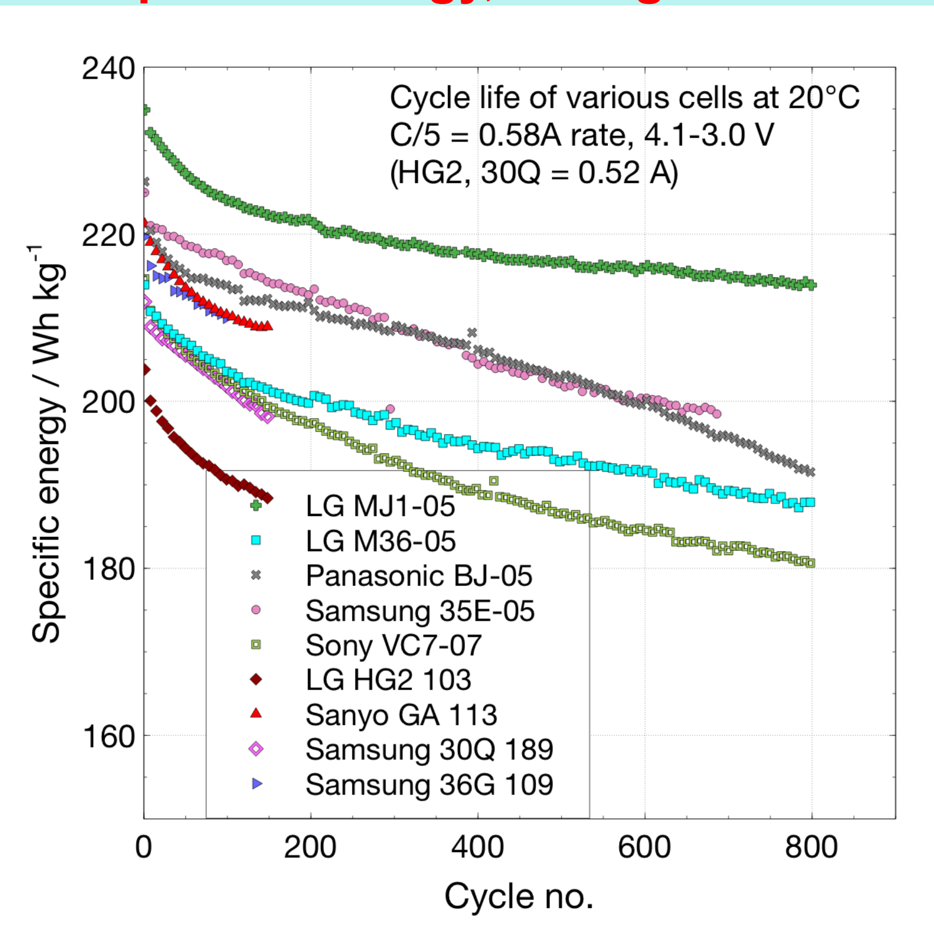
	Anode	Cathode	Electrolyte
LGMJ1	graphite	$Ni_{0.81}Co_{0.13}Mn_{0.06}$ by EDX*	EC, DMC, $LiPF_6$, LiFSI (lots)
SA35E-10	graphite, ~2% Si by EDX	$Ni_{0.83}Co_{0.15}Al_{0.02}$ by EDX	EC, DMC, additive, $LiPF_6$, LiFSI
PBJ-10	graphite	$Ni_{0.81}Co_{0.16}Al_{0.04}$ by EDX	EC, DMC (assumed), $LiPF_6$, LiFSI
LM36-10	graphite (less crystalline)	$Ni_{0.86}Co_{0.12}Al_{0.02}$ and $LiMn_2O_4$ (95:5)*	EC, DMC, $LiPF_6$, LiFSI (lots)
SOVC7-10	graphite (least crystalline)	$Ni_{0.90}Co_{0.08}Al_{0.02}$ by EDX$	EC, DMC (assumed), $LiPF_6$, LiFSI (least)

- Cathodes: NCA, Ni-rich NMC and blend of NCA and LMO
- Anodes: Graphite (small amounts of Si)
- Electrolyte: Carbonate solvents with LiPF6 and LiFSI

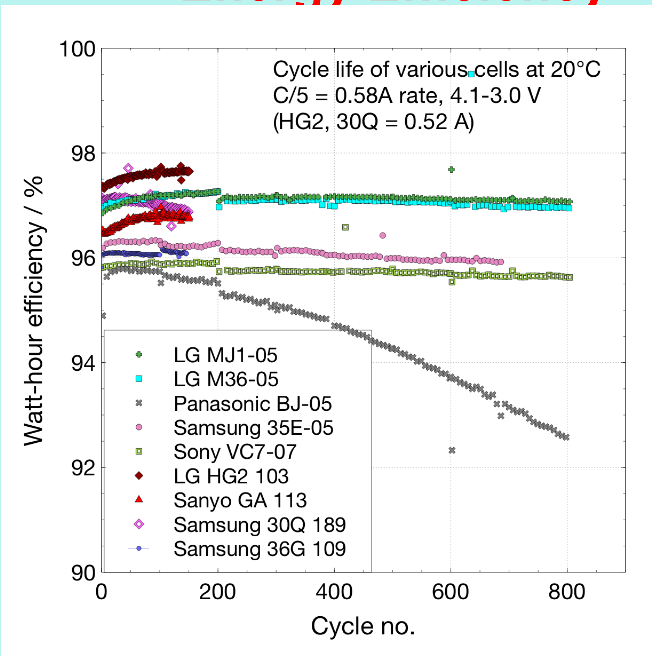
Cycle life at +20 ºC – Batch 1

100% DOD cycling at C/5, 4.10 – 3.00 V

Specific Energy, Wh/kg



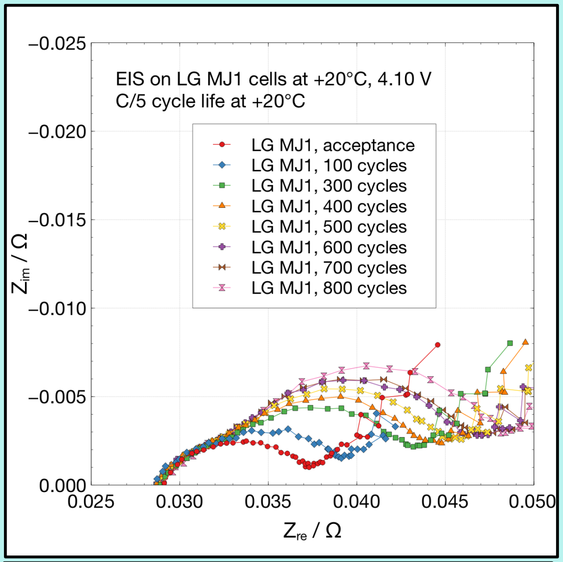
Energy Efficiency

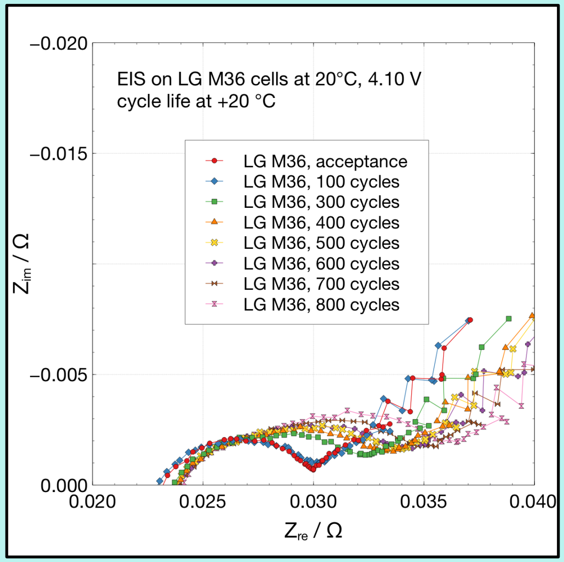


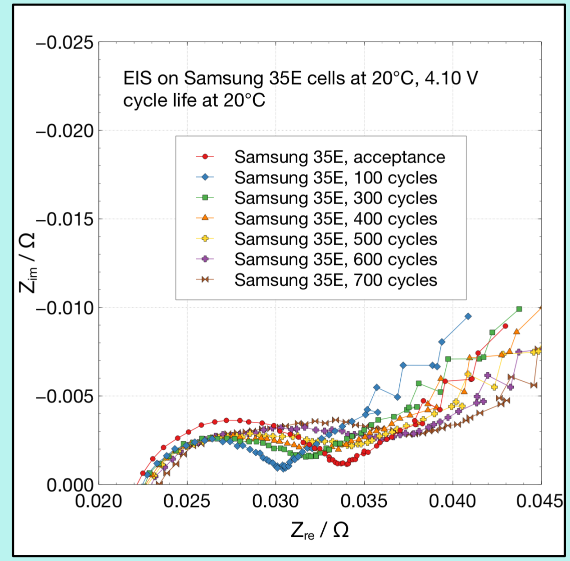
Cell	Capacity retention, cycle 500 (%)
LG M36	90
LG MJ1	92
Panasonic BJ	90
Samsung 35E	90
Sony VC7	87

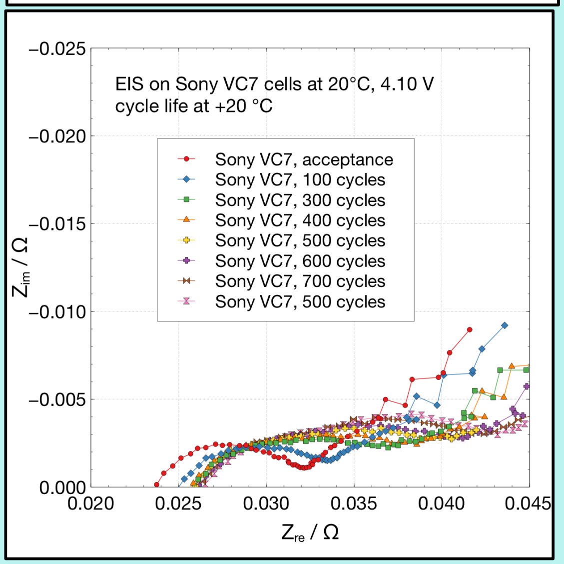
- All the cells have shown good cycle life
- LG Chem MJ1 cells exhibit the highest specific energy and efficiency

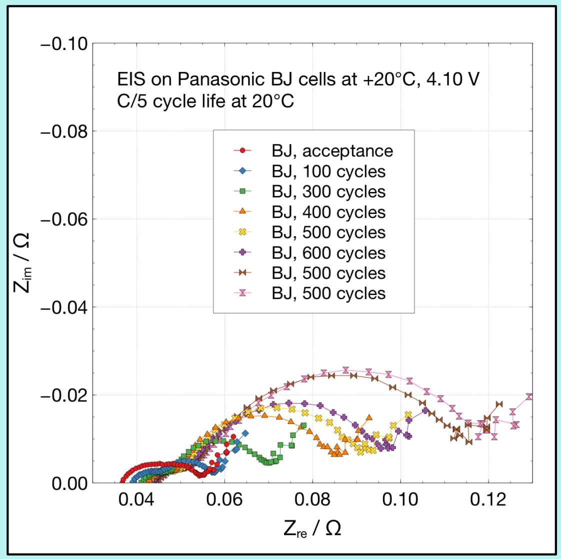
EIS vs. cycle life at +20 ºC

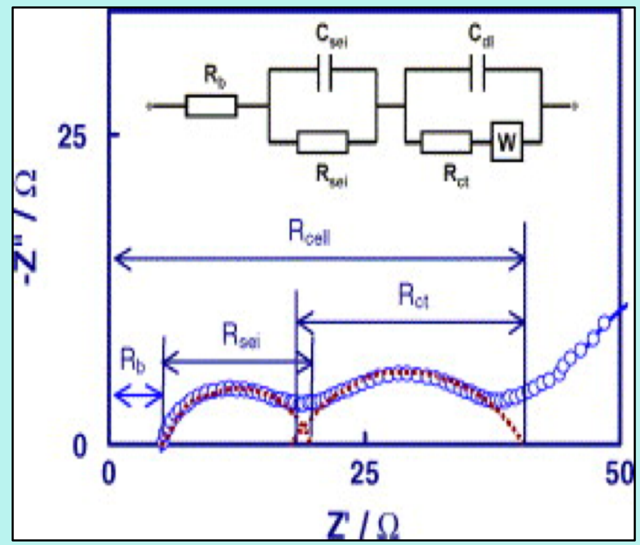










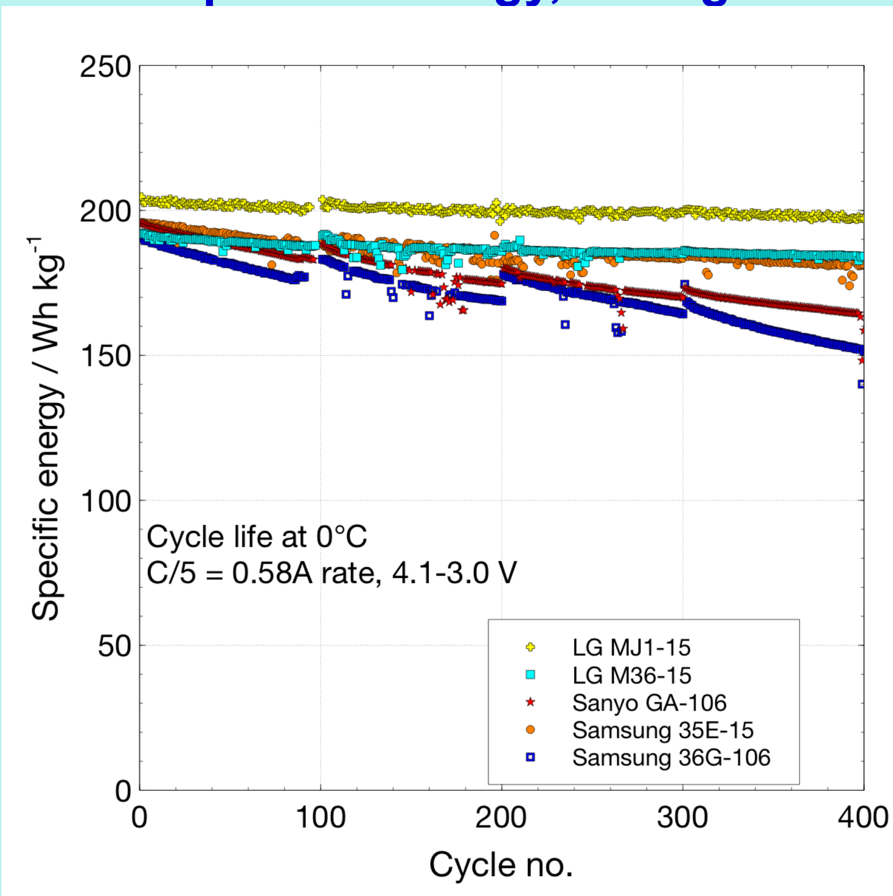


Typical Eq. Circuit

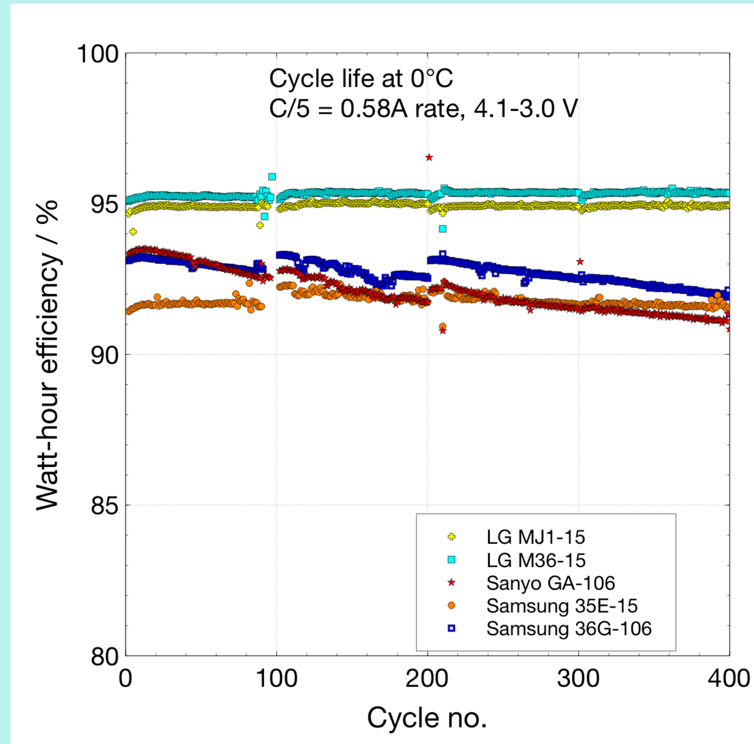
- All cells have shown some growth impedance over 500 cycles
- LG M36 and Samsung 35E cells had the least growth, while Panasonic cell shows the highest growth during cycling.
- Impedance from the second loop is dominant (Charge transfer kinetics of cathode)

Cycle life at 0 ºC - (Batch 2 cells)

Specific Energy, Wh/kg



Energy Efficiency

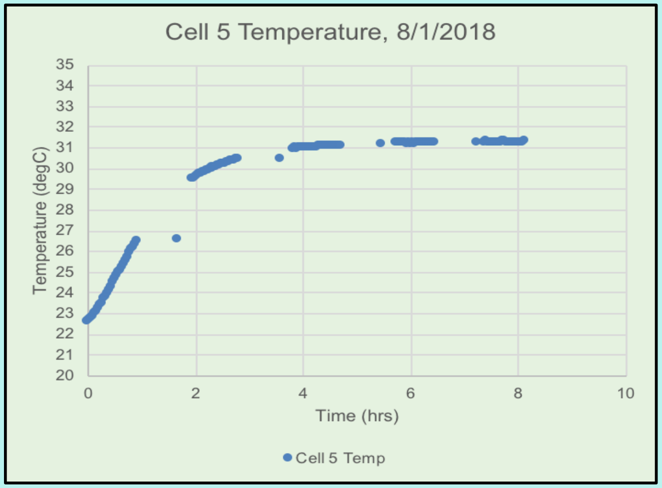


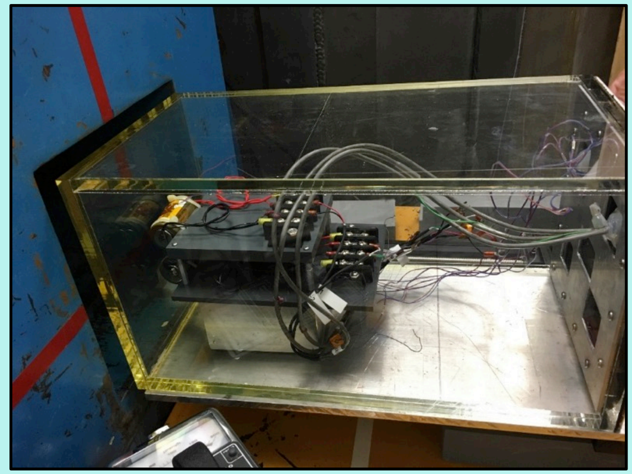
- All the cells have shown high specific energy of 190 Wh/kg at 0ºC, with LG Chem MJ1 cells offering the ~205 Wh/kg.

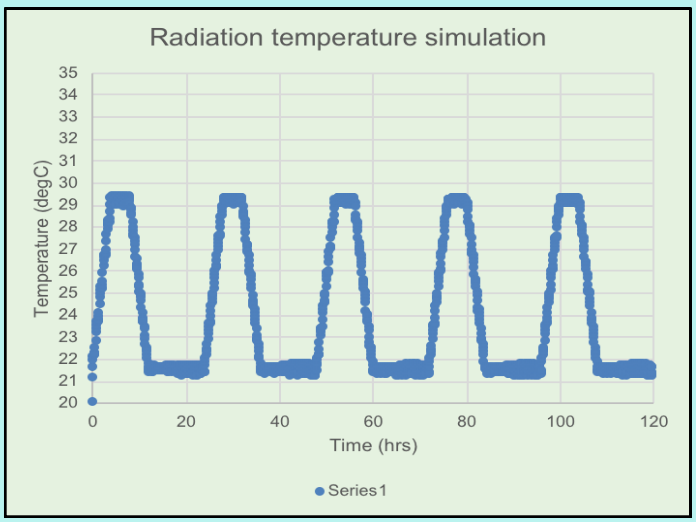
Cell	Capacity retention, cycle 250 (%)
LG M36	97
LG MJ1	97
Sanyo GA	89
Samsung 35E	94
Samsung 36G	89

Exposure to Cobalt-60 (^{60}Co) Radiation

- Two exposures: 12 Mrad and 8 Mrad for a total of 20 Mrad TID (12 MRad for planetary protection and 8 MRad from the Jupiter/Europa environment
- Cells were at full SOC (4.10 V) during exposure
- Control cells: At the same temperatures the radiation cells experienced during irradiation

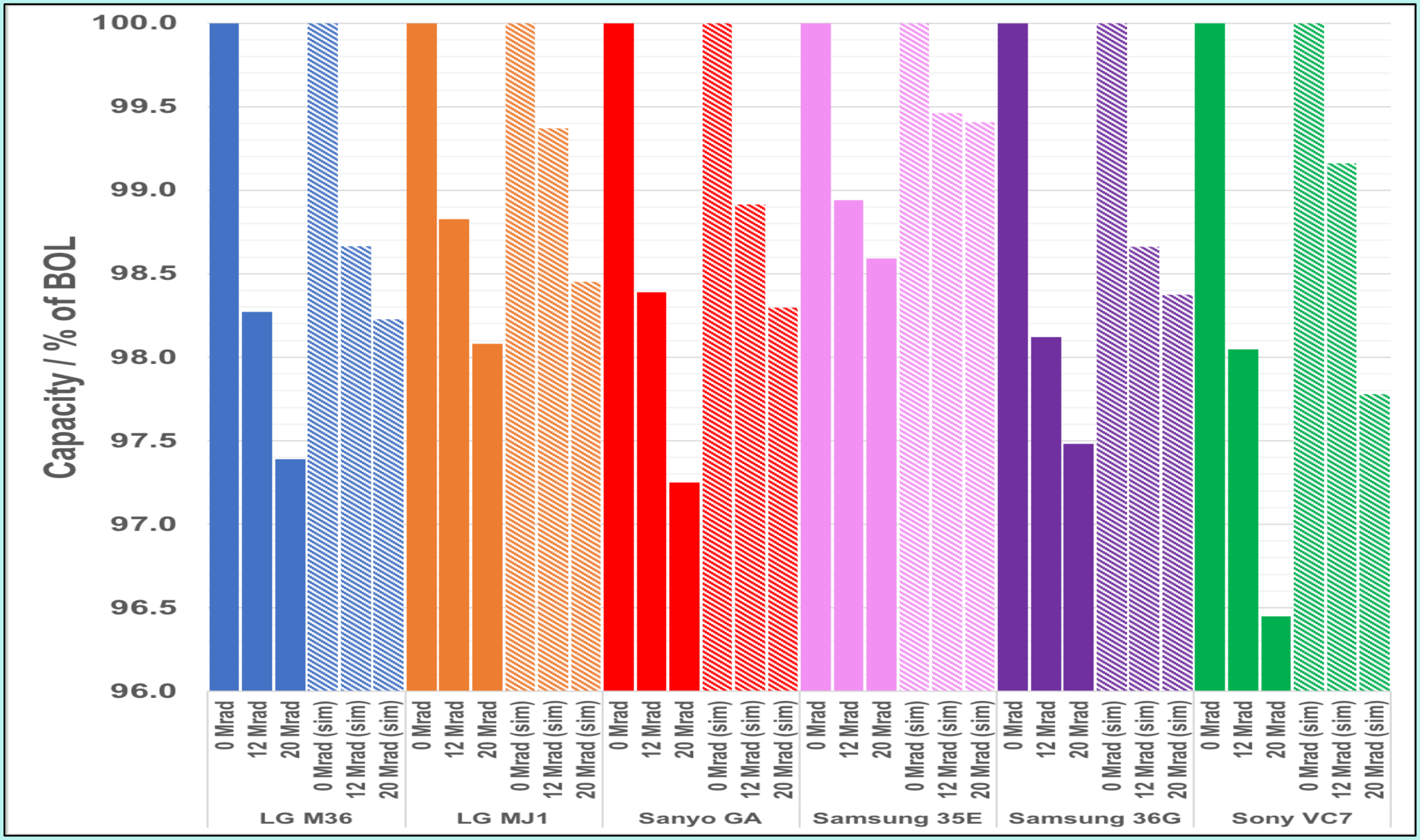






Exposure to Cobalt-60 (^{60}Co) Radiation

Capacity vs Radiation dose



M36 MJ1 GA 35E 36G VC7

- Solid: Irradiated; 0 , 12 and 20 Mrad hashed: 0 control, after equivalent stand periods
- All the cells show impressive tolerance to radiation with <2% capacity loss (vs control cells) after 20 Mrad exposure.
- Radiation tolerance: Samsung 35E> MJ1> Samsung 36G> M36> Sanyo GA > Sony VC7

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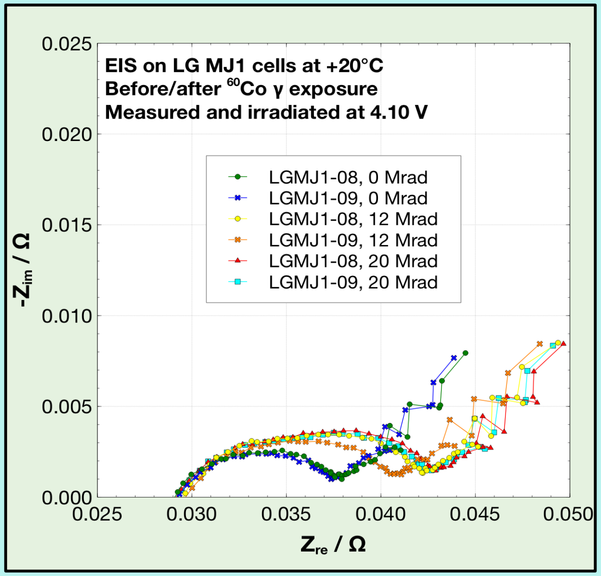
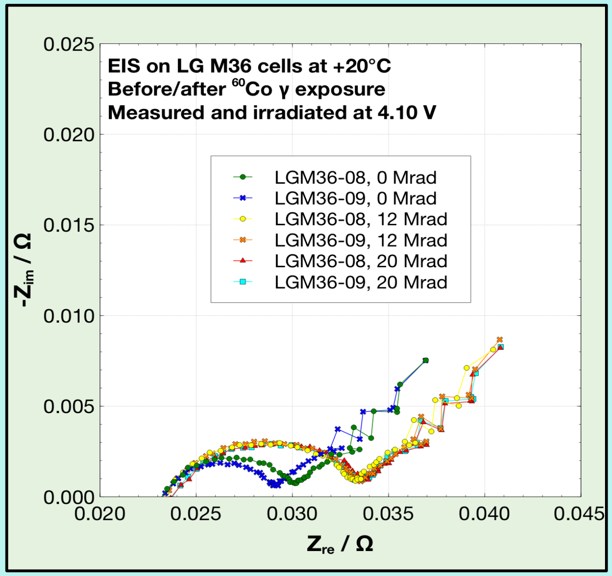
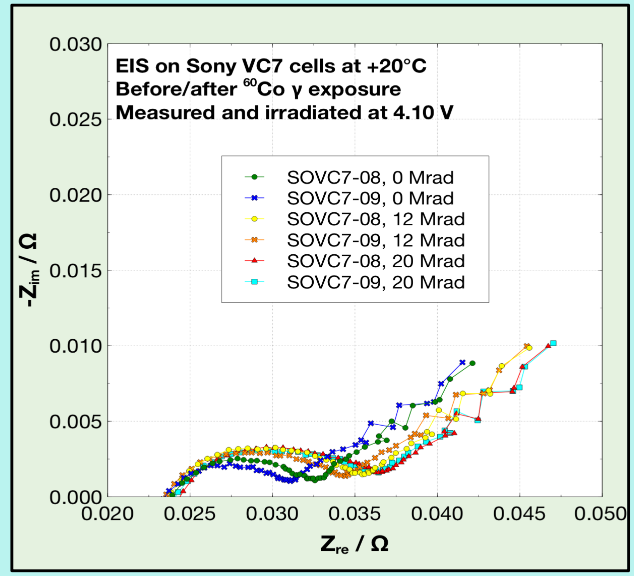
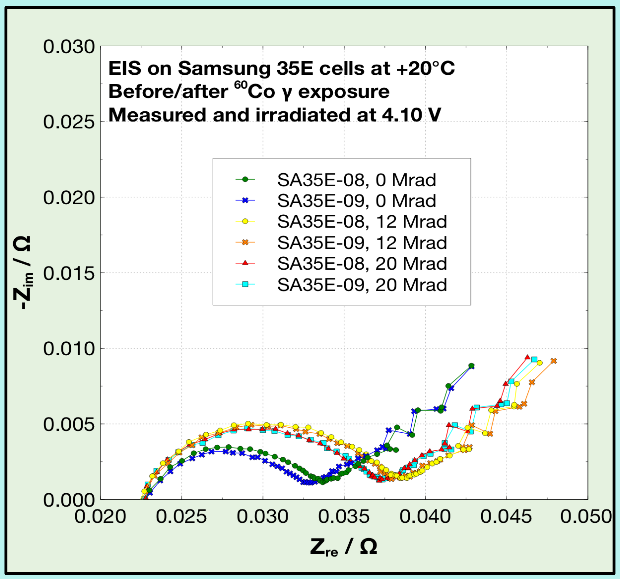
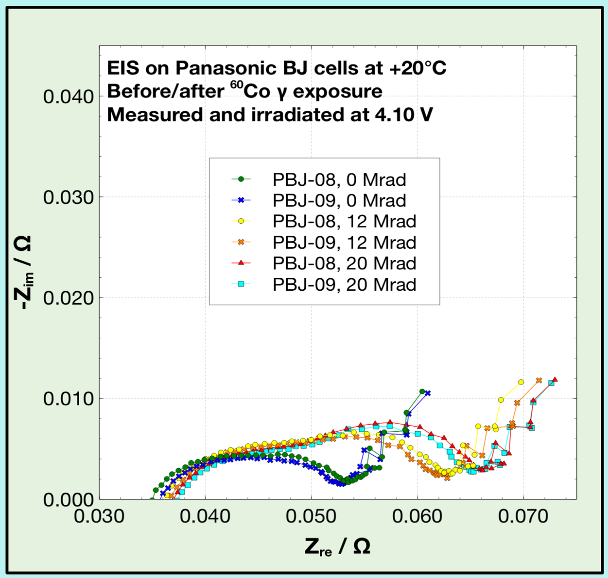
EIS (at 20C) after Radiation

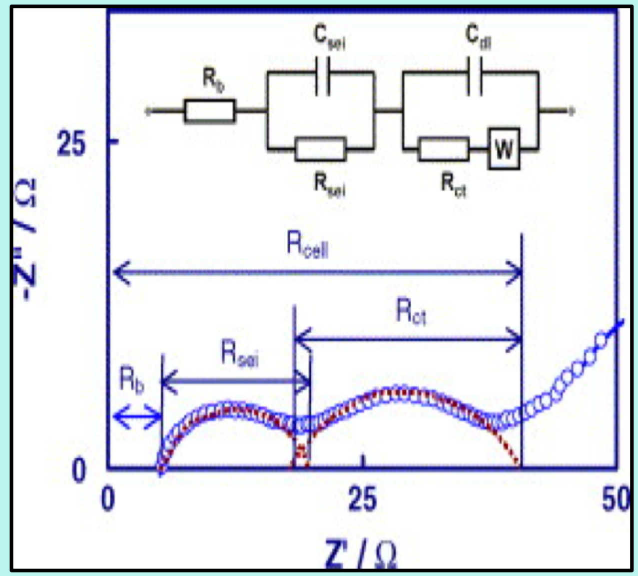












- Only very small increase in series resistance
- Increase in breadth of impedance loop
- Minimal change in Sony VC7 cells and maximum change in Panasonic BJ cells

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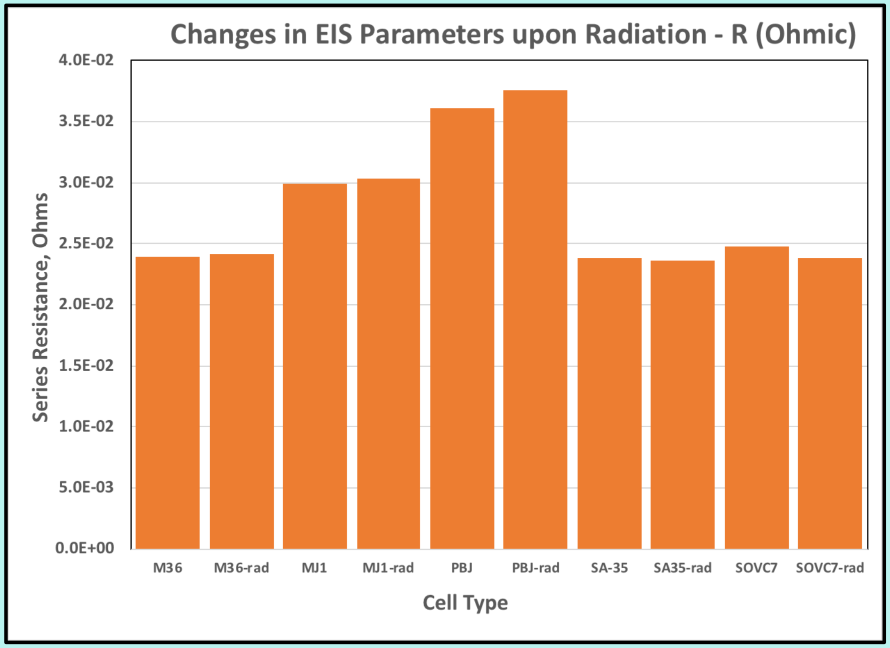
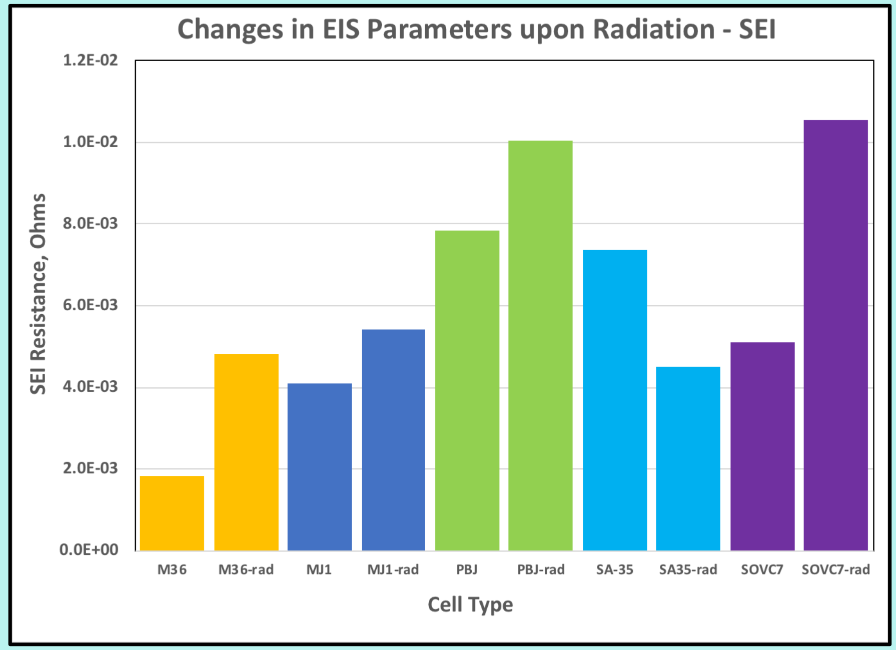
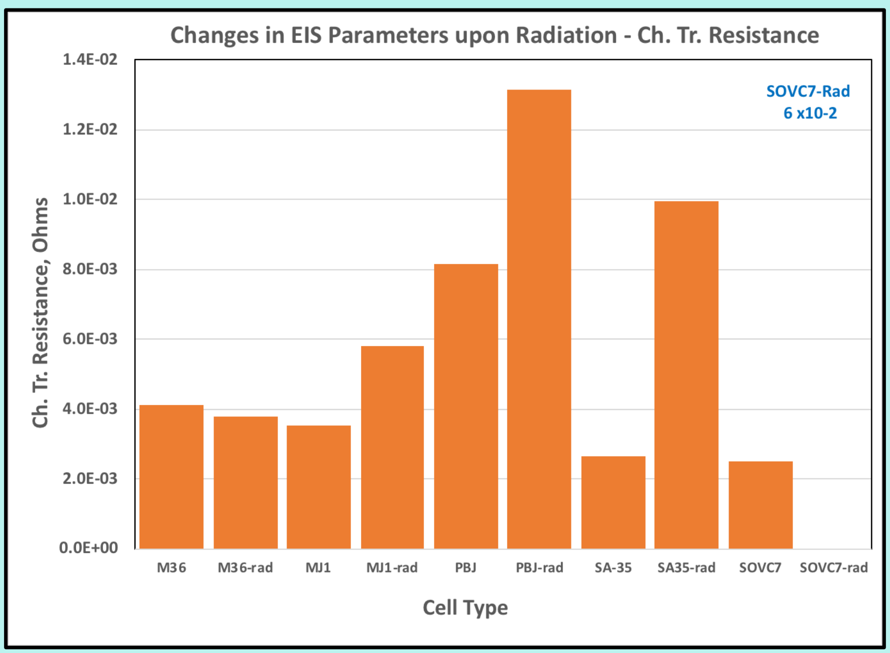
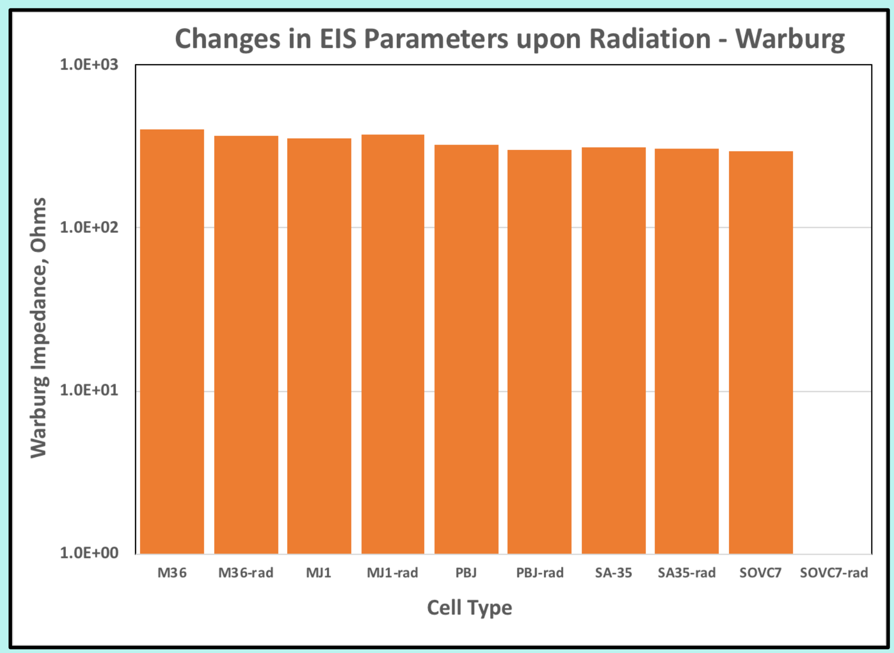
Radiation Effects on EIS Parameters



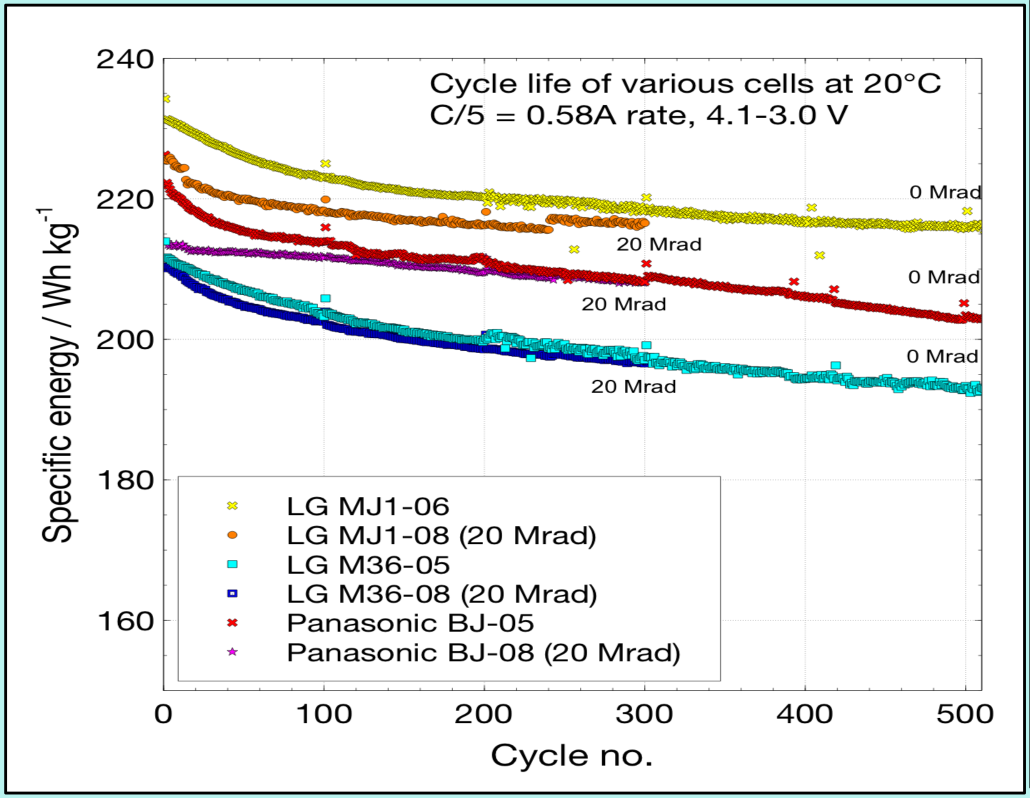


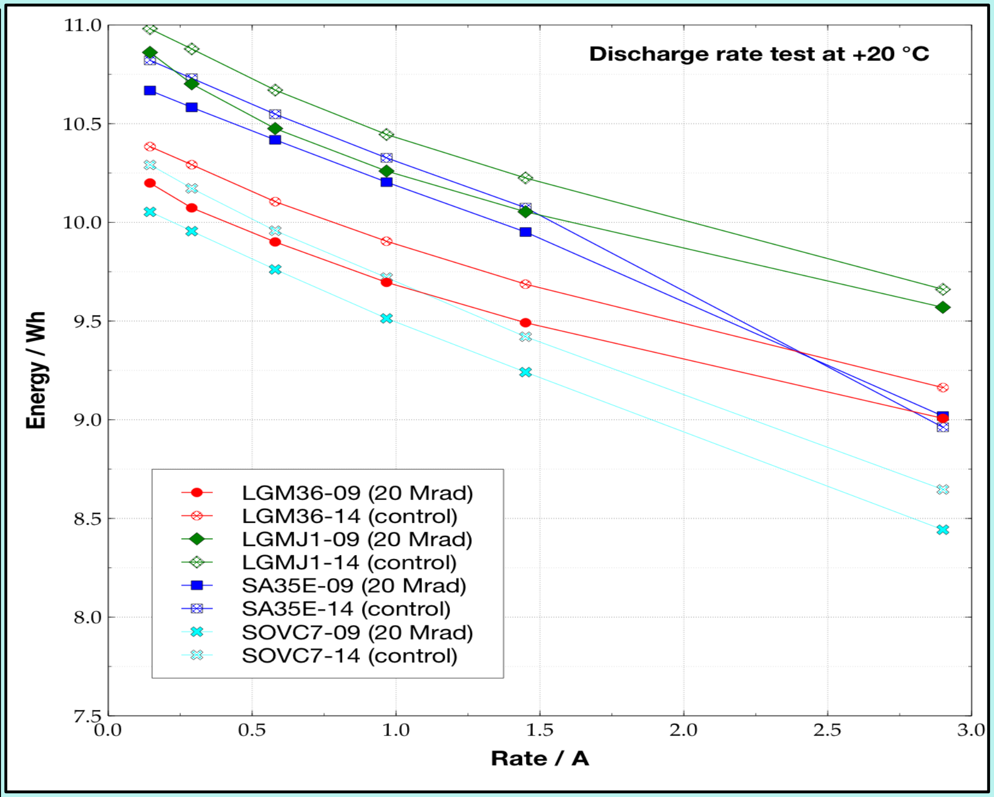




Post-Radiation Testing

Cycling of radiated cells

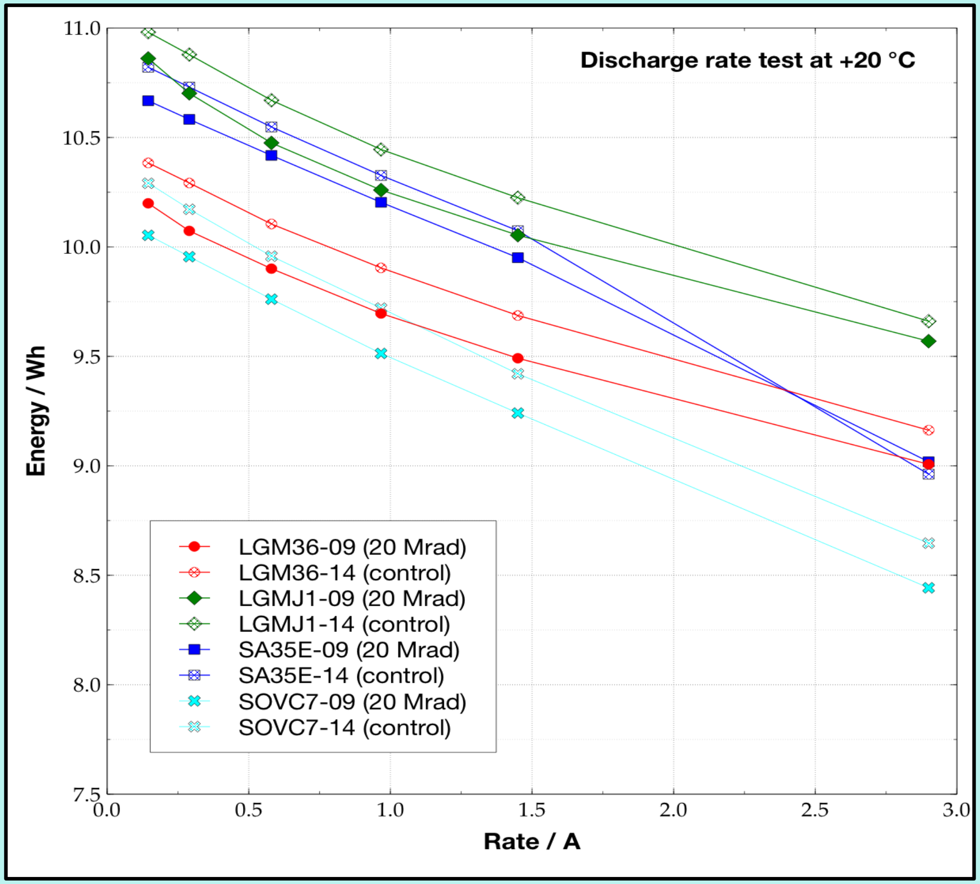


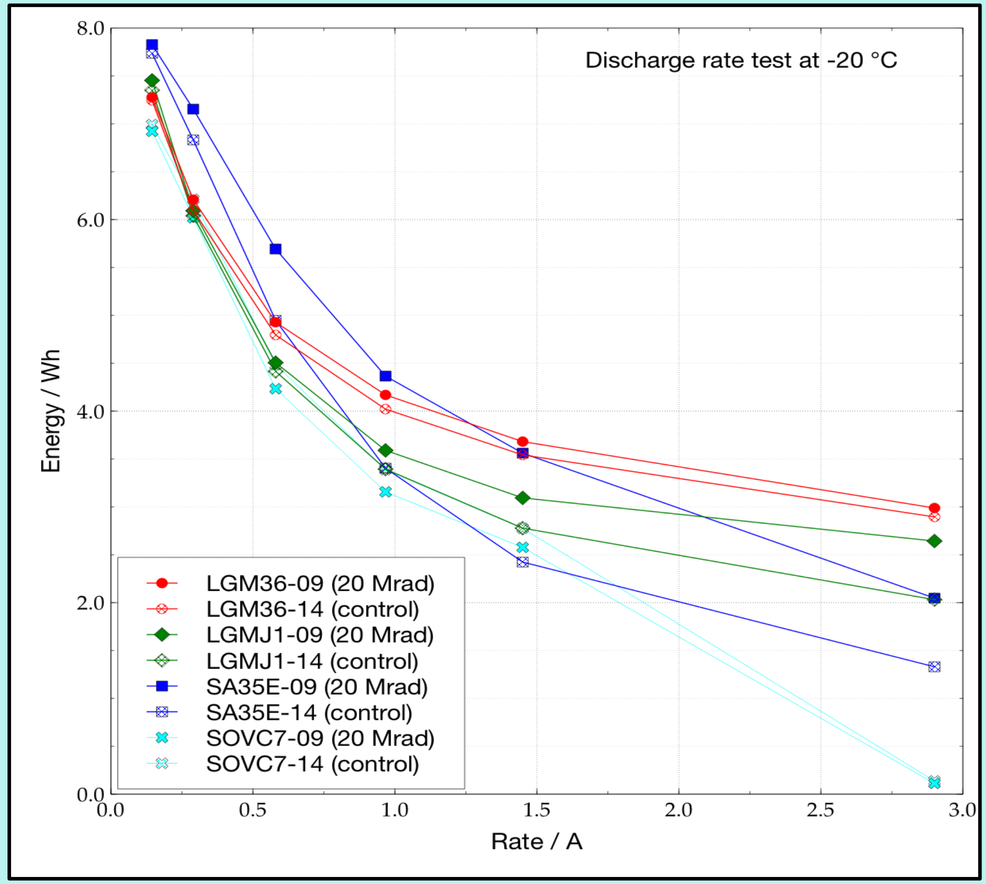


- Radiated cells are cycling well; slightly lower specific energy, but less fade rate.
- No change in the rate capability after radiation exposure (20 Mrad)

Discharge rate test at +20ºC and -20ºC

Irradiated vs. control

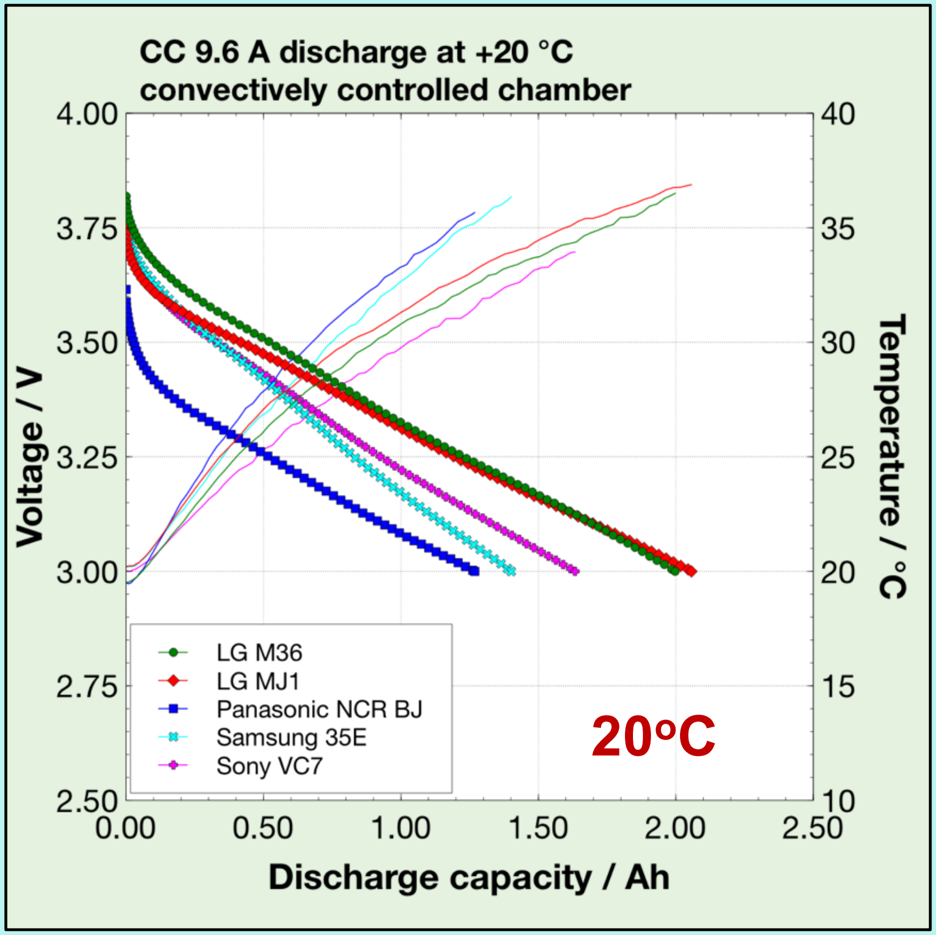


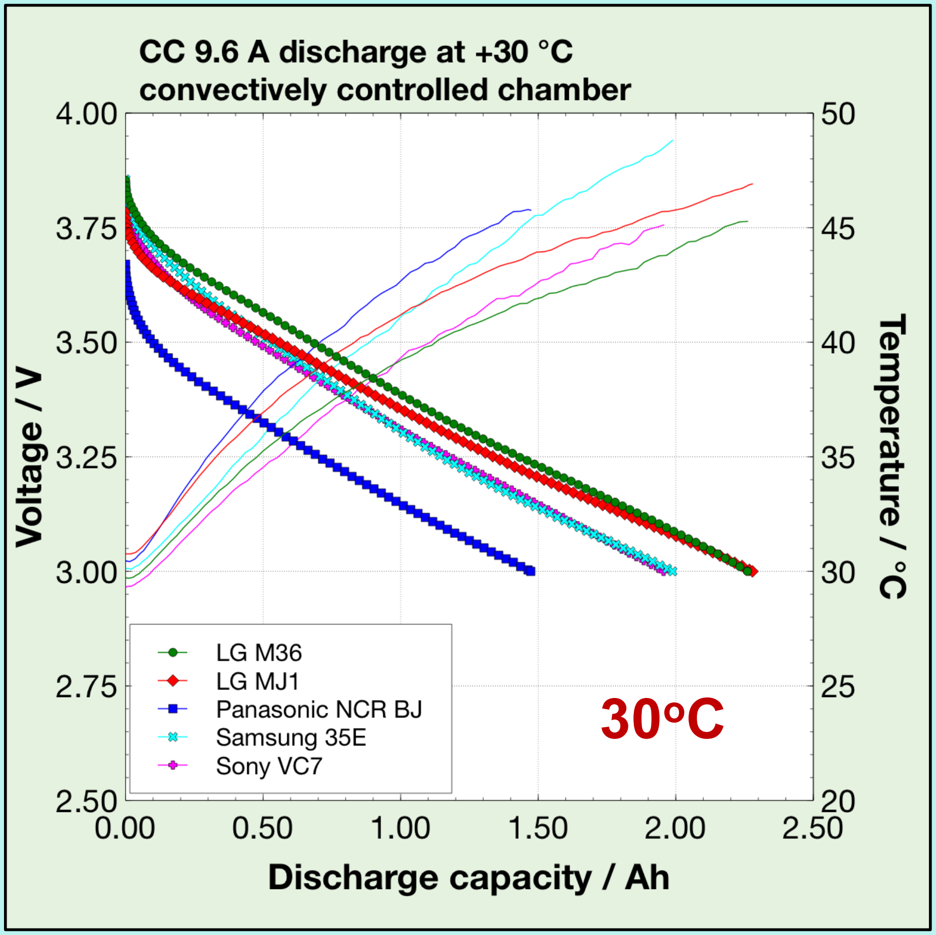


- No change in the rate capability after radiation exposure (20 Mrad)

High Rate Testing (9.6 A)

Discharge profiles at 9.6 A - Comparison of cells

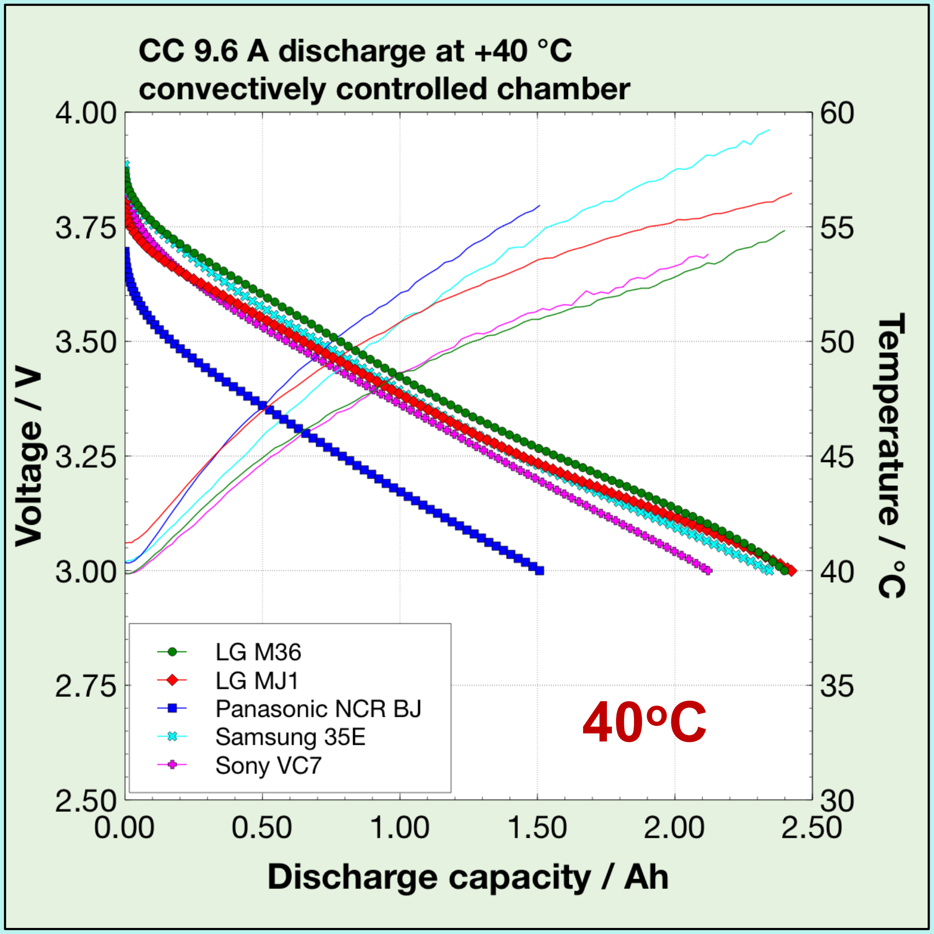


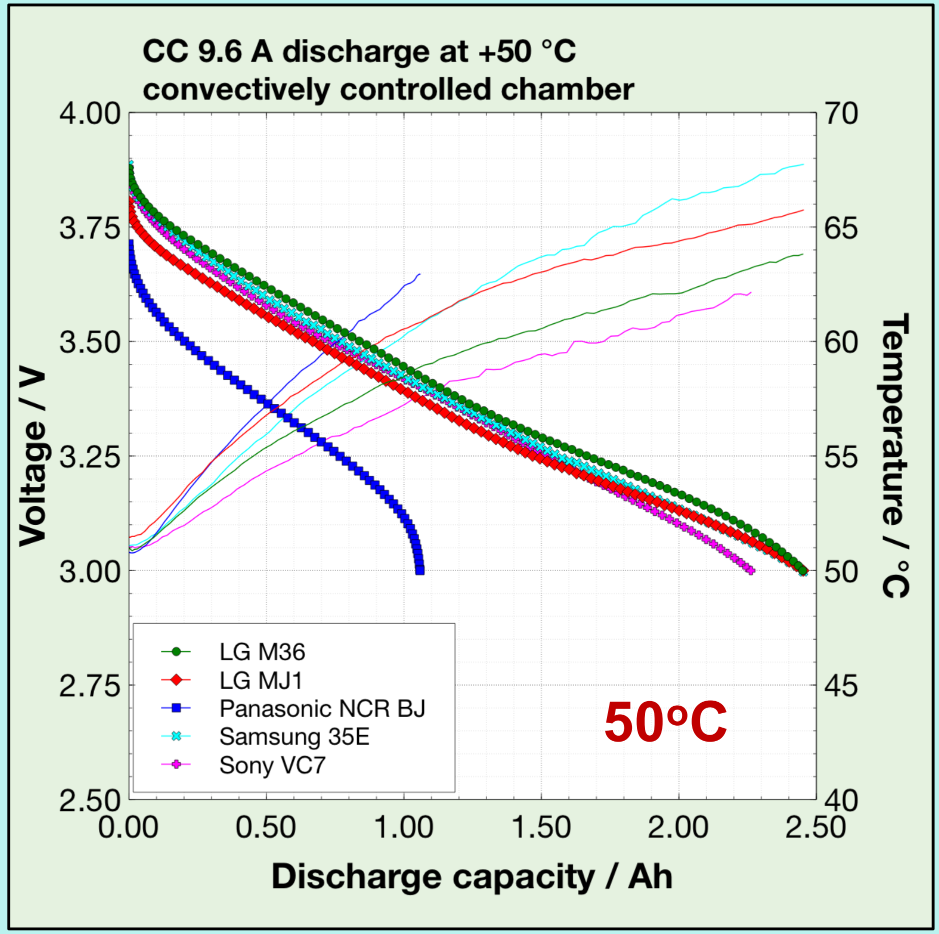


- Considerable cell warm up in a convectively controlled chamber

High Rate Testing (9.6 A)

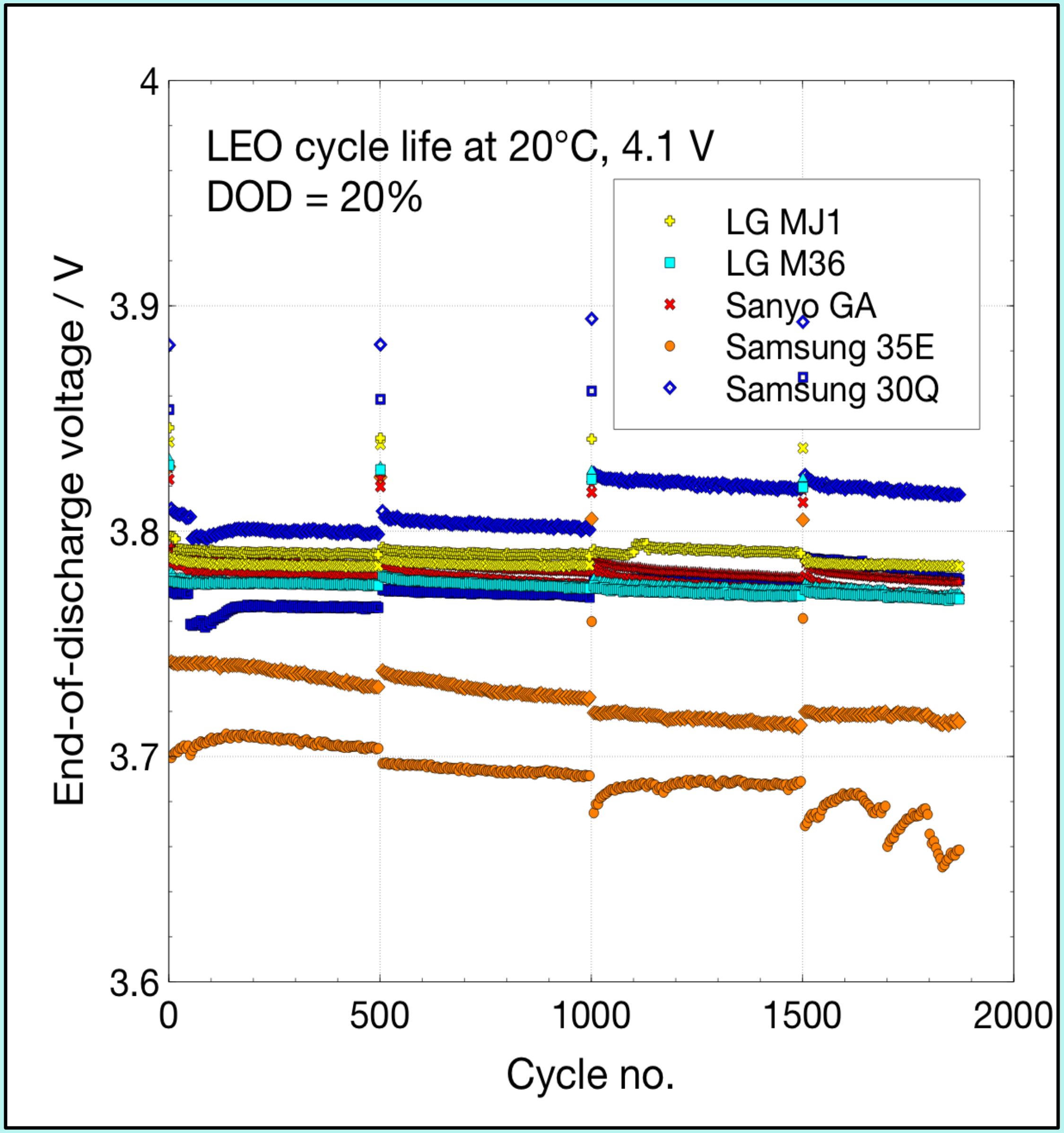
Discharge profiles at 9.6 A - Comparison of cells

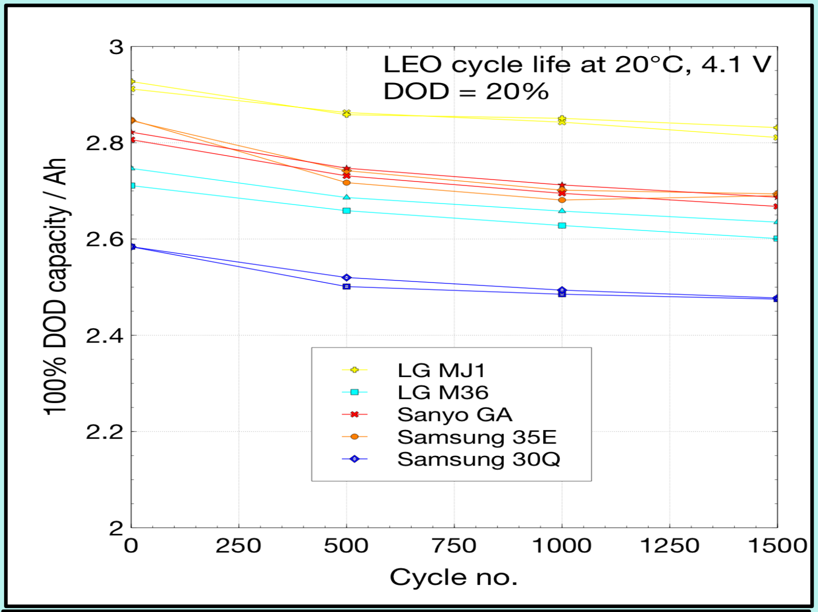


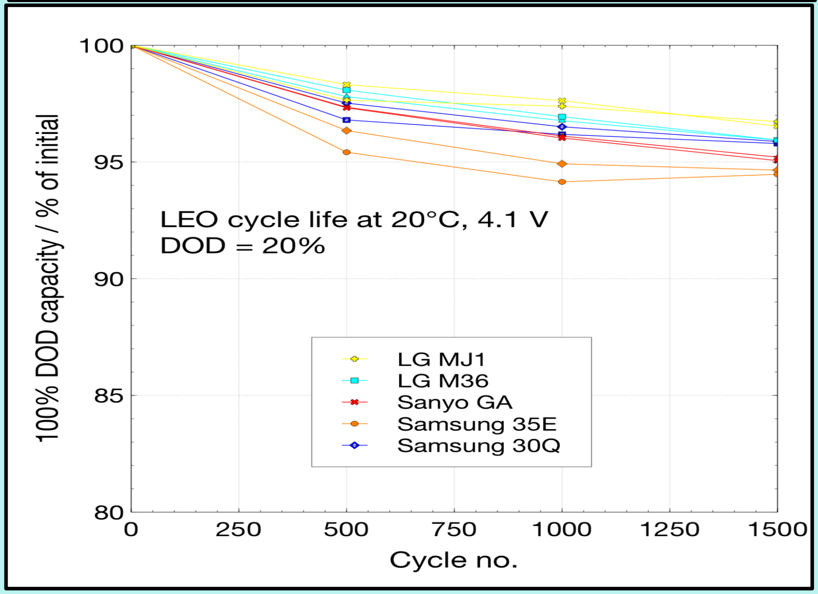


- LG Chem cells provide high power densities at 20-50°C, while other chemistries provide only at warm temperatures.

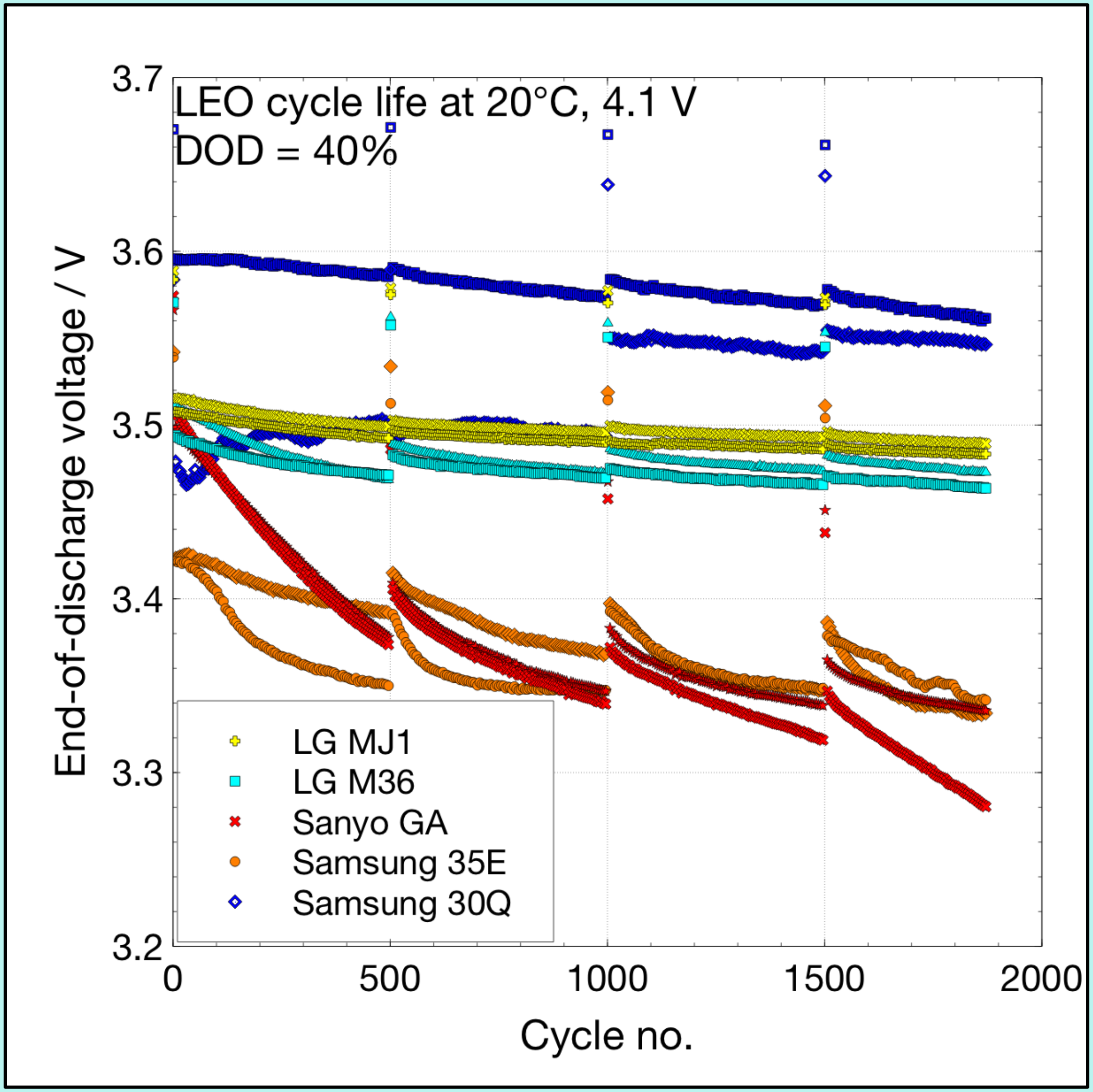
18650 LEO Cycle Life – 20 % DOD

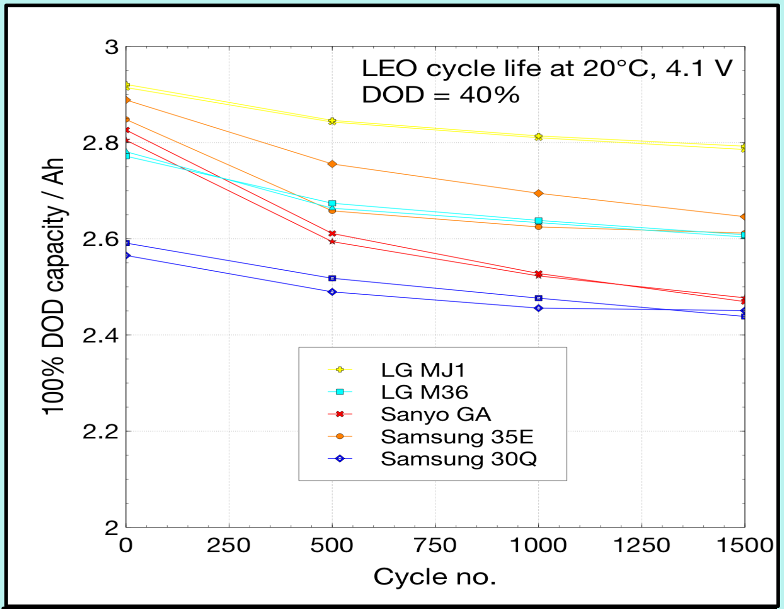


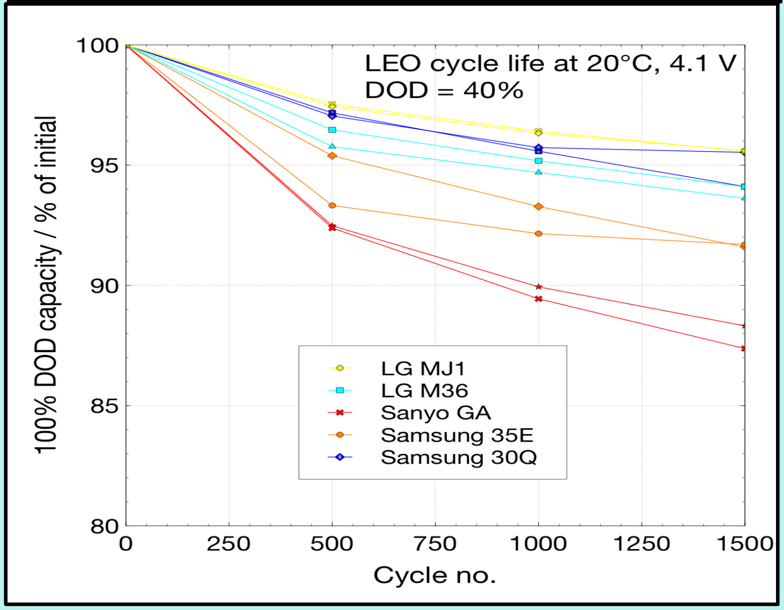




18650 LEO Cycle Life – 40 % DOD

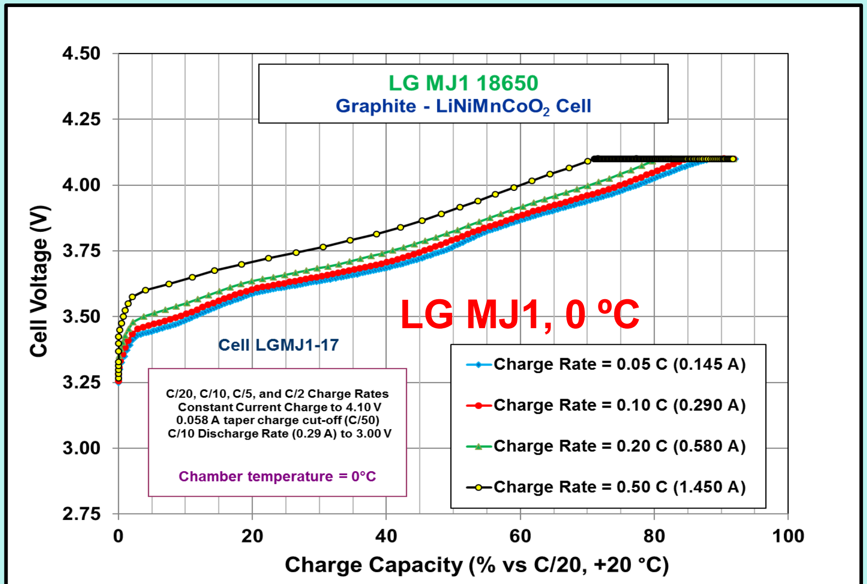


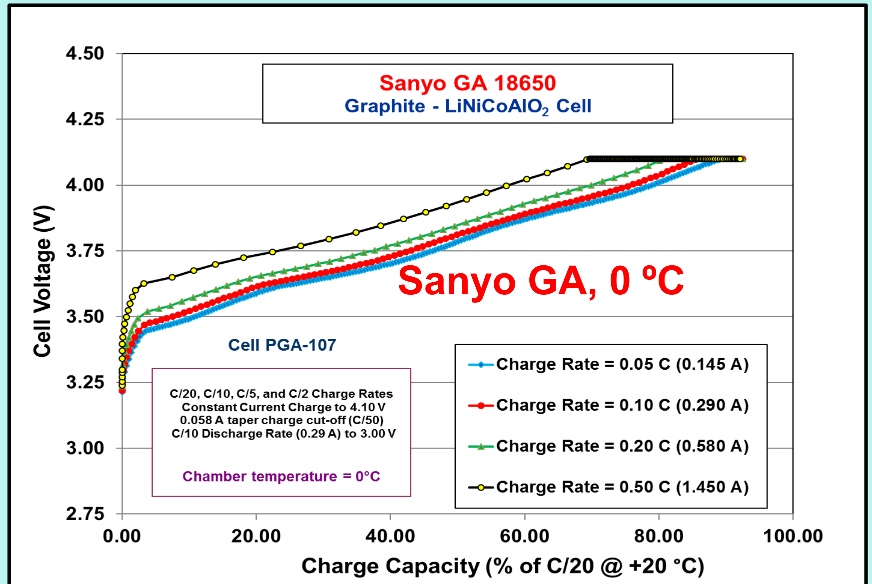


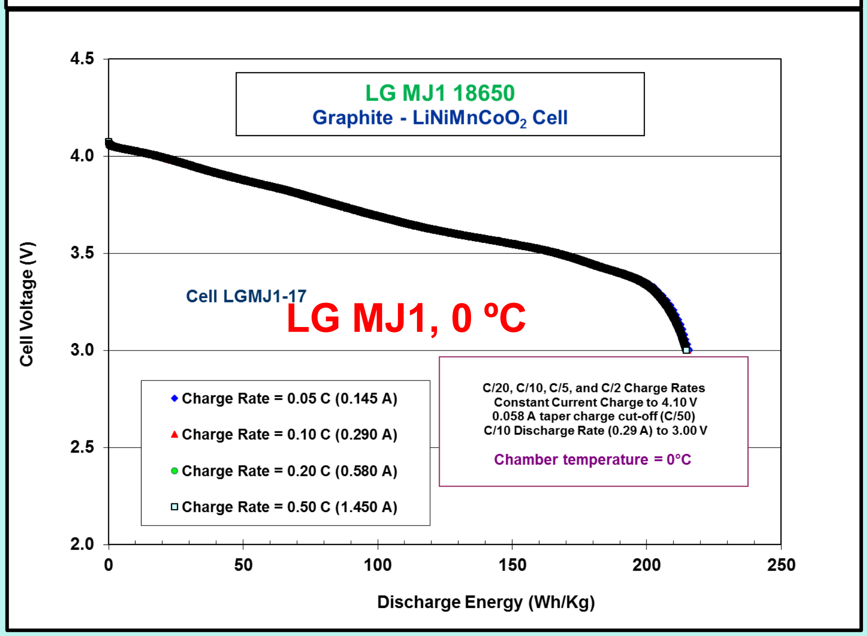


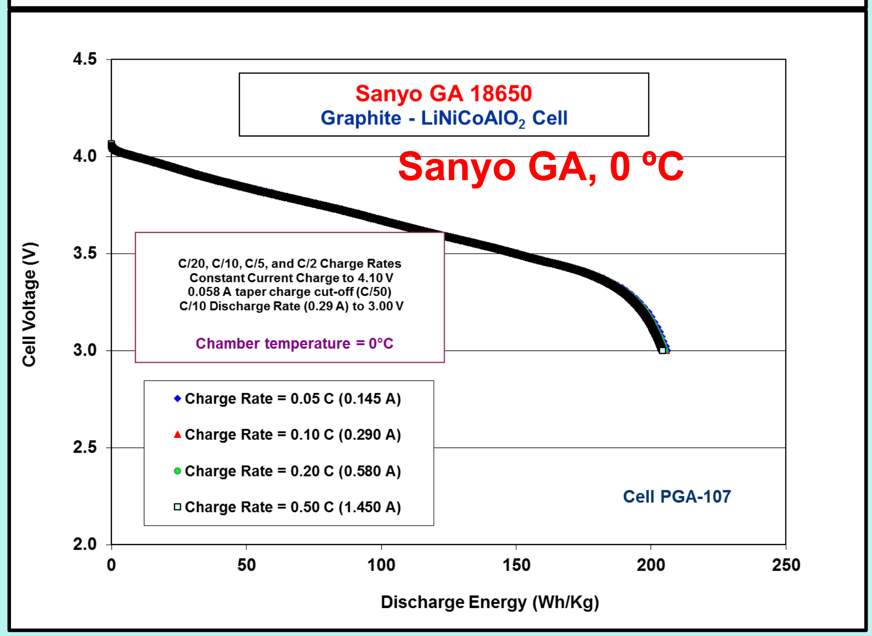
Charge rate test at 0C

- Same temperature for charge and discharge
- Charge rates C/20 — 0.5C with taper at 4.10 V (taper to C/50); All discharges at C/10



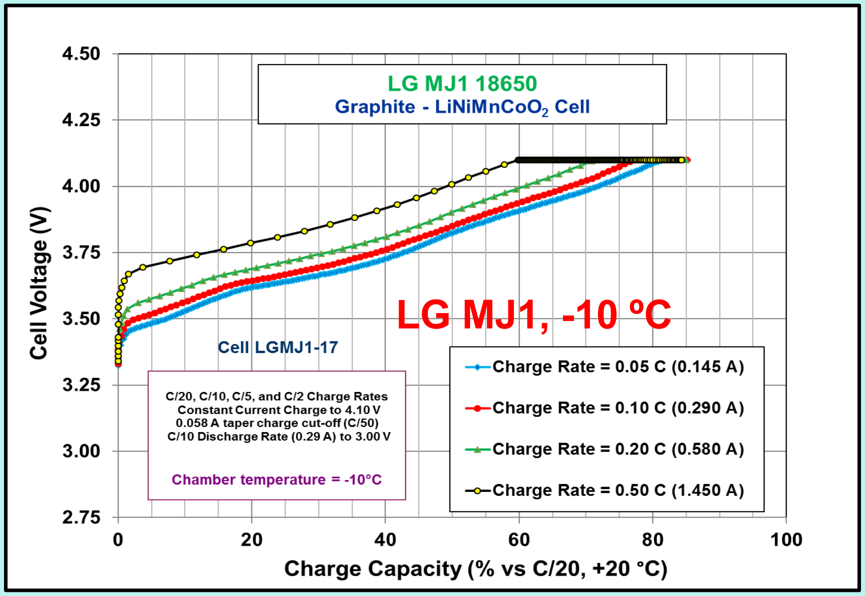


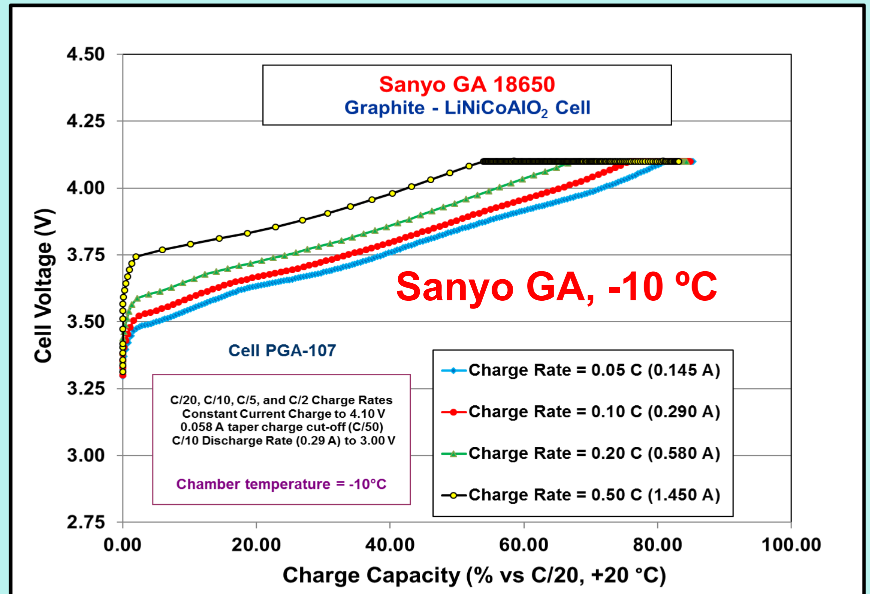


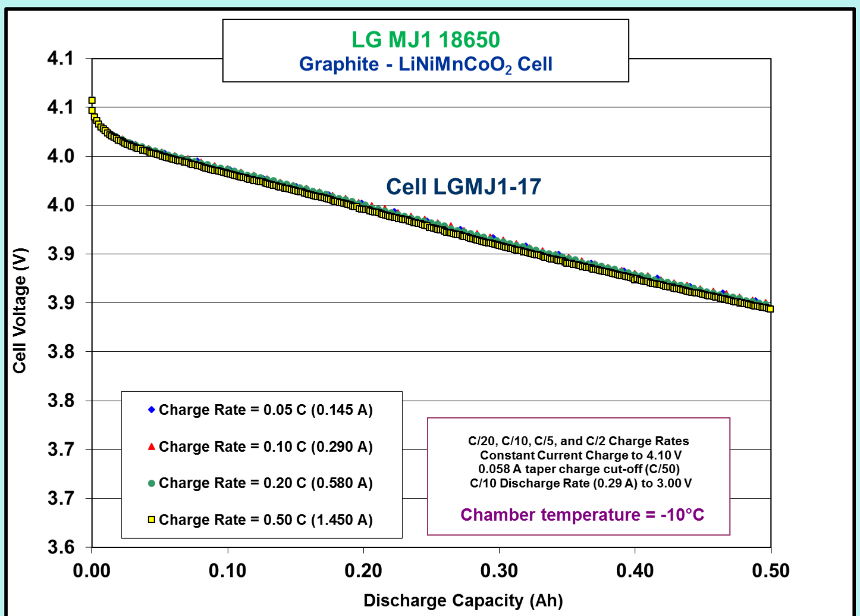


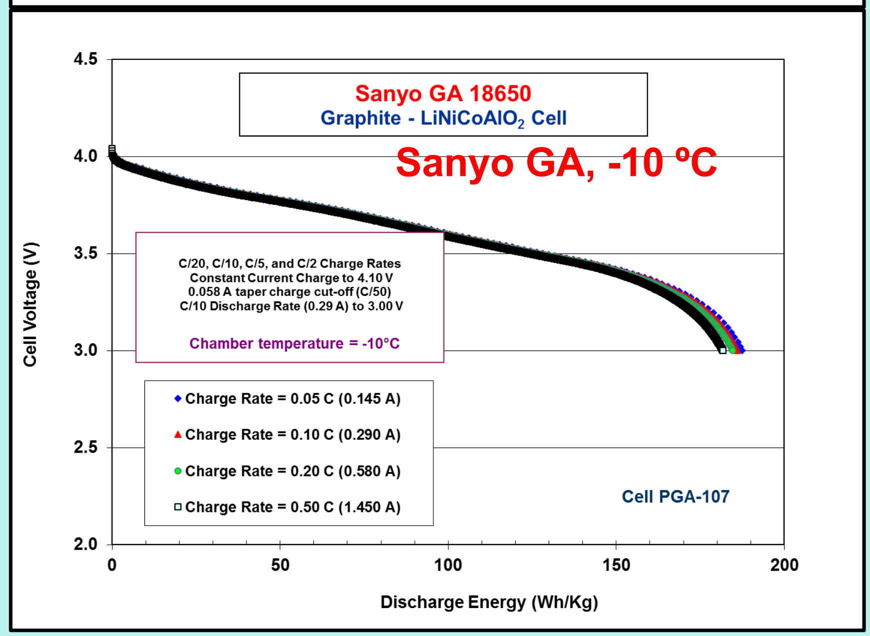
Charge rate test at -10C

- Same temperature for charge and discharge
- Charge rates C/20 — 0.5C with taper at 4.10 V (taper to C/50); All discharges at C/10









Charge rate test at -20C

- Same temperature for charge and discharge
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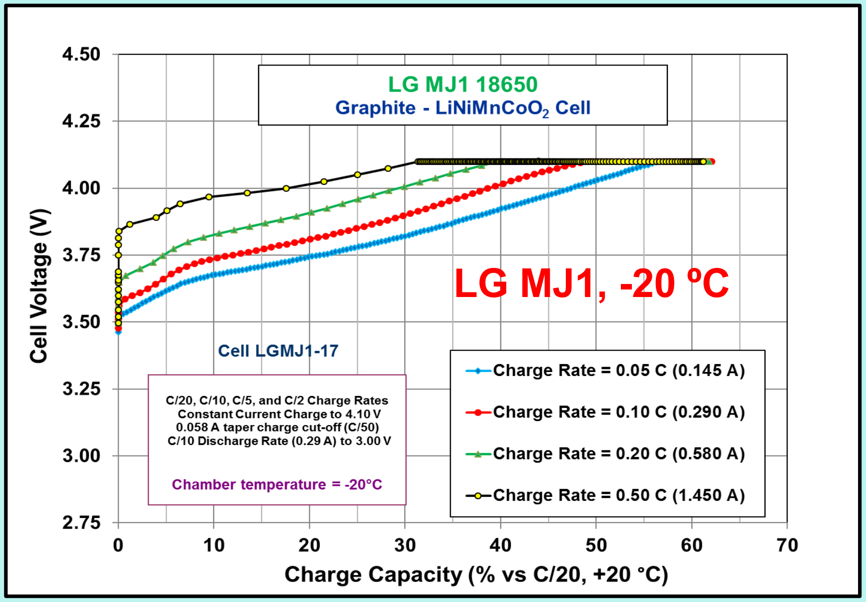
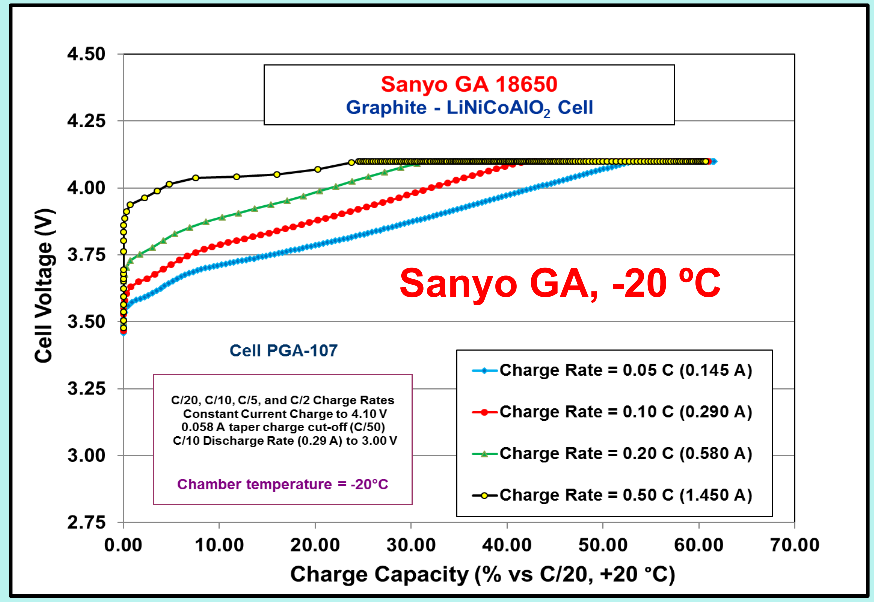
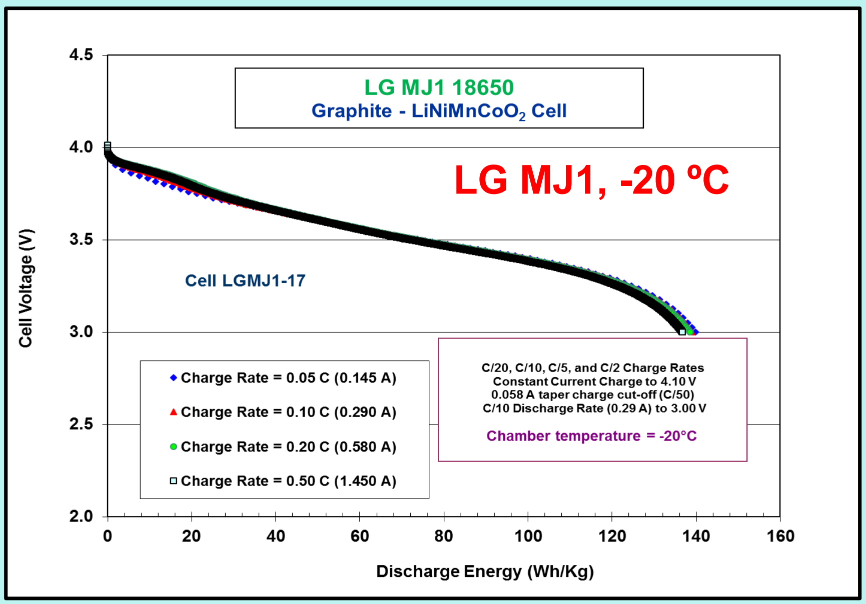
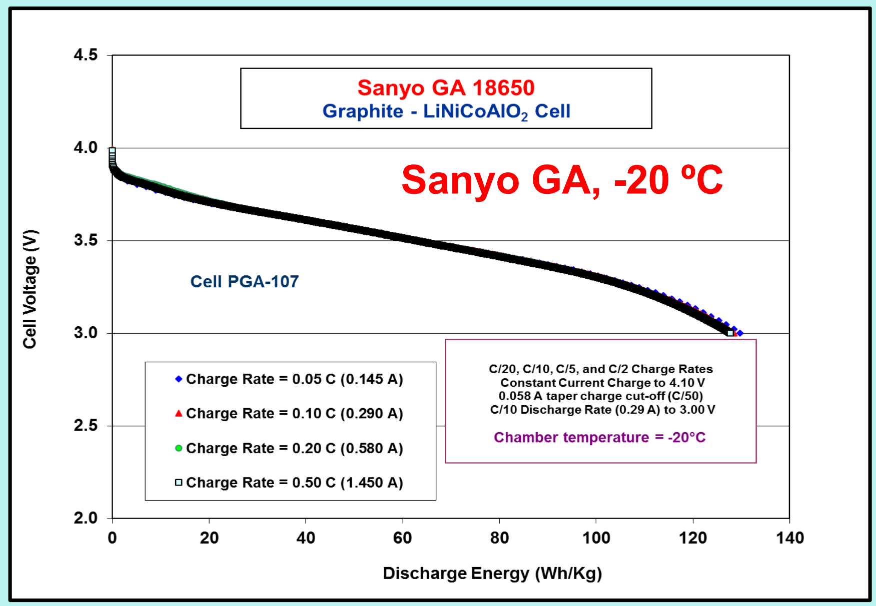


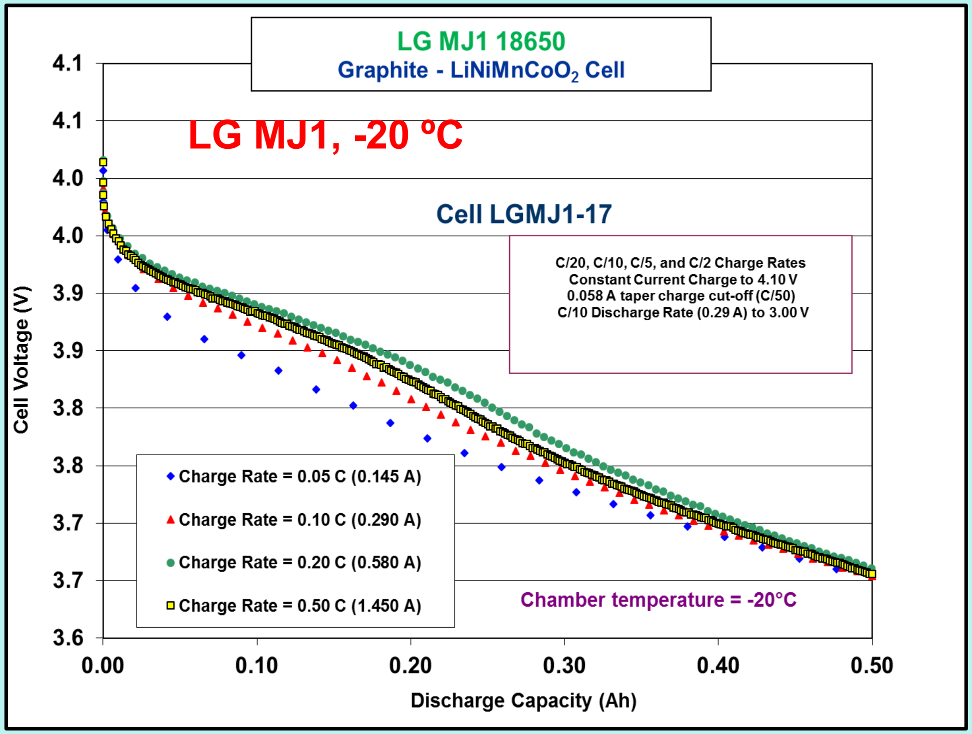


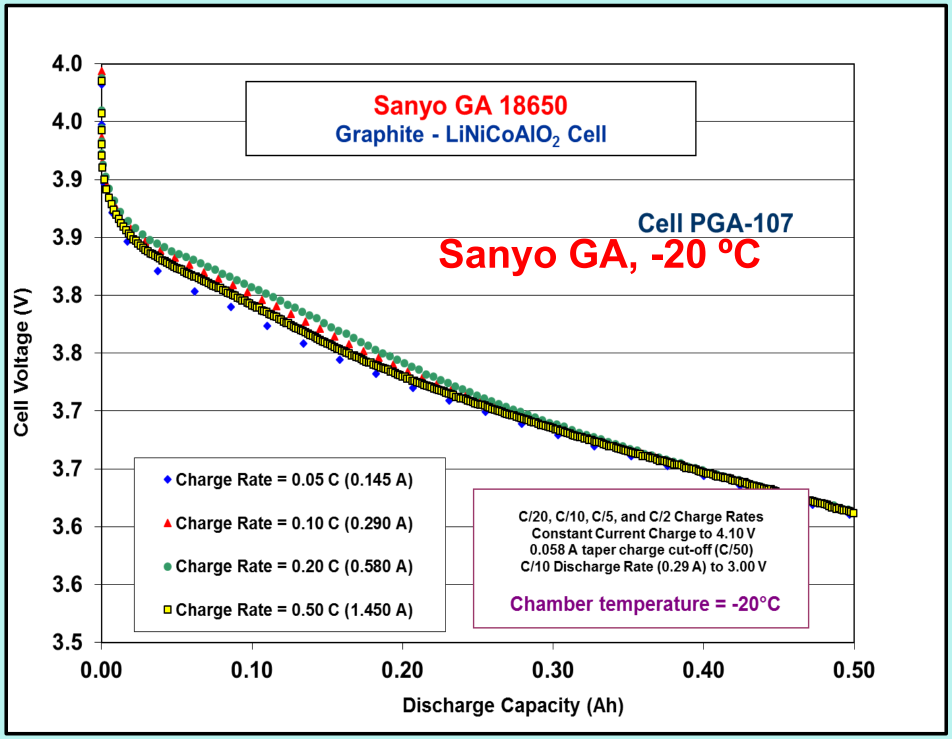




Charge rate test at -20C (Li Plating)

- Same temperature for charge and discharge
- Charge rates C/20 — 0.5C with taper at 4.10 V (taper to C/50); All discharges at C/10





Charge rate test at -20C (Li Plating)

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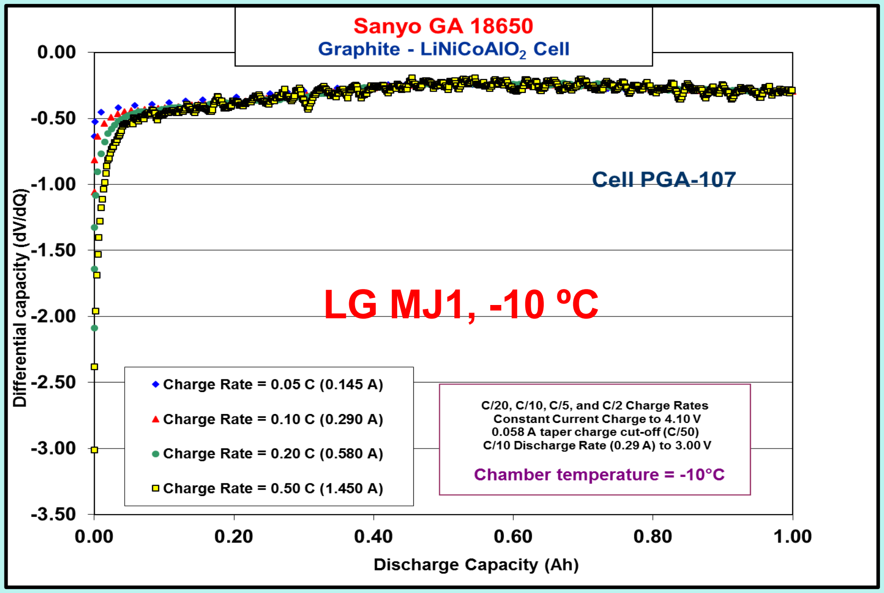

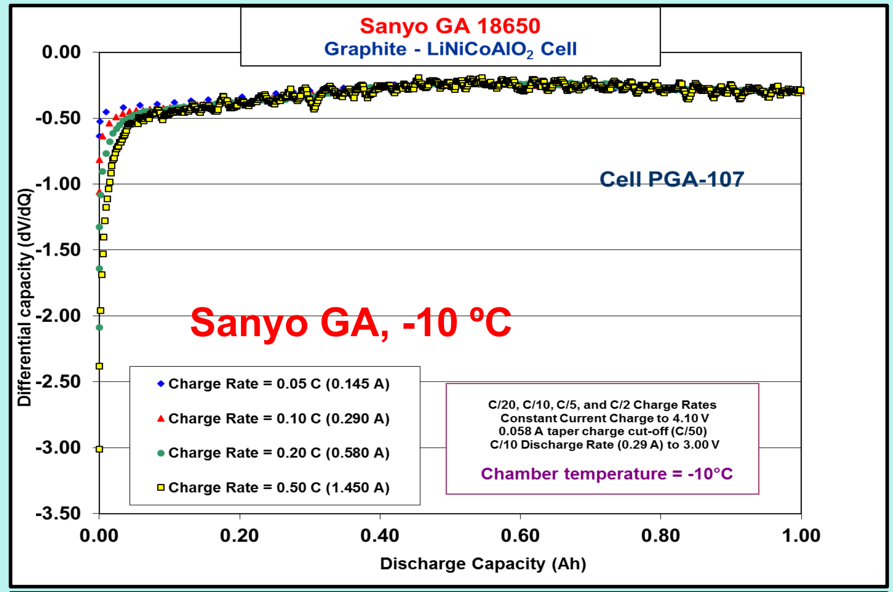

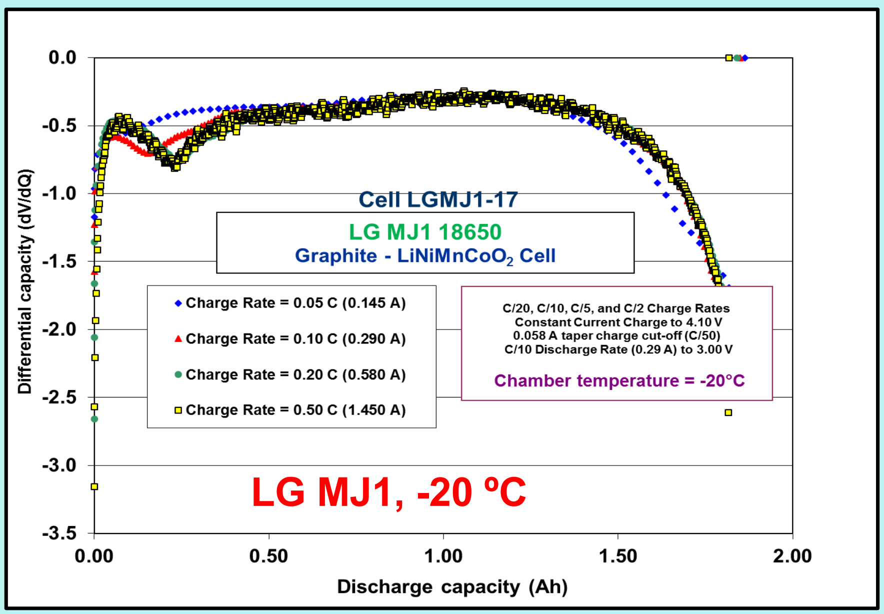

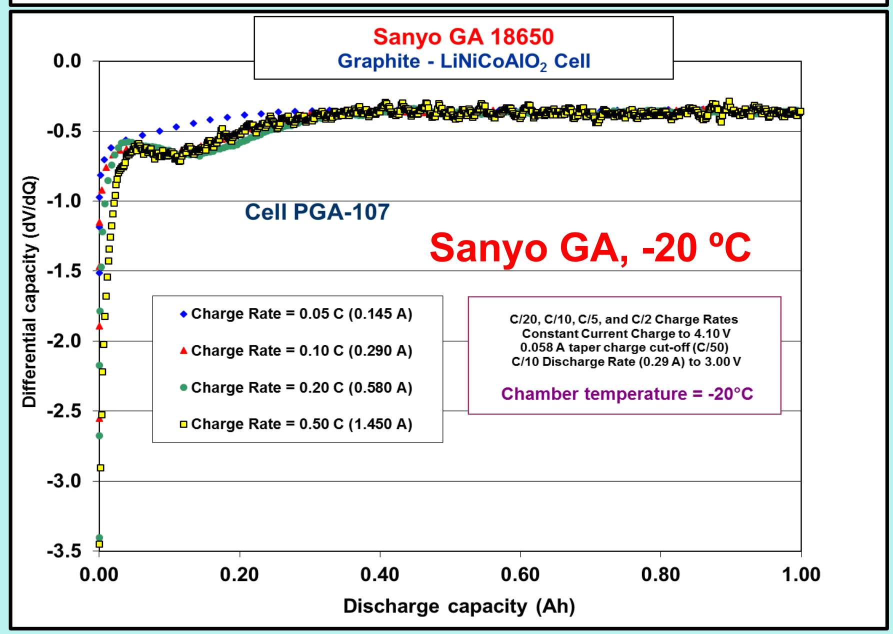

Summary and Conclusions

- A wide variety of 18650 format Li-ion cells are available with a high degree of manufacturing quality and consistency, in high-energy, high-power, and "hybrid" designs
- Effect of irradiation up to 20 Mrad is relatively minor
- The LG MJ1 cell appears to offer the most favorable combination of energy, cycling stability, and high rate capability up to 10 A
- Unlike other most other cell designs, LG MJ1 and M36 have most of their energy accessible at room temperature
- Only minor variations were detectable by DPA of commercial cells, which appear to use highly optimized combinations of well-known materials (NMC, NCA, LiFSI, etc.)
- Some of these COTS 18650 cells are viable replacements for thermal batteries to support critical Entry Descent and Landing (EDL) operation for planetary surface missions (landers and rovers) with higher specific energy and testability.

Acknowledgements

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