Performance of High Energy/high Power Li-ion cells in Radiation Environments

Kumar Bugga, Charlie Krause, Keith Billings, John-Paul Ruiz, Simon jones, Erik Brandon and Richard Ewell

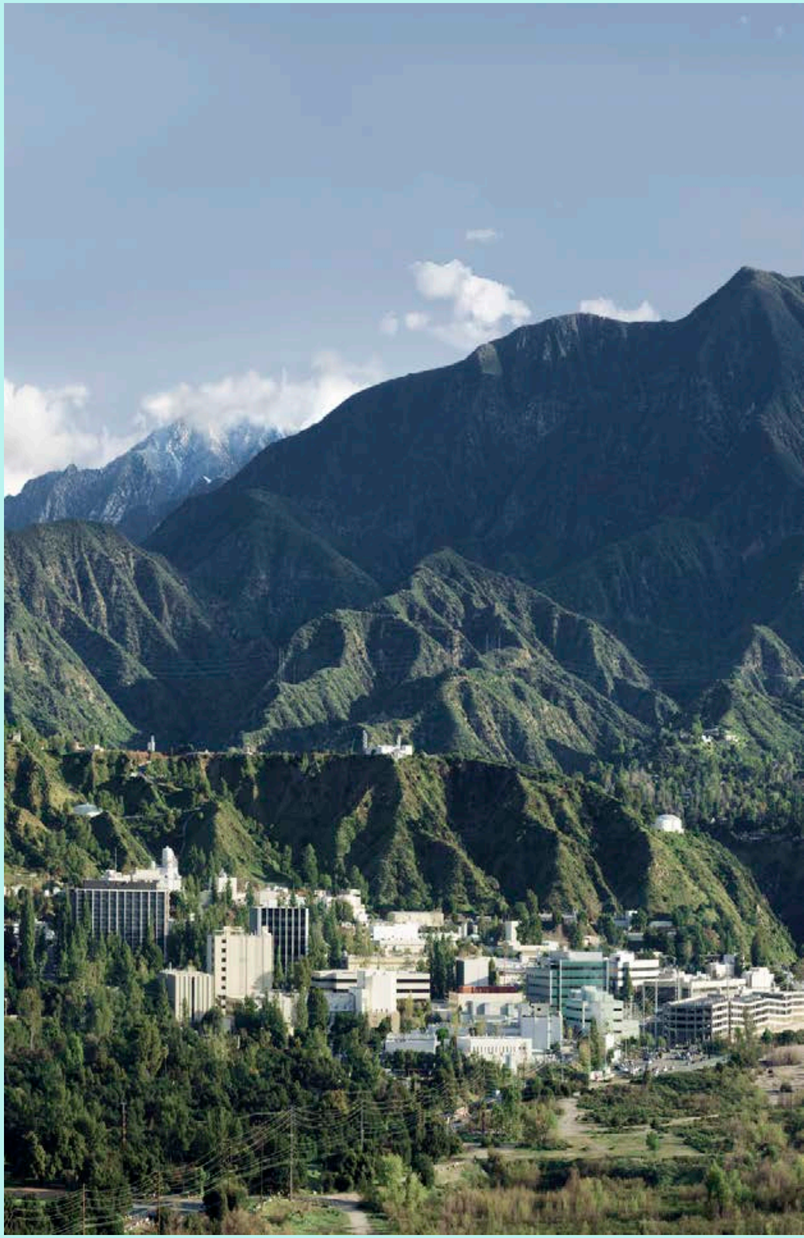
Jet Propulsion Laboratory,
California Institute of Technology
Pasadena, CA 91108

Eric Darcy

Johnson Space Center, Houston, Texas and

Chris Iannello

NASA Kennedy Space Center, Florida



Space Power Workshop

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Marriott Redondo Beach Hotel, Torrance, CA

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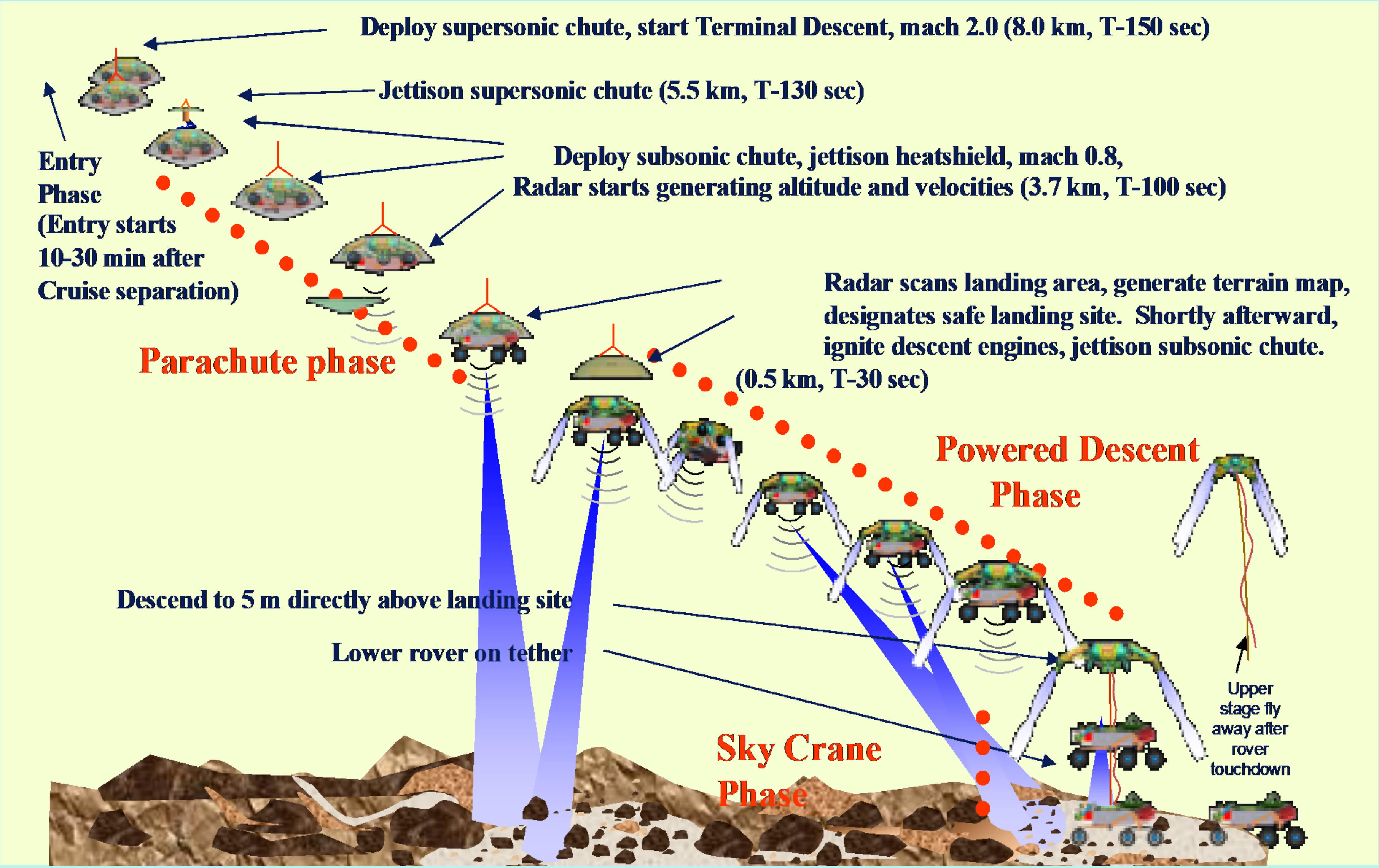
Background and Relevance

- 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 would have high energy Li-ion batteries (in conjunction with solar array for the Cruise stage and exclusively for the Descent Stage)
- Applications: Planetary helicopters, Planetary Ascent vehicles Unmanned aerial vehicles, Hybrid power systems

Entry, Descent, and Landing



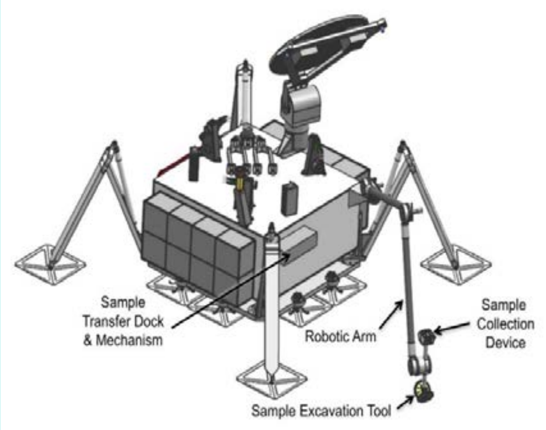
Europa Lander Descent Stage

Mission Concept Requirement

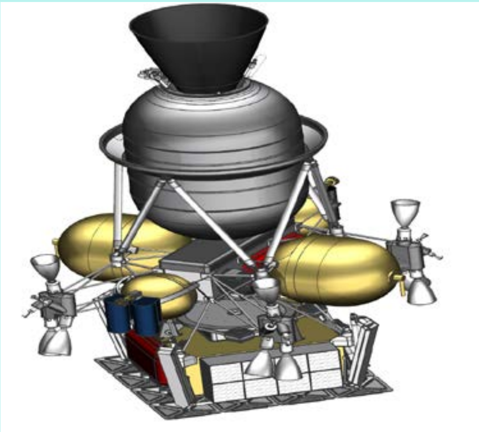
- •Energy: ~2375 Wh
- •Power: 3375 W (peak)
- •185 minutes
- •Battery temperature 0-70ºC
- •Approximately 20-25 kg

Original Battery Design Concept

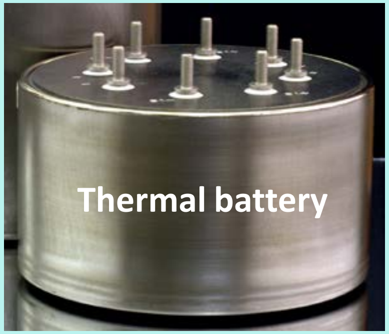
- •Primary Batteries and thermal batteries
- •Primary Battery through 180 min
  - Li/CF_x–MnO_2 12s12p (144 D cells)
  - Power: 790 W; Energy: 2237 Wh
- •Thermal Batteries for high power (3)
  - MSL Pyro batteries
  - Power: 3375 W; Energy: 138 Wh
  - Duration: 5 min
- Current Baseline
  - High Energy/Power Li-ion battery



Notional Lander Design

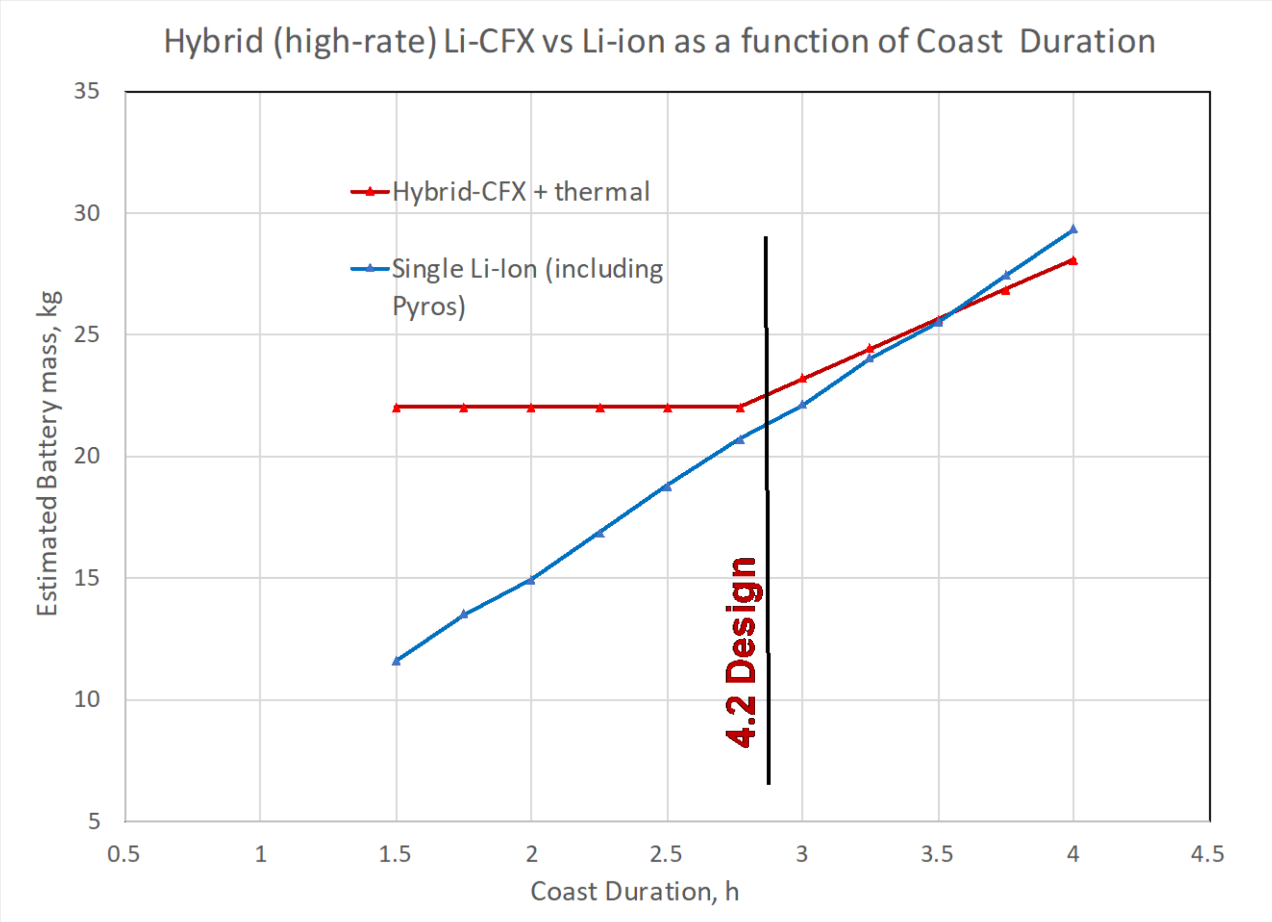


Notional Descent Stage Design



Pre-Decisional Information — For Planning and Discussion Purposes Only

Trade off: Li-ion Battery vs Hybrid Li-CFX primary + Thermal



- Baseline system (CFx + thermal) doesn't decrease with the coast duration (battery size driven by the power of hybrid CFX battery, not energy).
- Li-ion battery size decreases almost linearly with the coast duration, since the size is driven by the energy (considerable power margin)
- Easier flexibility and modularity and testability

High Energy and High Power COTS LI-Ion Cells

COTS 18650 Cells
(259- 276 Wh/kg and 704-735 Wh/l)

Batch 1 cells
LG M36
LG MJ1
Panasonic BJ
Samsung 35E
Sony VC7 (Bottom Vent)

Batch 2 cells
LG M36
LG MJ1
Panasonic/Sanyo GA,
Samsung 3
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

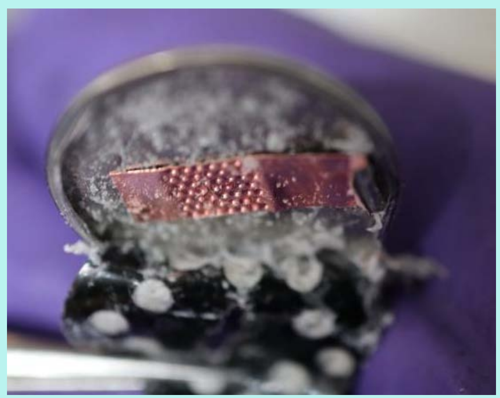
Types of Tests

- Initial Characterization
- Rate characterization
  - At different rates and temperatures
  - High rate testing
- EIS (Electrochemical Impedance)
- Cycle life testing
- Radiation exposure to 18 MRad
- High rate testing

DPA of High Energy and High Power Li-Ion Cells

Identification and characterization of various elements

Cell Type	Anode		Cathode		Separator
	L (mm)	W (mm)	L (mm)	W (mm)	Thickness (mm)
Panasonic BJ	603.3	60.32	584.2	54.77	0.018
LG M36	653.2	60.32	606.4	59.63	0.02
LG MJ1	660.4	60.32	609.6	58.74	0.015
Samsung 35E	603.3	60.32	615.9	57.94	0.015
Sony VC7	603.3	59.53	615.9	59.53	0.018



Evidence of some corrosion in Sony VC7 cells

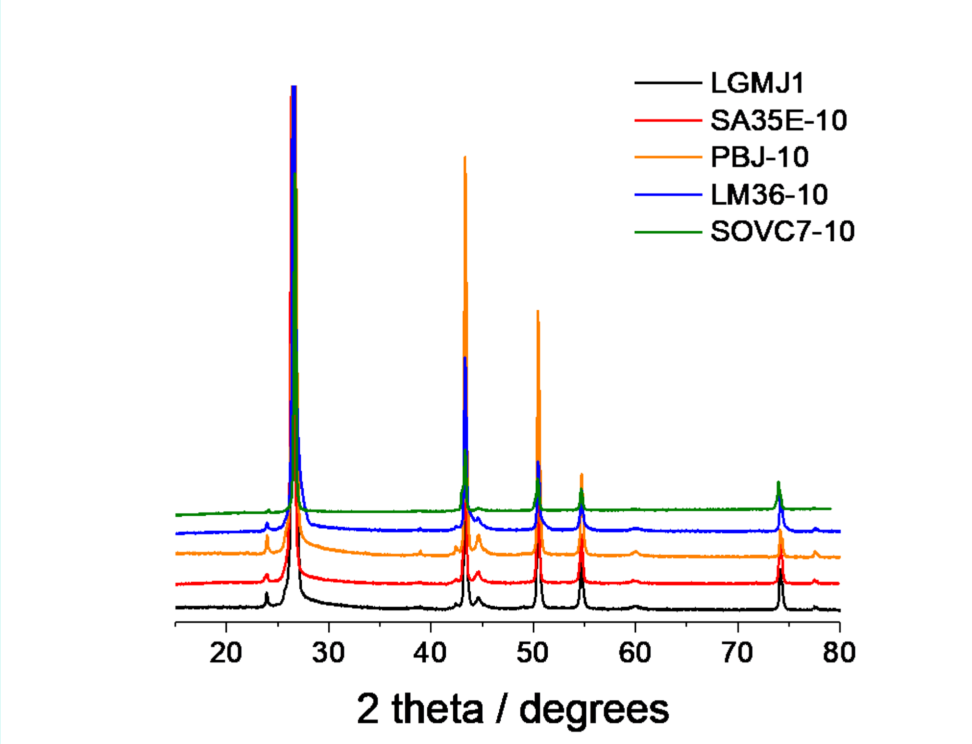
- **CID (shown in 35E):**

- **Bottom vent (VC7, 36G):**

- **Mandrel (shown in 35E):**

Cells Chemistries

Anodes



- Cells dissected in the discharged state and the components were subjected to ex-situ analyses
  - XRD for cathodes and anodes
  - NMR and MS for electrolyte
  - SEM and EDAX

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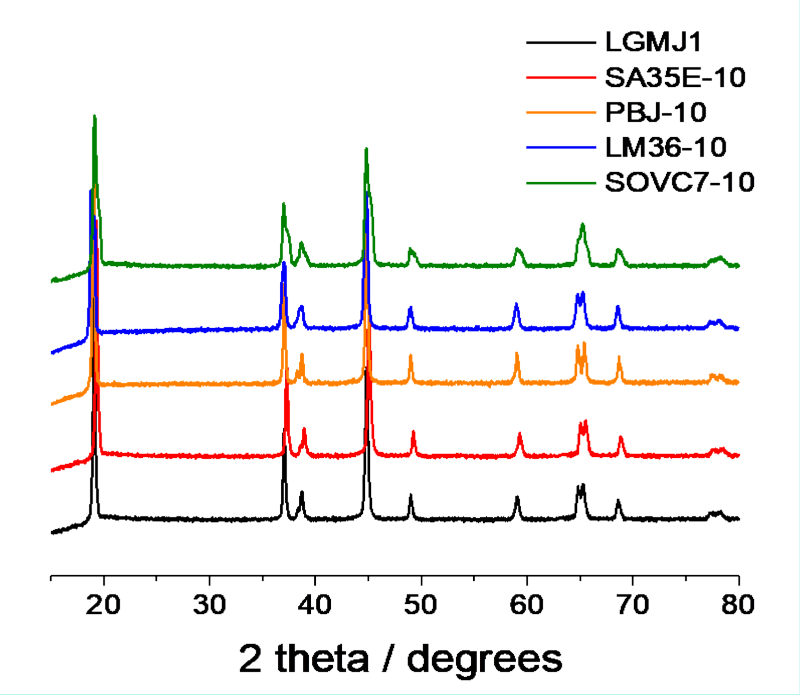
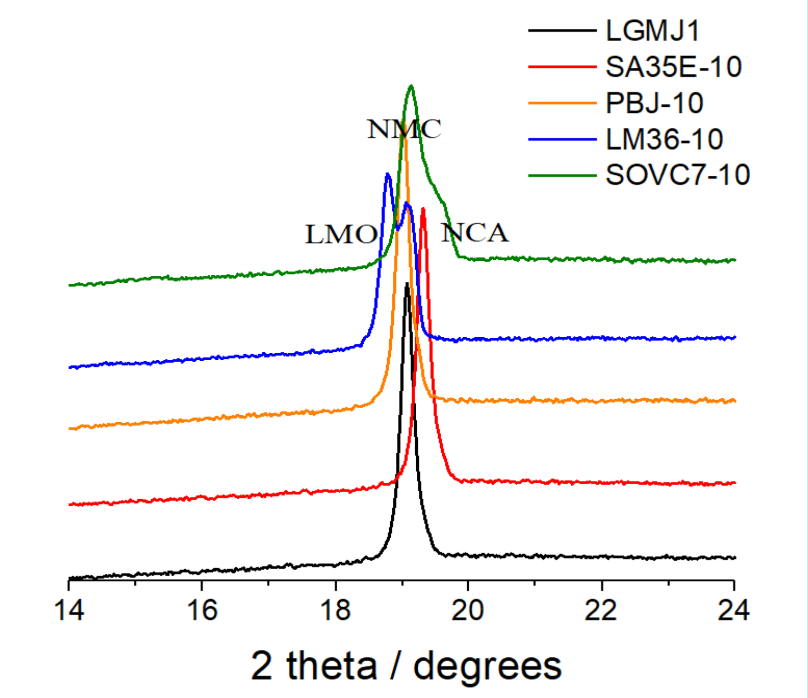
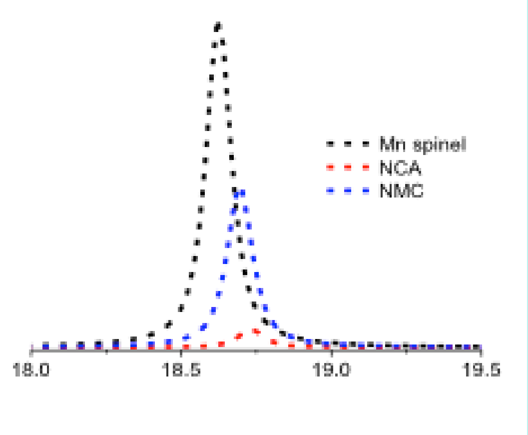
DPA of Li-Ion Cells - Cathodes

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



(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 ($LiNi_{1-x-y}Mn_xCo_yO_2$)

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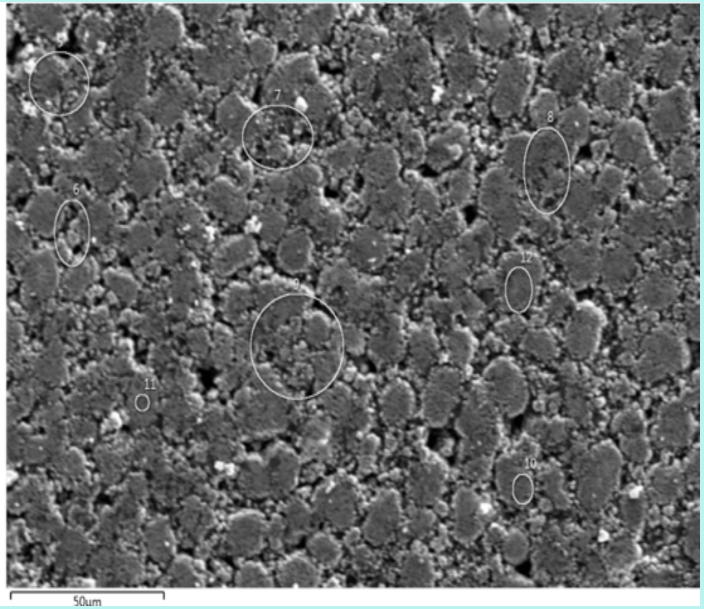
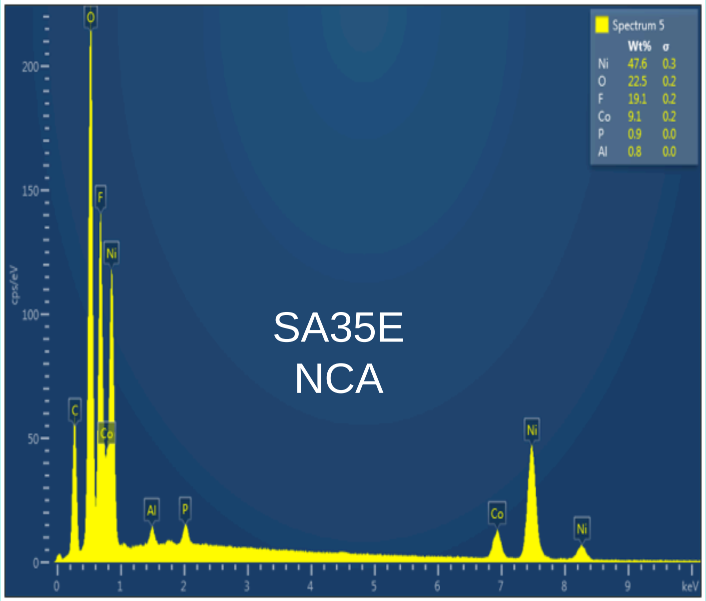
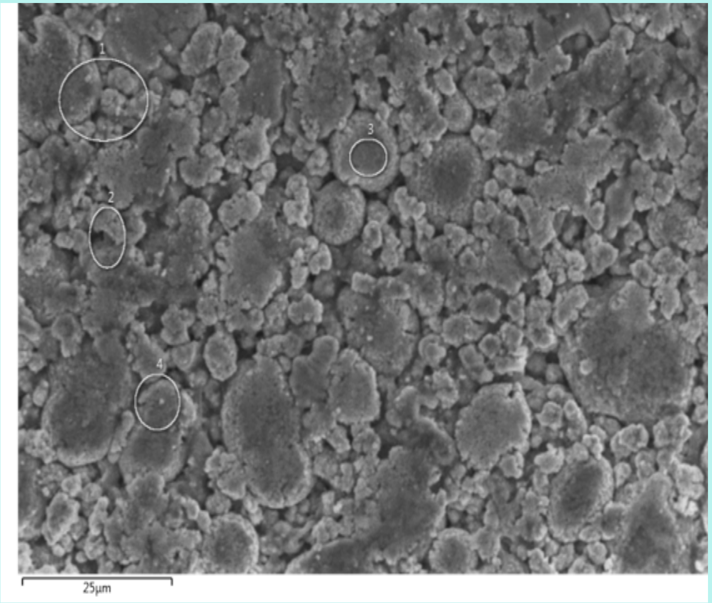
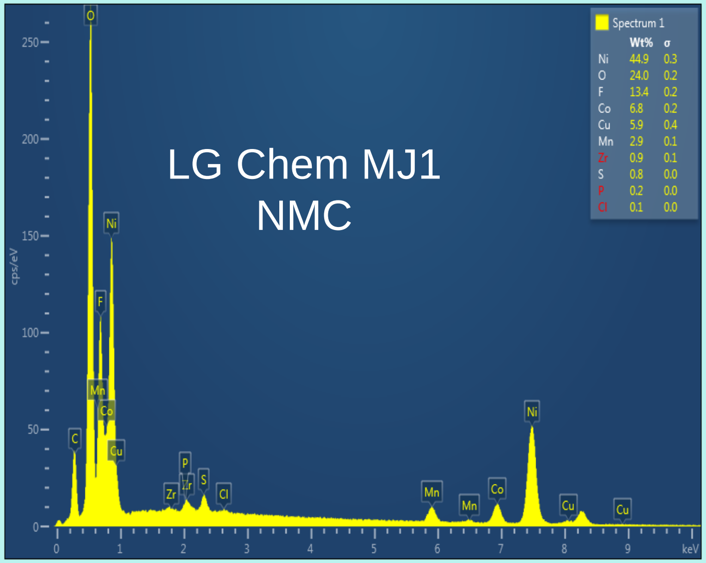
Cathode Analyses





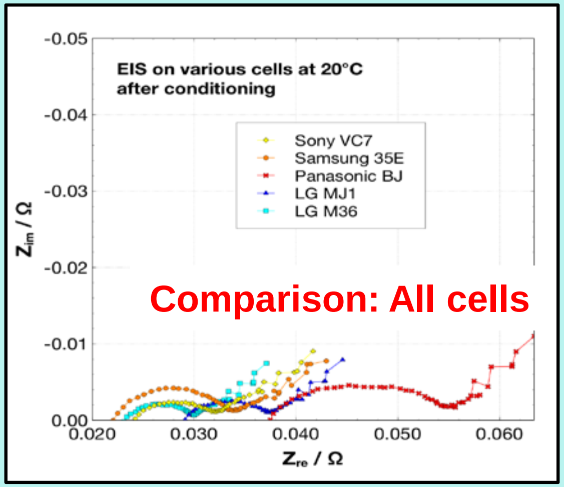


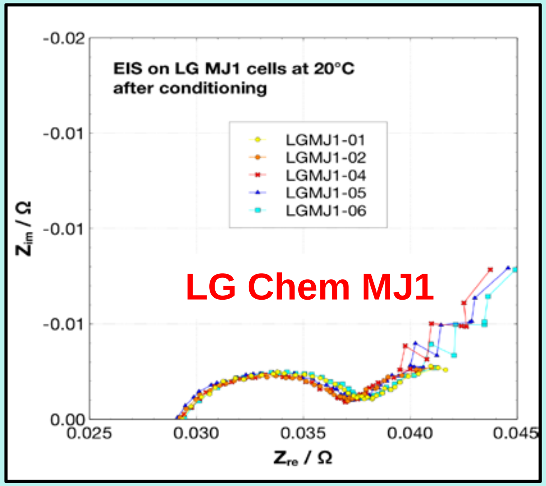


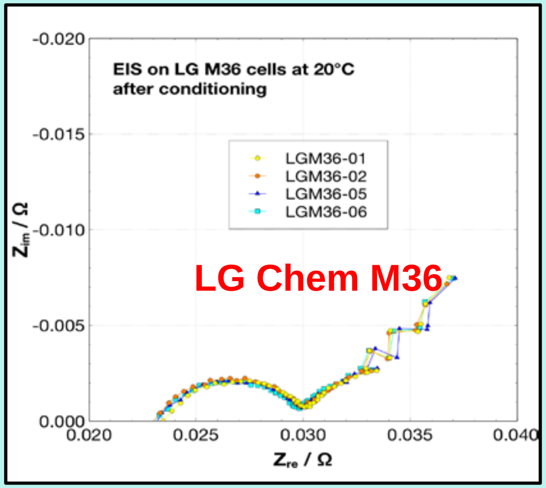
DPA of Li-Ion Cells- Summary

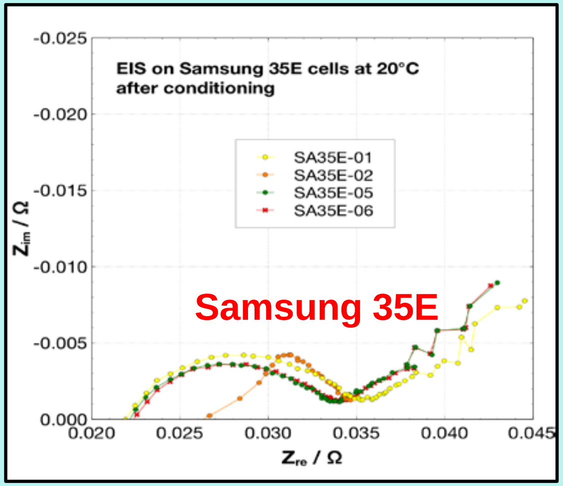
	Anode	Cathode	Electrolyte
LGMJ1	graphite	$Ni_{0.81}Co_{0.13}Mn_{0.06}$ by EDX*	EC, DMC, $LiPF_6$, LiFSI (lots)
SA35E-10	graphite, ~2% Si by EDX	$Ni_{0.83}Co_{0.15}Al_{0.02}$ by EDX	EC, DMC, additive, $LiPF_6$, LiFSI
PBJ-10	graphite	$Ni_{0.81}Co_{0.16}Al_{0.04}$ by EDX	EC, DMC (assumed), $LiPF_6$, LiFSI
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)

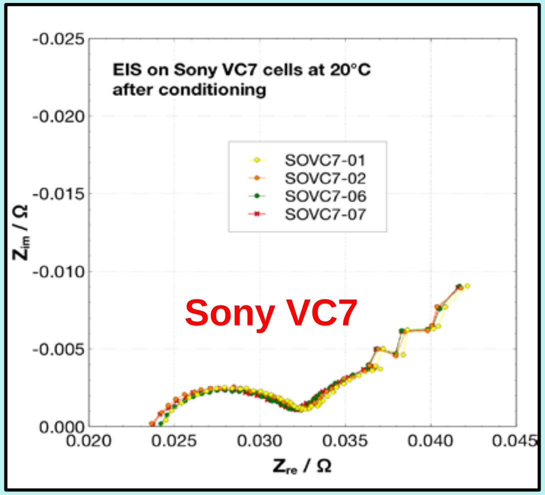
EIS after conditioning (Batch1 cells)

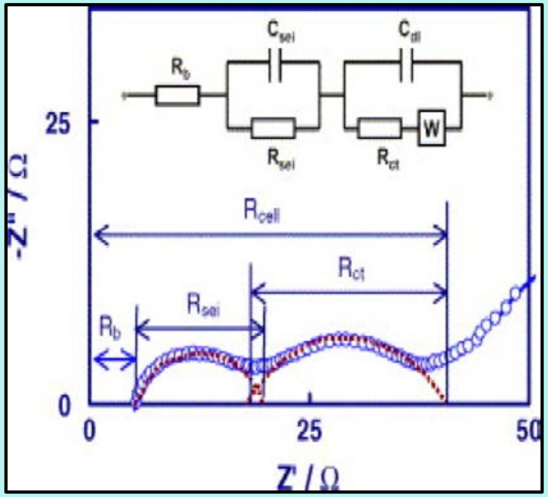












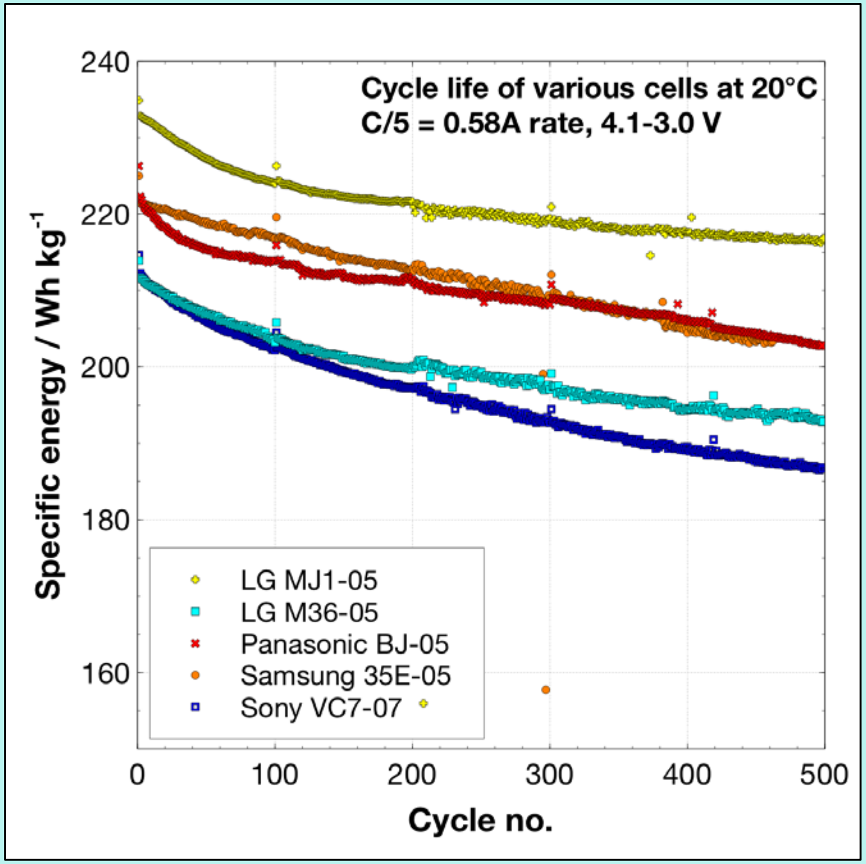
Typical Eq. Circuit

- Cells have very good cell-to-cell reproducibility in EIS spectra at +20 ºC
- Panasonic BJ cells appear to have greater film resistance, possibly due to suspected low-temperature optimized electrolyte
- LG M36 shows narrowest loop in BOL spectrum

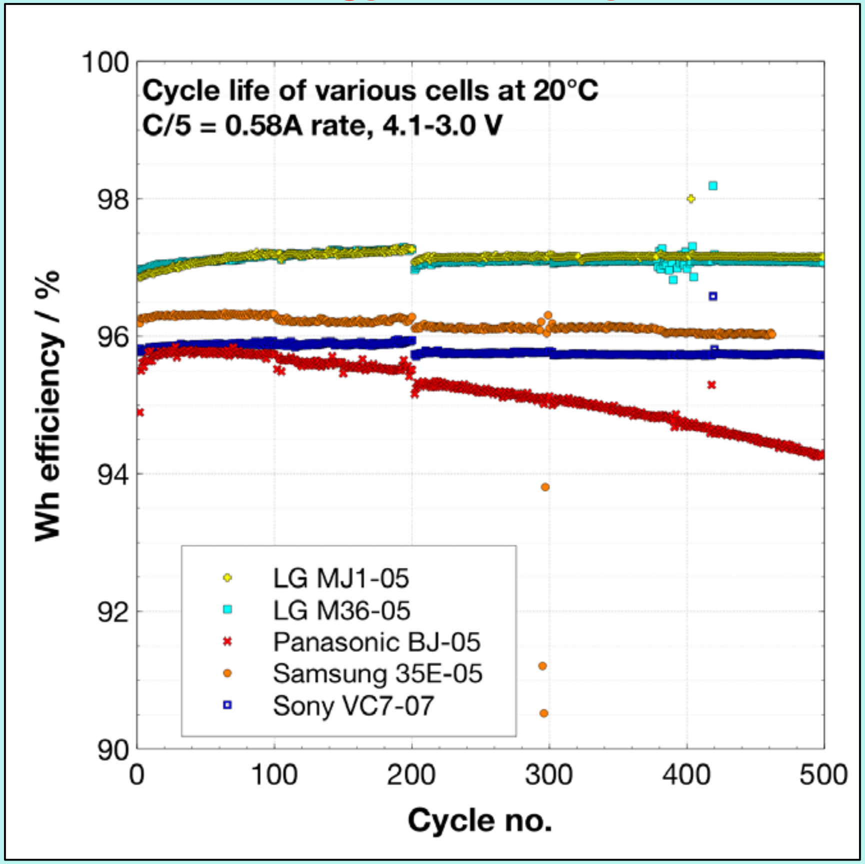
Cycle life at +20 ºC – Batch 1

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

Specific Energy, Wh/kg



Energy Efficiency



- 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

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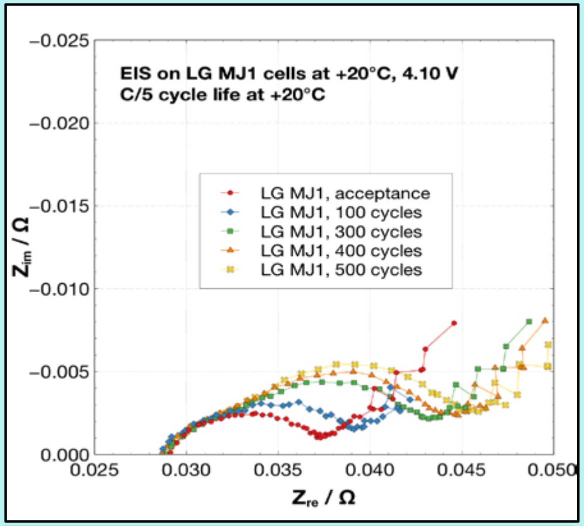
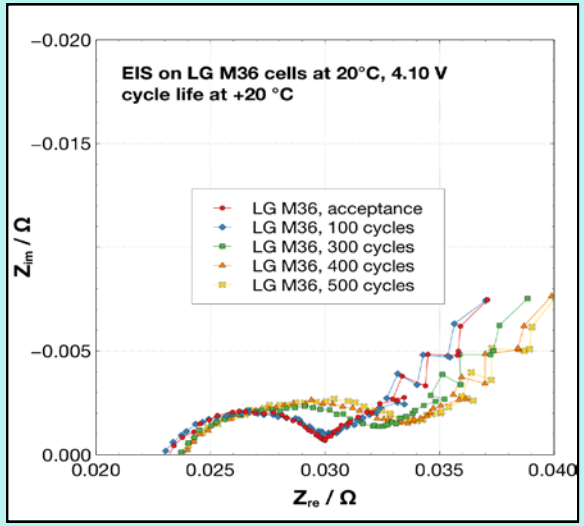
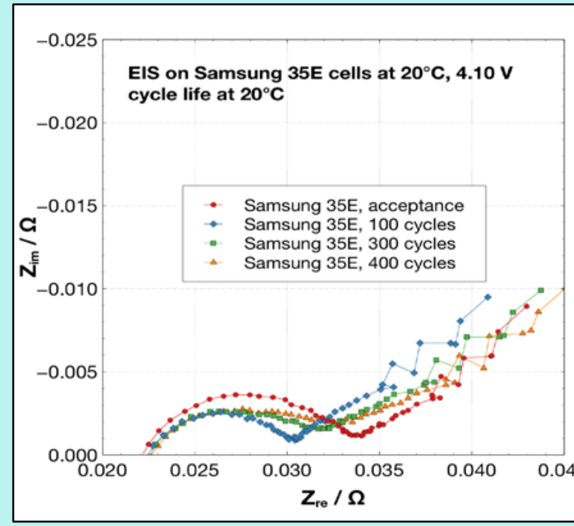
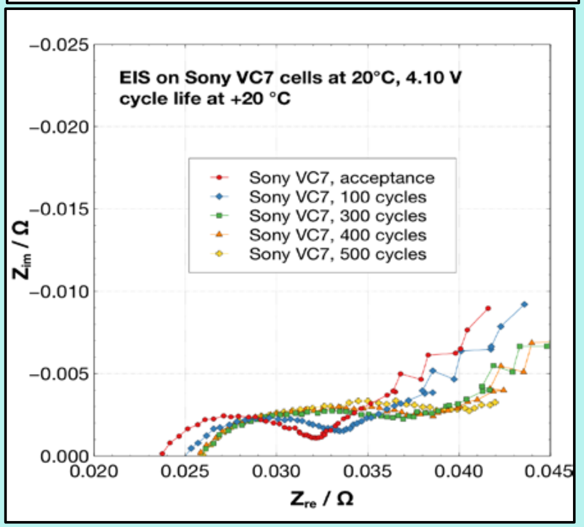
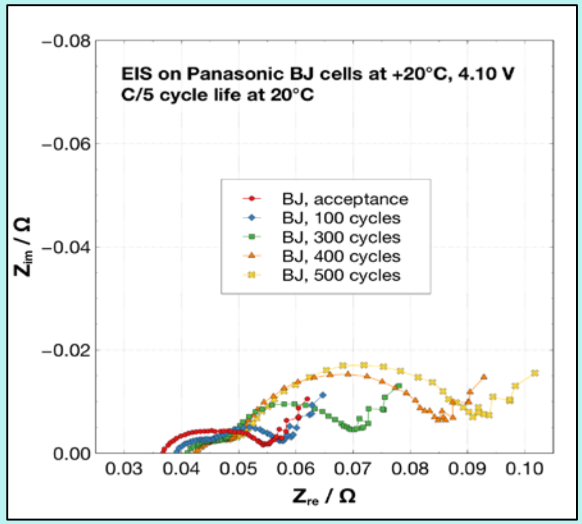
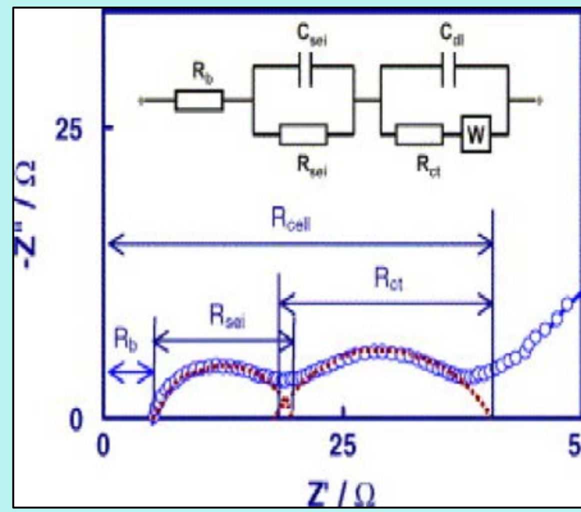








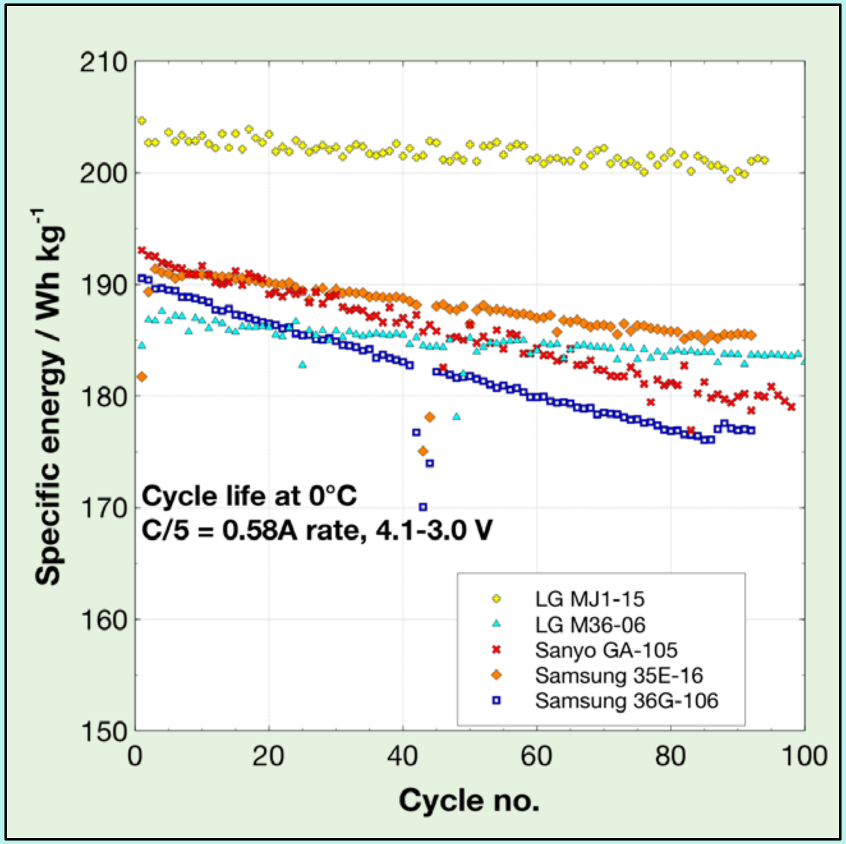




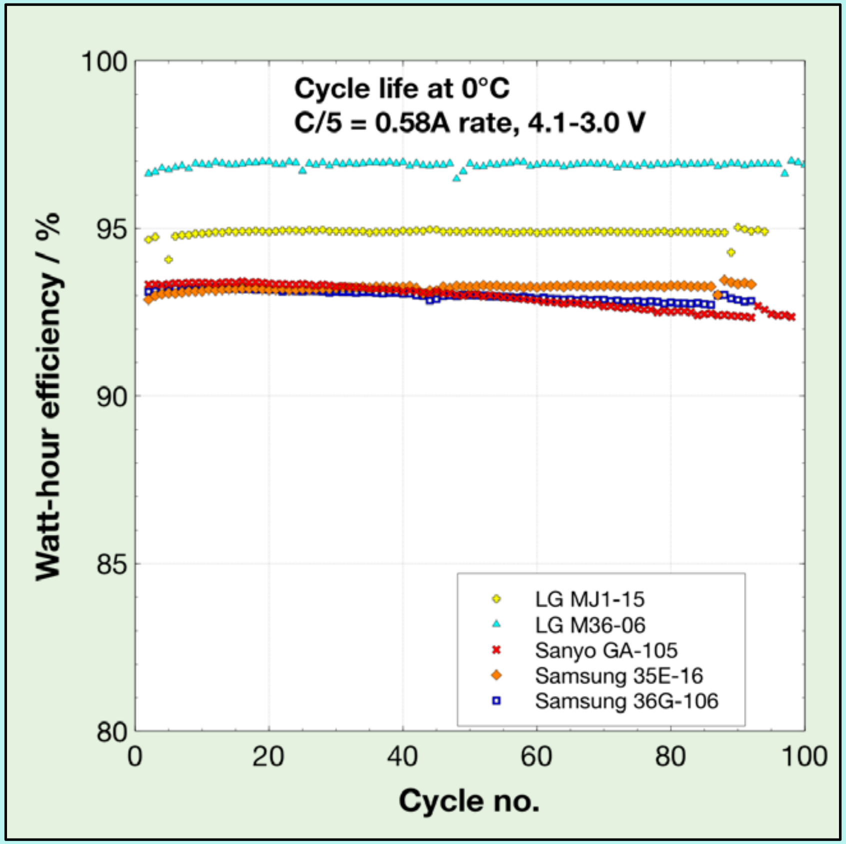
- All cells have shown some growth impedance over 500 cycles **Typical Eq. Circuit**
- LG M36 and Samsung 35E cells had the least growth, while Panasonic cell shows the highest growth during cycling.
- Impedance from the second loop is dominant (Charge transfer kinetics of cathode)

Cycle life at 0 ºC - (Batch 2 cells)

Specific Energy, Wh/kg



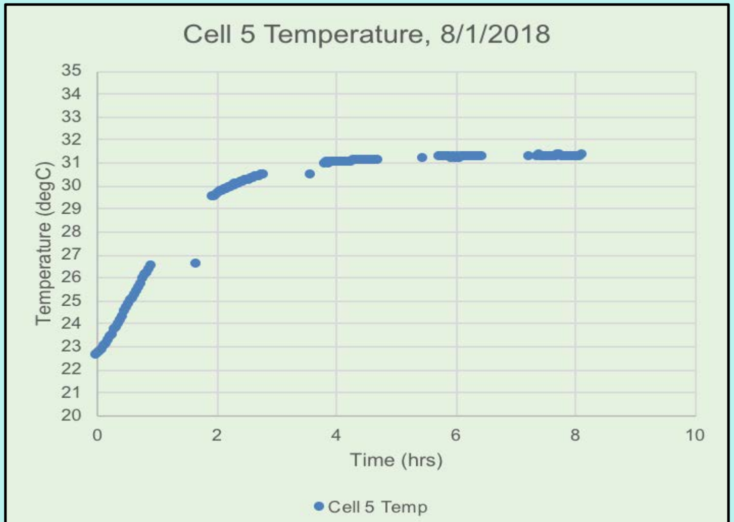
Energy Efficiency

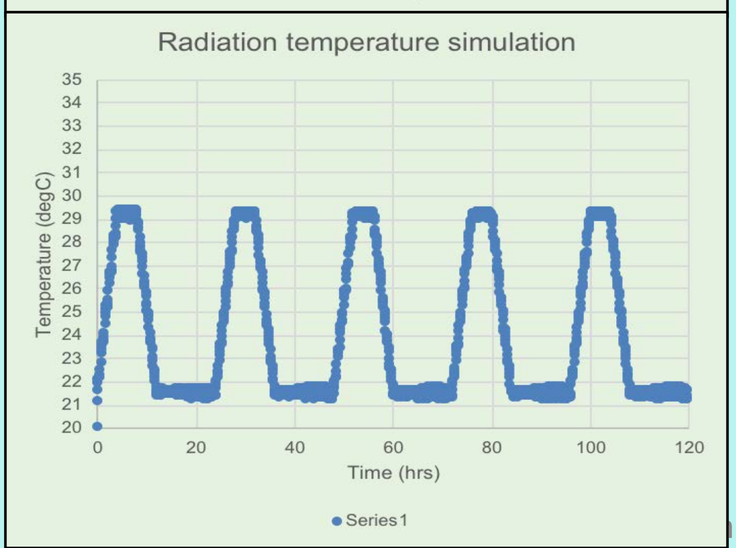


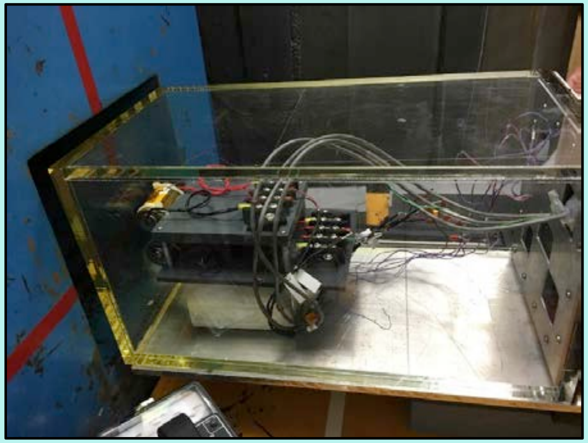
- All the cells have shown high specific energy of 190 Wh/kg at 0C, with LG Chem MJ1 cells offering the ~205 Wh/kg.

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

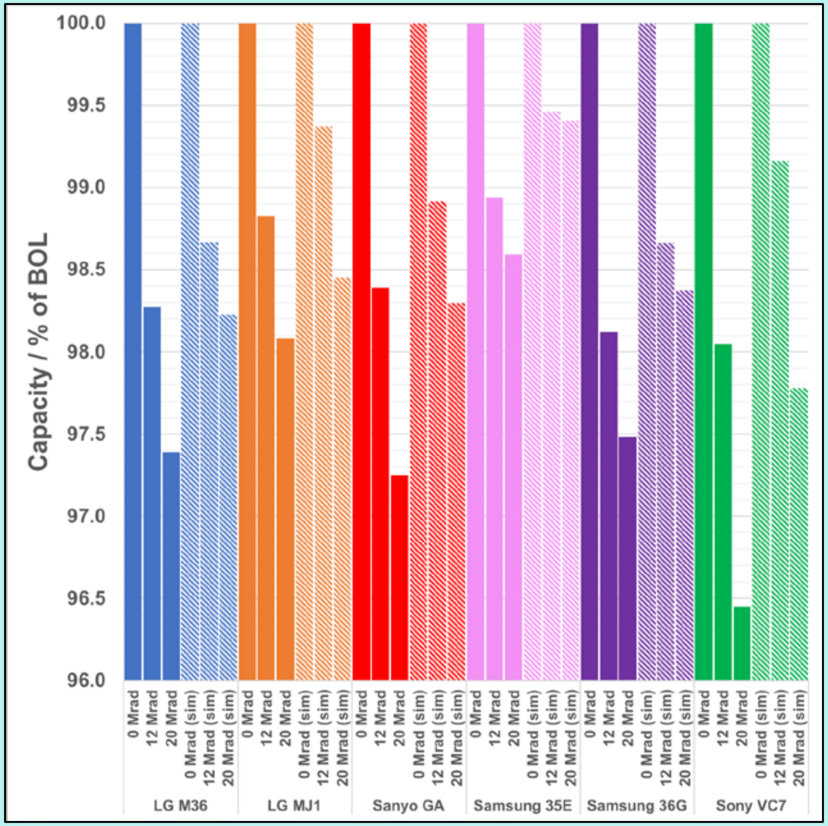






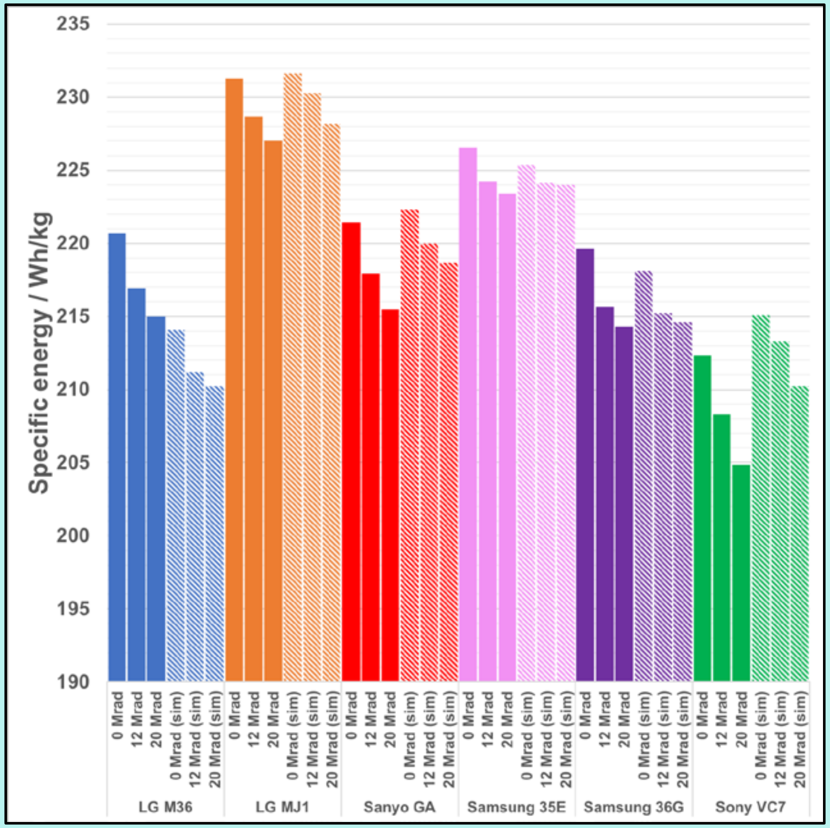
Irradiation of cells in two stages

Capacity vs Radiation dose



M36 MJ1 GA 35E 36G VC7

Specific Energy vs Radiation dose



M36 MJ1 GA 35E 36G VC7

- Solid: radiation exposed; 0 Mrad, 12 Mrad, 20 Mrad
- hashed: 0 rad control group, after stand periods equivalent to irradiation duration
- All the cells show impressive tolerance to radiation with about <2% capacity loss (compared to control cells) after 20 Mrad exposure.
- Again, LG Chem MJ1 cells have the highest specific energy

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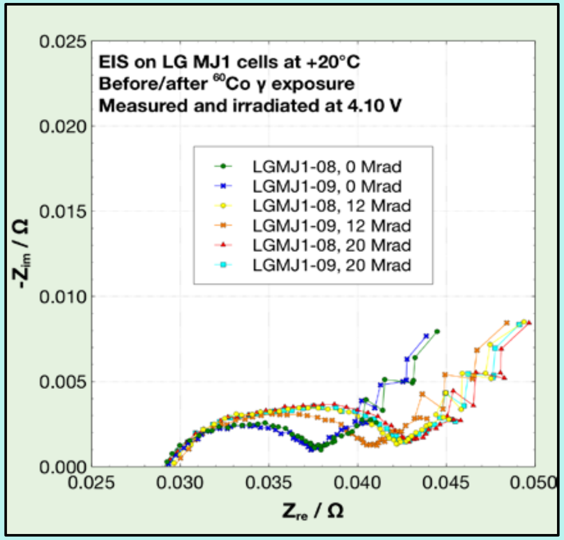
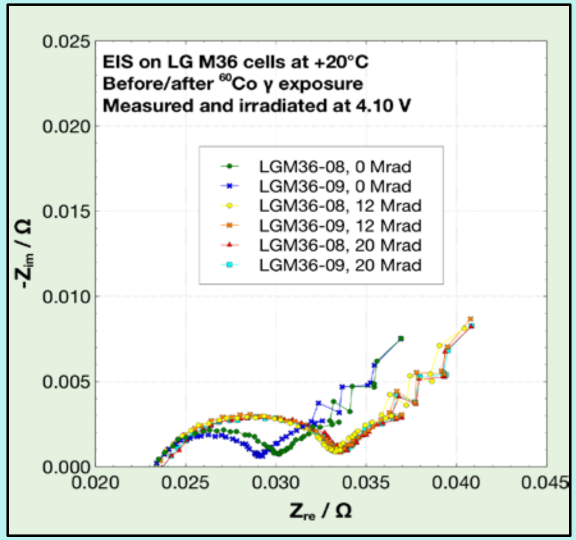
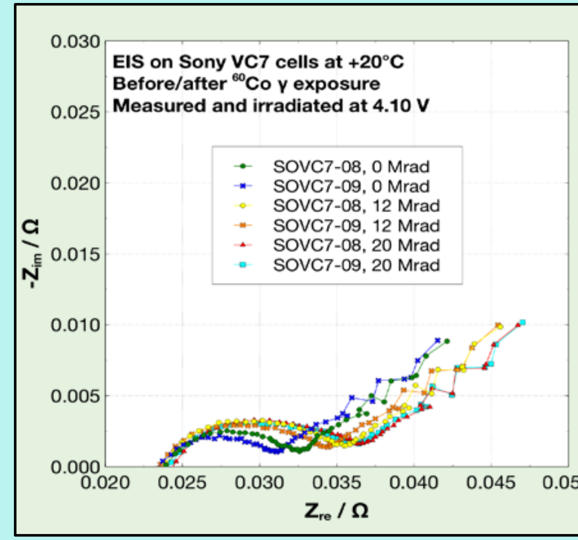
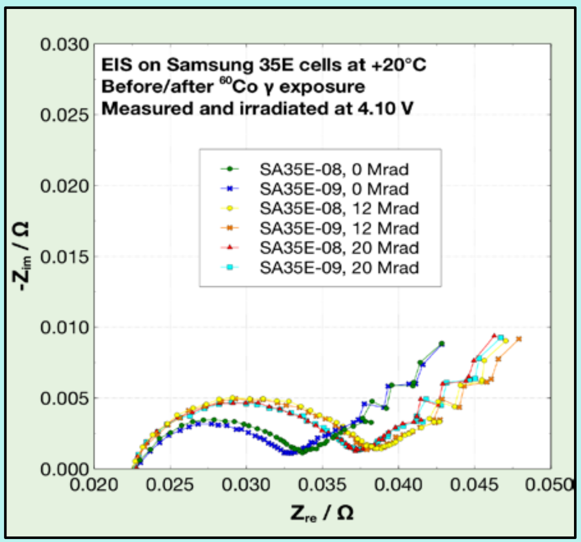
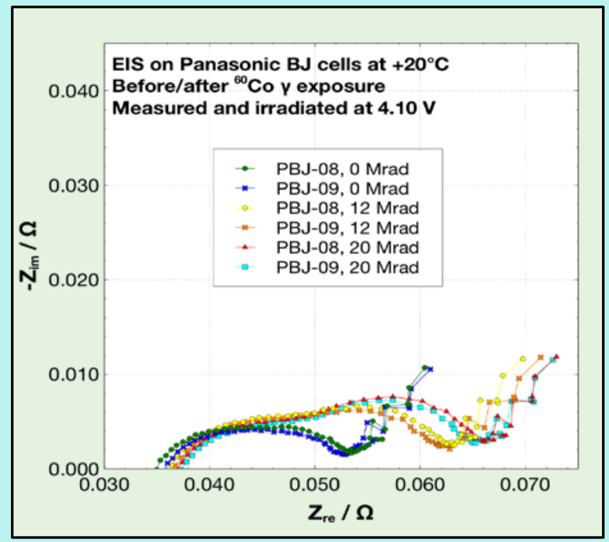
EIS (at 20C) after Radiation (Batch1)







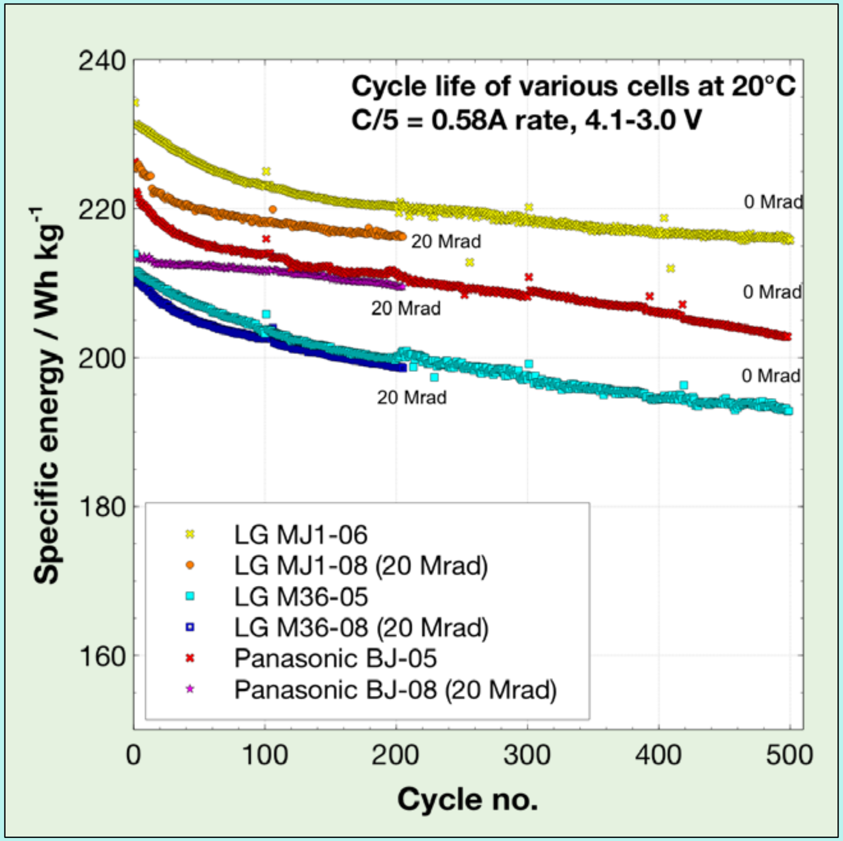




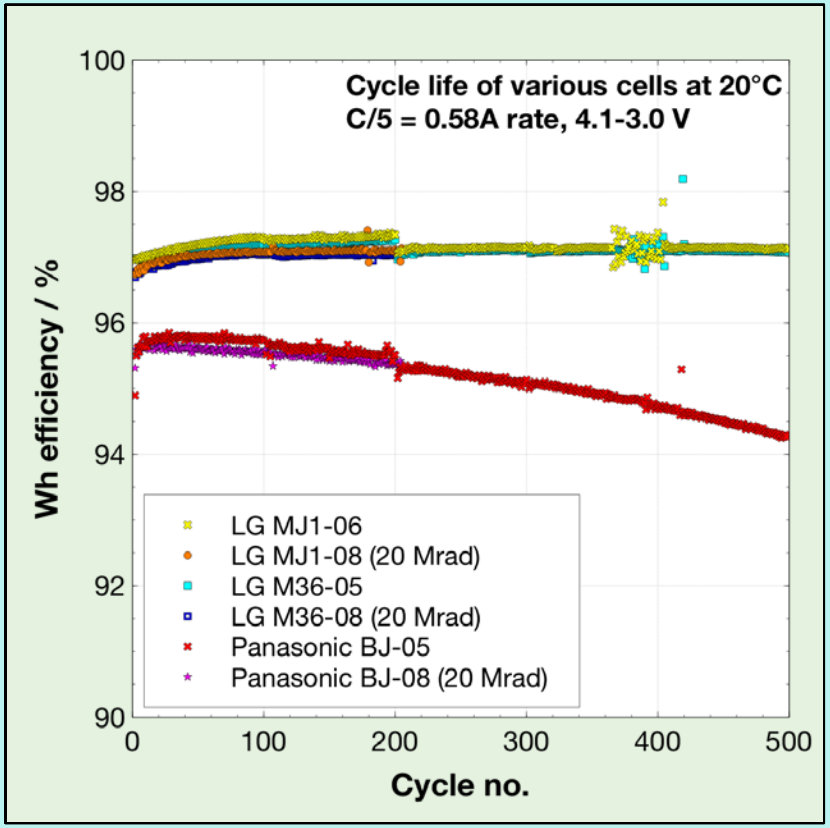
- Only very small increase in series resistance
- Increase in breadth of impedance loop
- Minimal change in Sony VC7 cells and maximum change in Panasonic BJ cells

Cycle life at +20 ºC - Irradiated (20 Mrad) vs. control

Specific Energy, Wh/kg

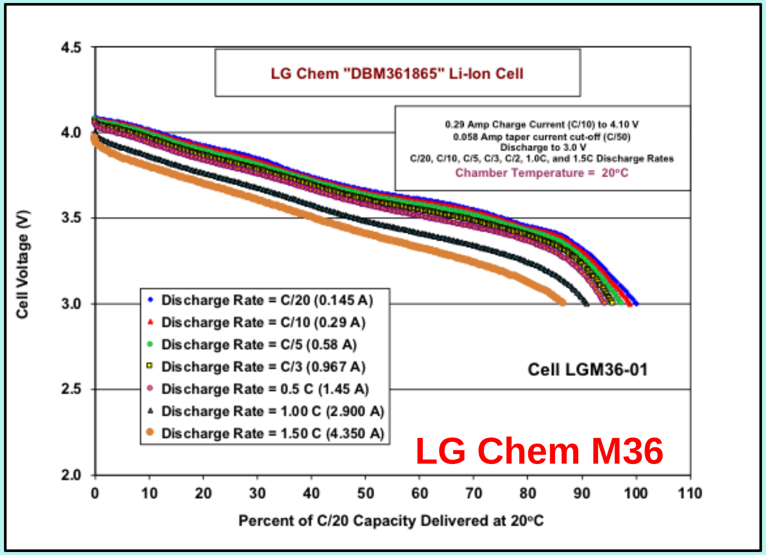


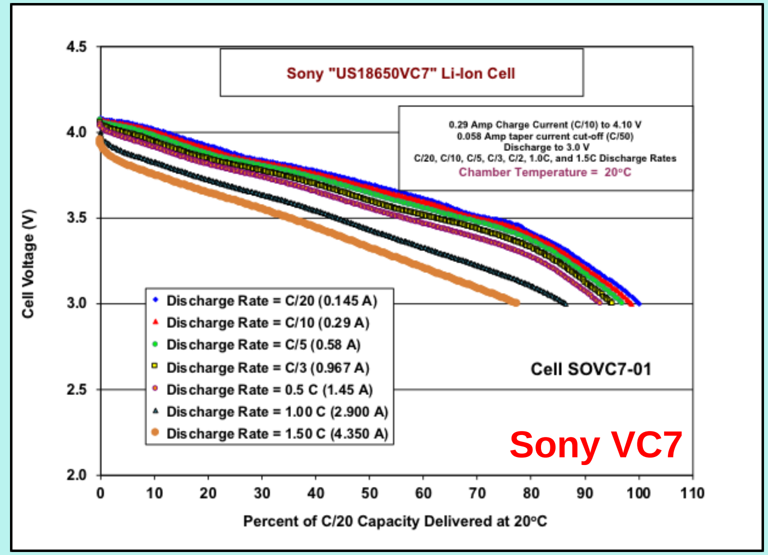
Energy Efficiency

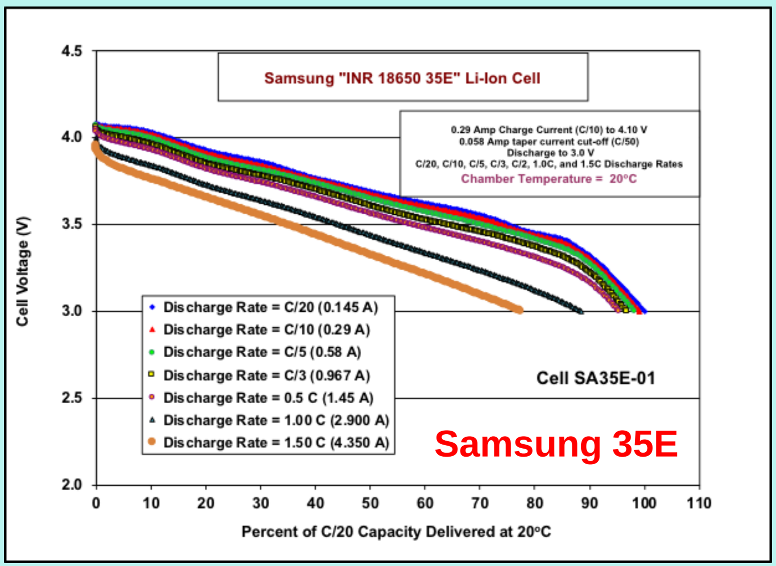


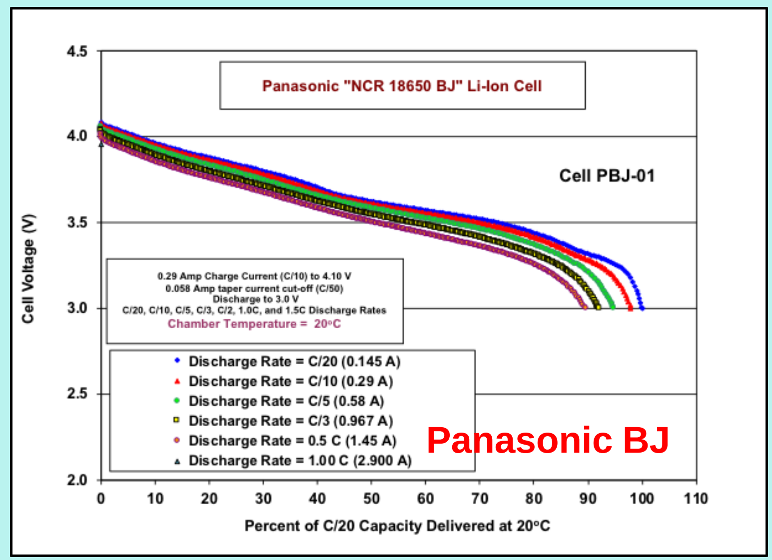
- Radiated cells are cycling well; slightly lower specific energy, but less fade rate.

Discharge rate test at +20 ^{o}C



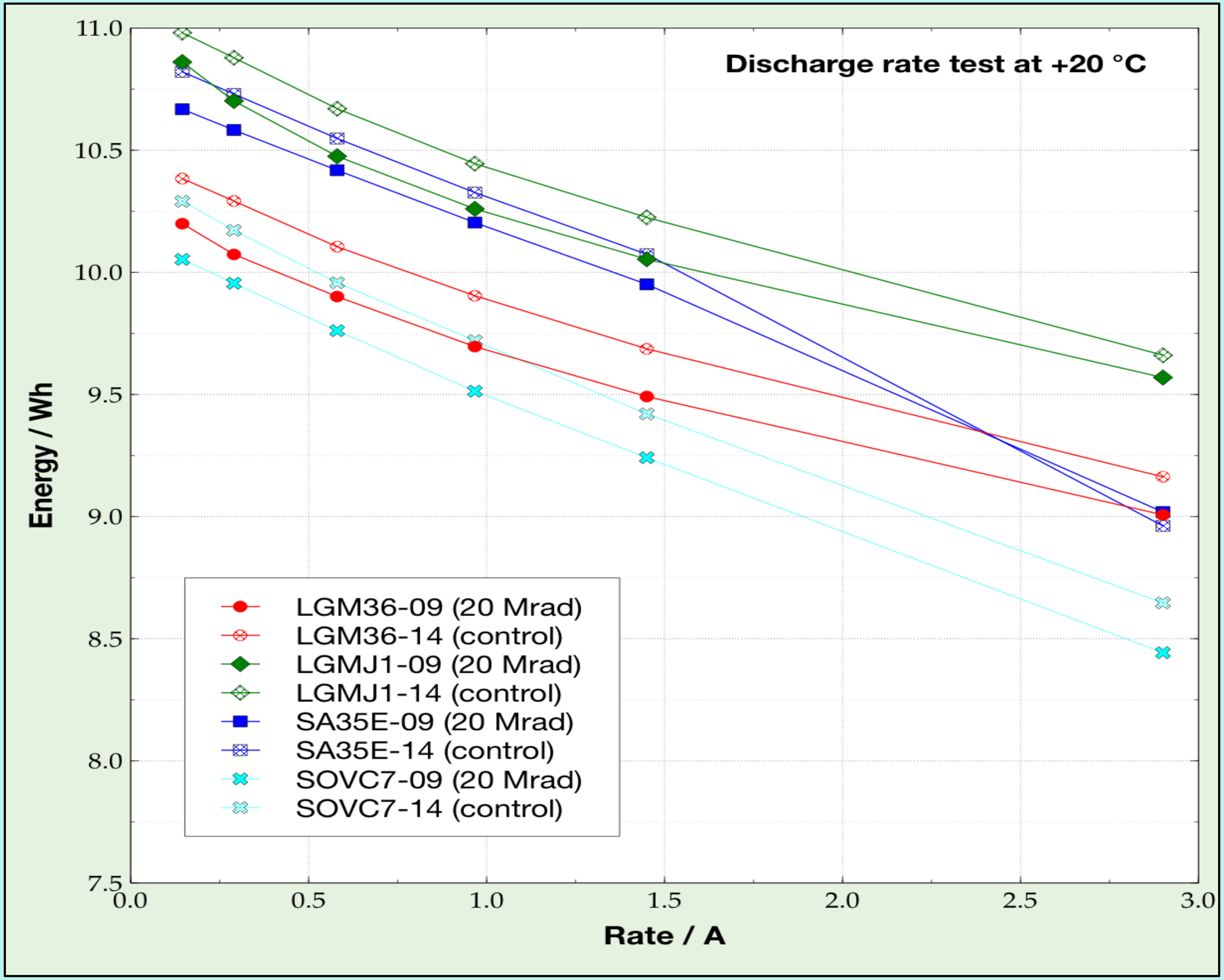






- Excellent rate capability with LG M36 Cells (90% of the capacity, 190 Wh/kg at 1.5C rate

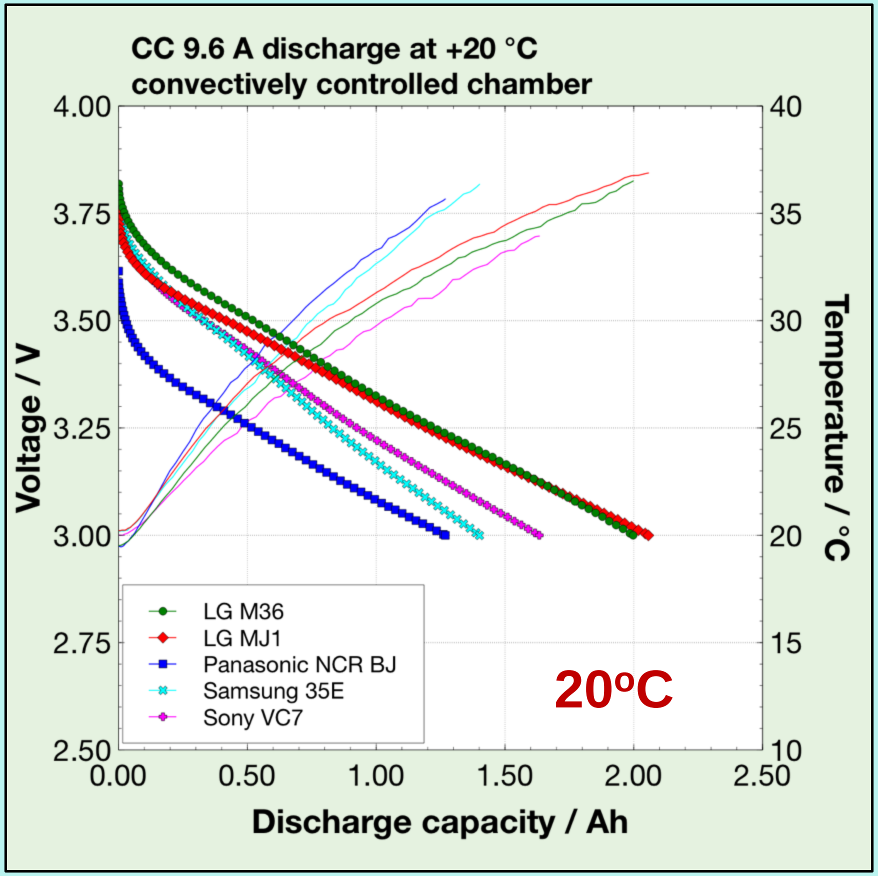
Discharge rate Effect (20 ºC) –Radiated vs Control

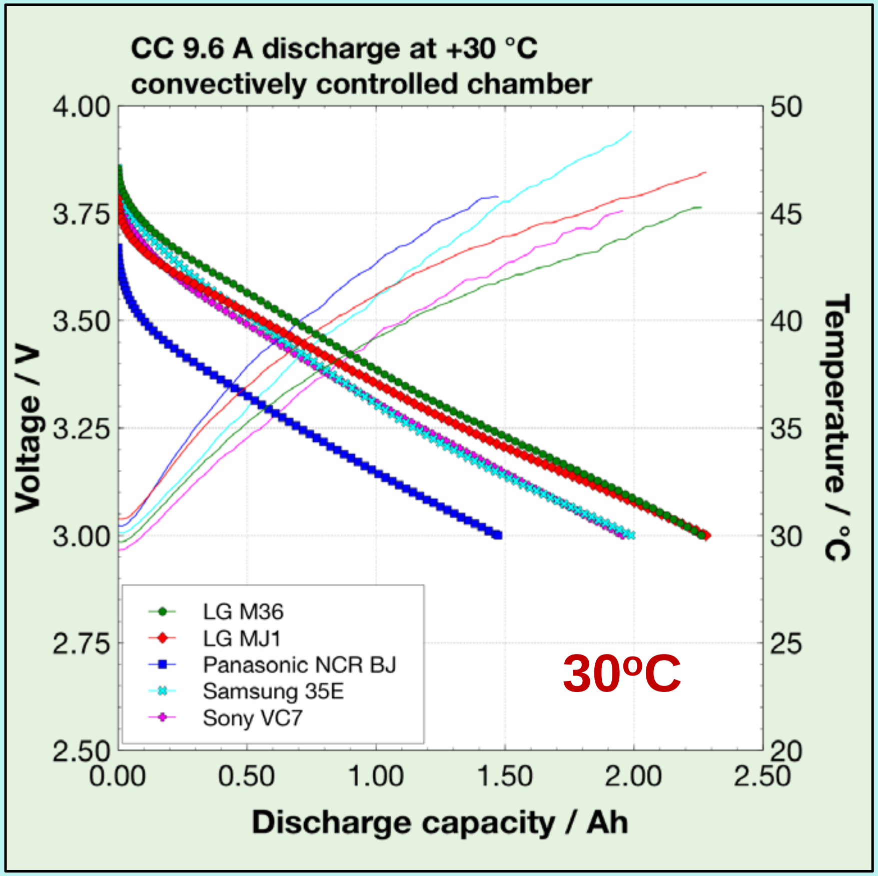


- No change in the rate capability after radiation exposure (20 Mrad)

High Rate Testing (9.6 A)

Discharge profiles at 9.6 A - Comparison of cells

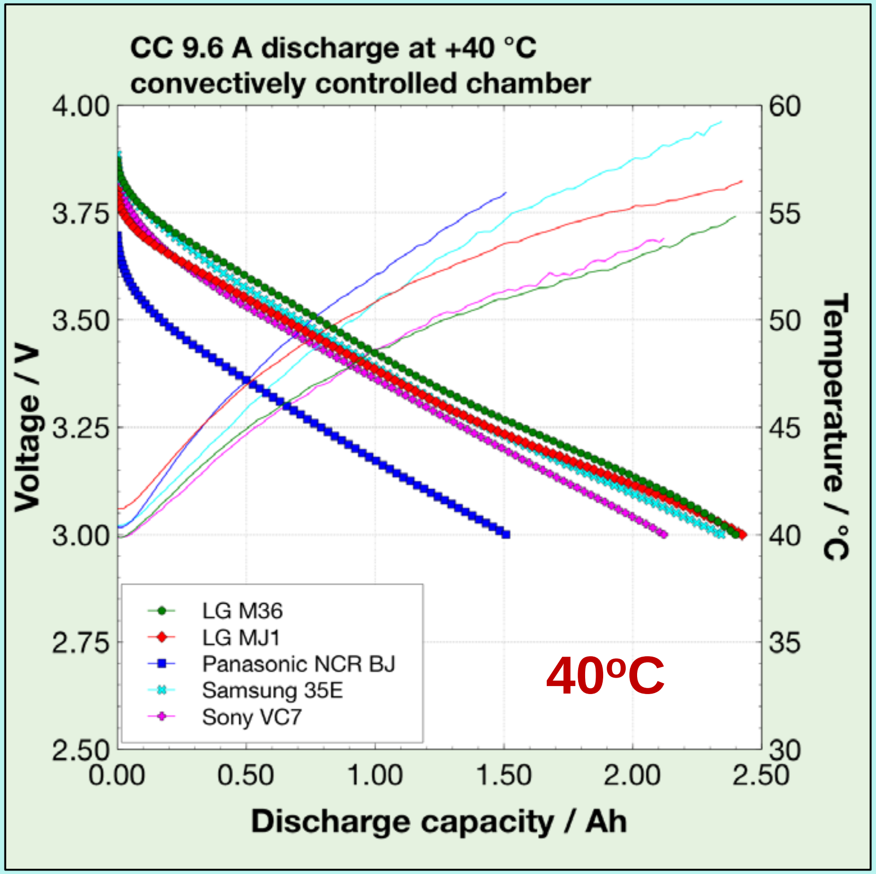


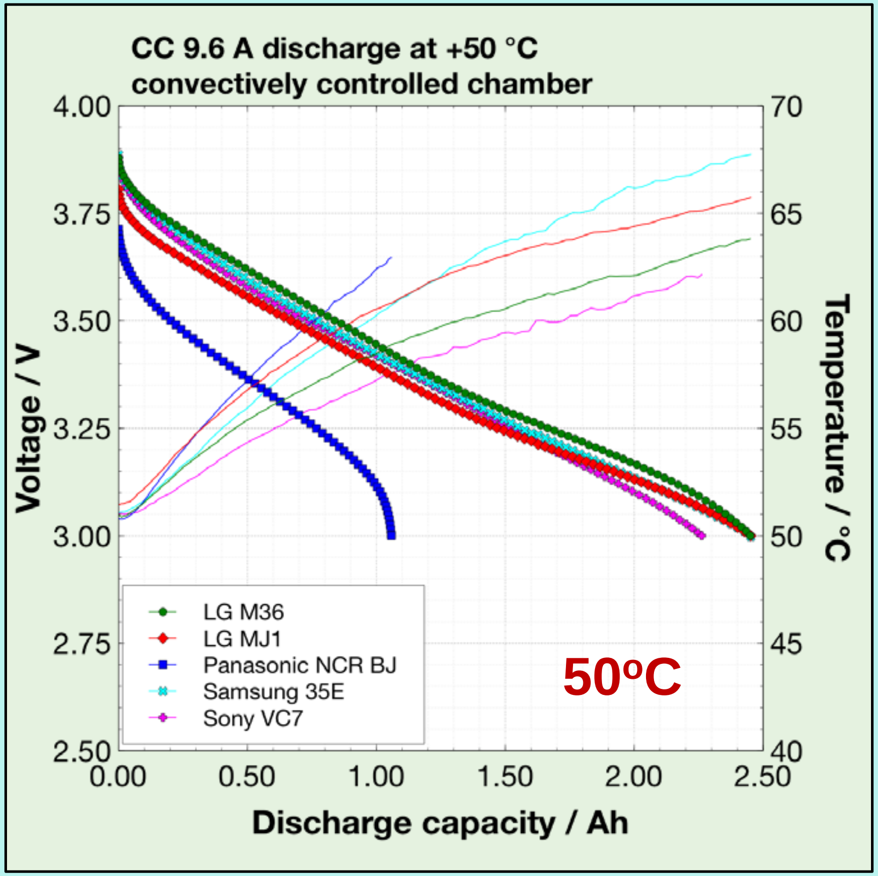


- Considerable cell warm up in a convectively controlled chamber

High Rate Testing (9.6 A)

Discharge profiles at 9.6 A - Comparison of cells





- Considerable cell warm up in a convectively controlled chamber

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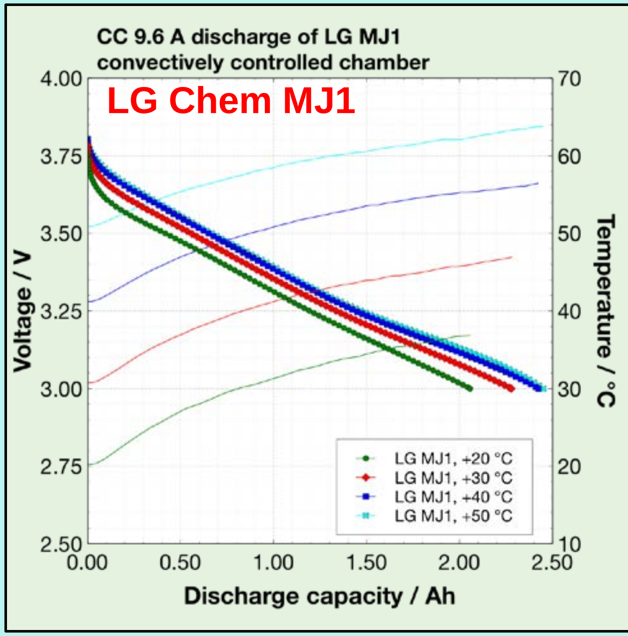
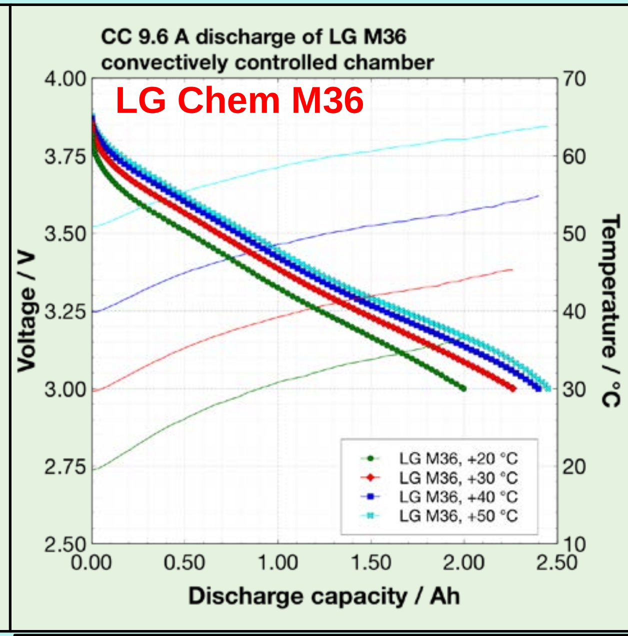
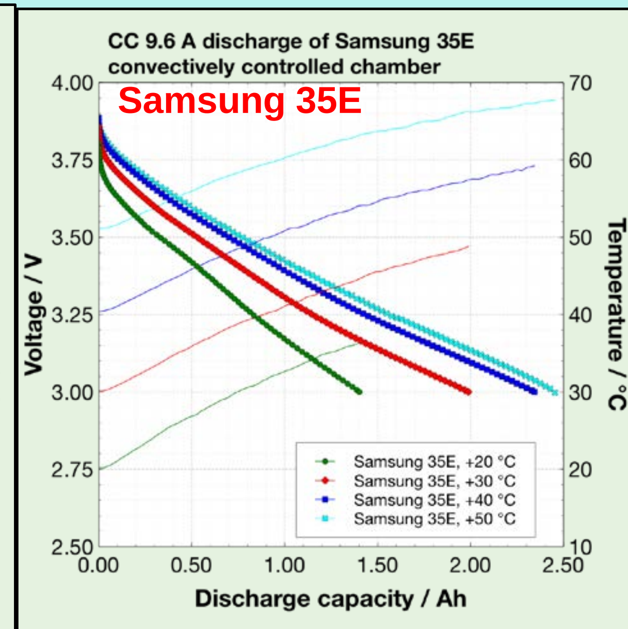
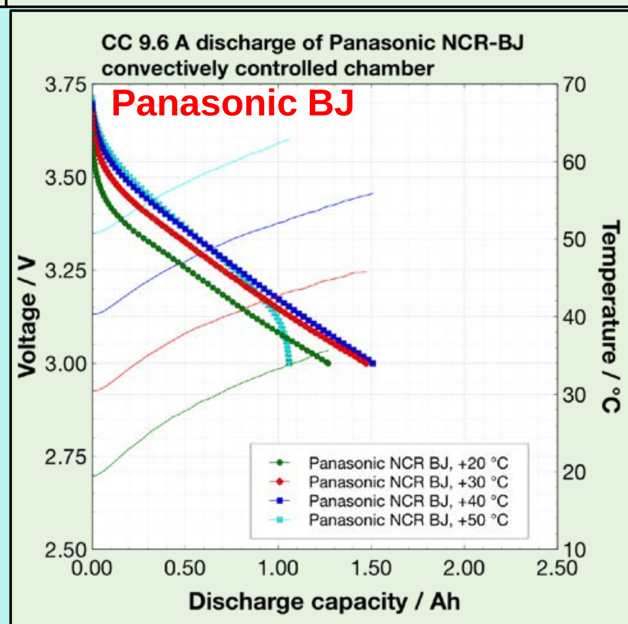
High Rate Testing (9.6 A)

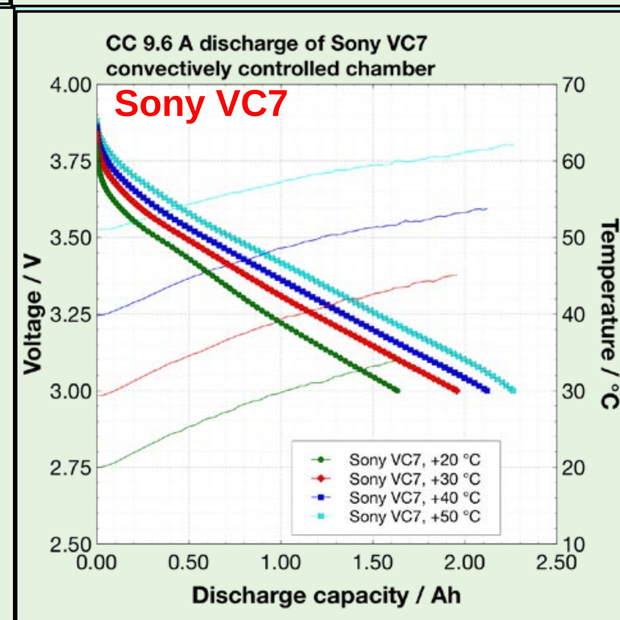






- LG Chem cells provide high power densities at 20-50C, while other chemistries provide only at warm temperatures.





Conclusions and Future Plans

- **Conclusions**
  - Recent Li-ion 18650 COTS cells provide high specific energy and high power density, good cycle life and resilience to high-intensity radiation environments.
  - LG Chem MJ1 cells show impressive performance in all the categories.
- **Future Plans**
  - Testing of multi-cell modules (8S5P) for cell divergence during cycling and storage
  - Capacity retention during (cruise) at different States of Charge
  - Post-radiation performance (storage and cycling)
  - Destructive Physical Analysis of irradiated cells for an understanding of radiation effects

Acknowledgements

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