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

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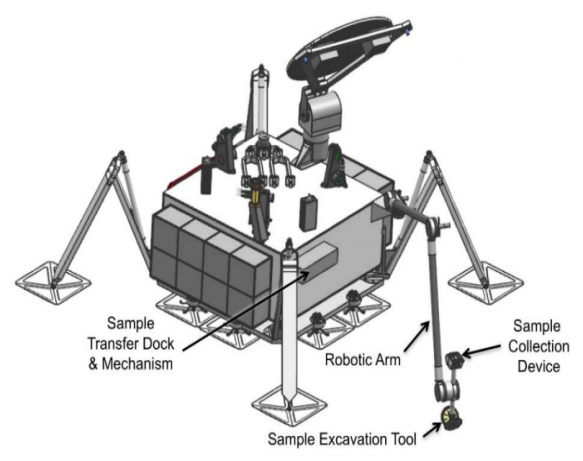
Background and Relevance

- Under an NESC-funded project NASA (JSC –Darcy et al) is developing thermal propagation -resistant high power/voltage batteries, demonstrating in 2 kWh battery module building blocks safe operation at 3C discharge rate, 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 a surface mission to Europa, the Icy moon of Jupiter, with the expectation of detecting 'extant' life underneath the icy crust.
  - Though the Lander is powered by a primary battery (Li-CF_X), the Carrier (Cruise Stage) and the Descent Stage elements will have high energy Li-ion batteries (in conjunction with solar array for the Cruise stage and exclusively for the Descent Stage)

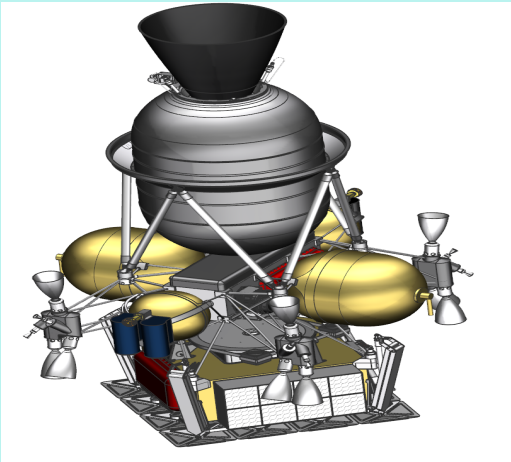
Europa Lander Descent Stage

Mission Requirement

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



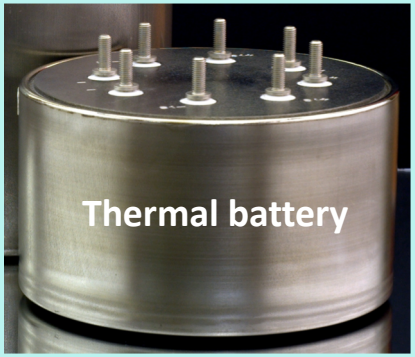
Notional Lander Design

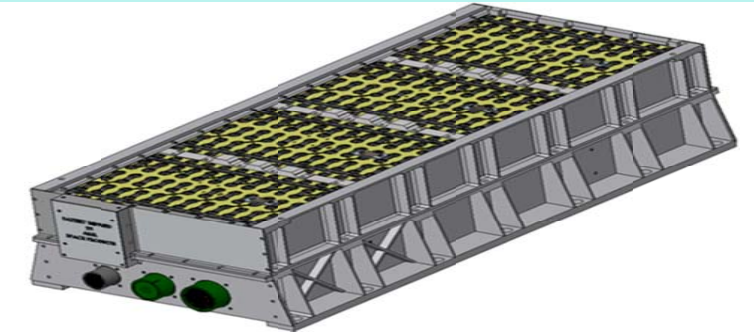


Notional Descent Stage Design

Original Battery Design Concept

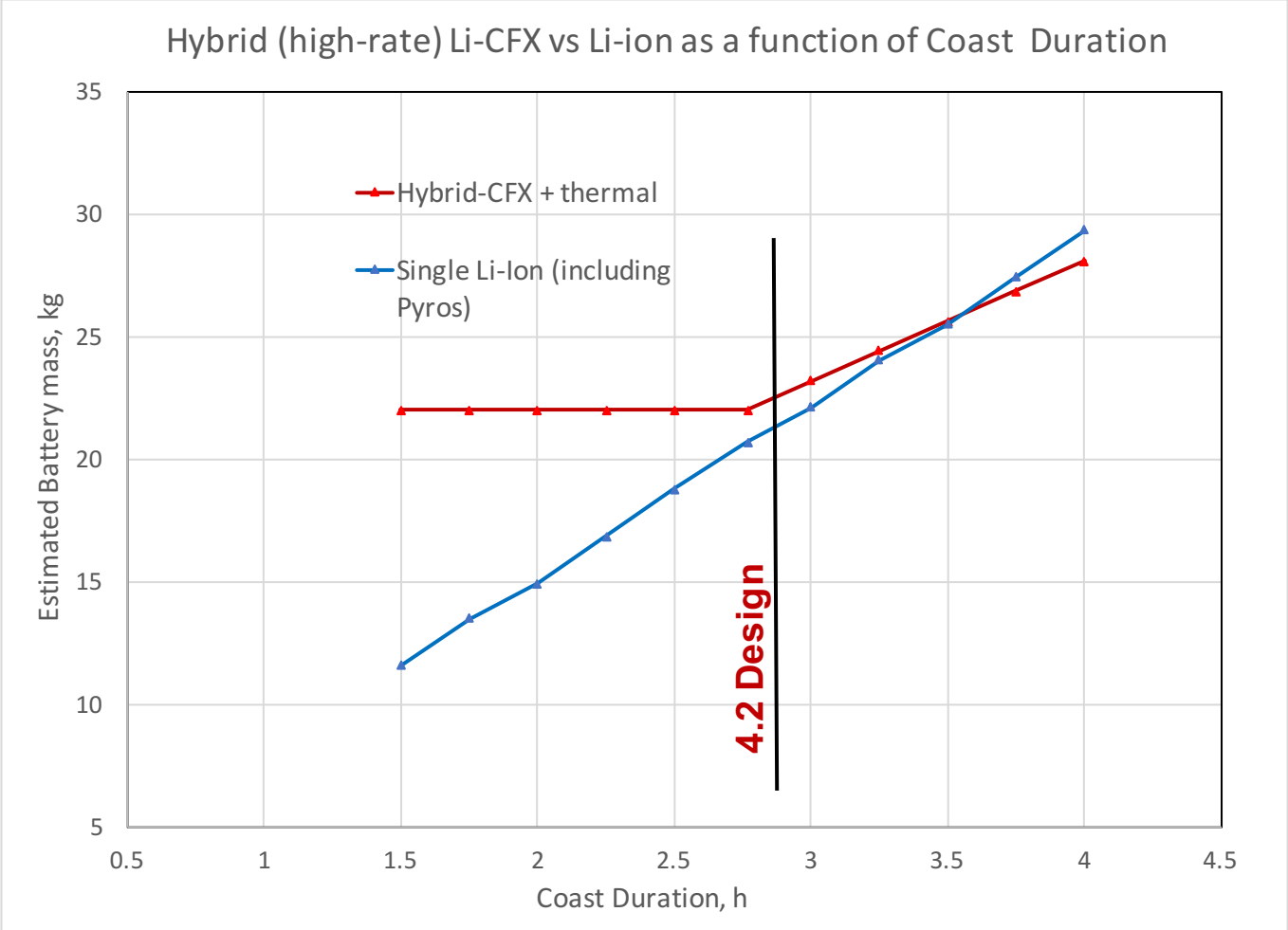
- Primary Batteries and thermal batteries
- Primary Battery through 180 min
  - $Li/CF_x–MnO_2$ 12s12p (144 D cells)
  - Power: 790 W; Energy: 2237 Wh
- Thermal Batteries for high power (3)
  - MSL Pyro batteries
  - Power: 3375 W; Energy: 138 Wh
  - Duration: 5 min
- Current Baseline
  - High Energy/Power Li-ion battery
  - 8S48P





Pre-Decisional Information — For Planning and Discussion Purposes Only

A Single Li-ion Battery vs Hybrid Li-CFX primary + Pyro 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

Chemistries

Five 18650 Cell Chemistries being tested

- LG MJ1,
- LG M36,
- Samsung 35E,
- Sony VC7,
- Panasonic BJ

Latest High Power/Energy 18650 Cell Designs

5

- Specific Energy Range 259-276 Wh/kg
- Energy Density Range 704-735 Wh/L

Panasonic NCR18650GA

LG INR18650 MJ1

Samsung INR18650-35E

Sony US18650VC7

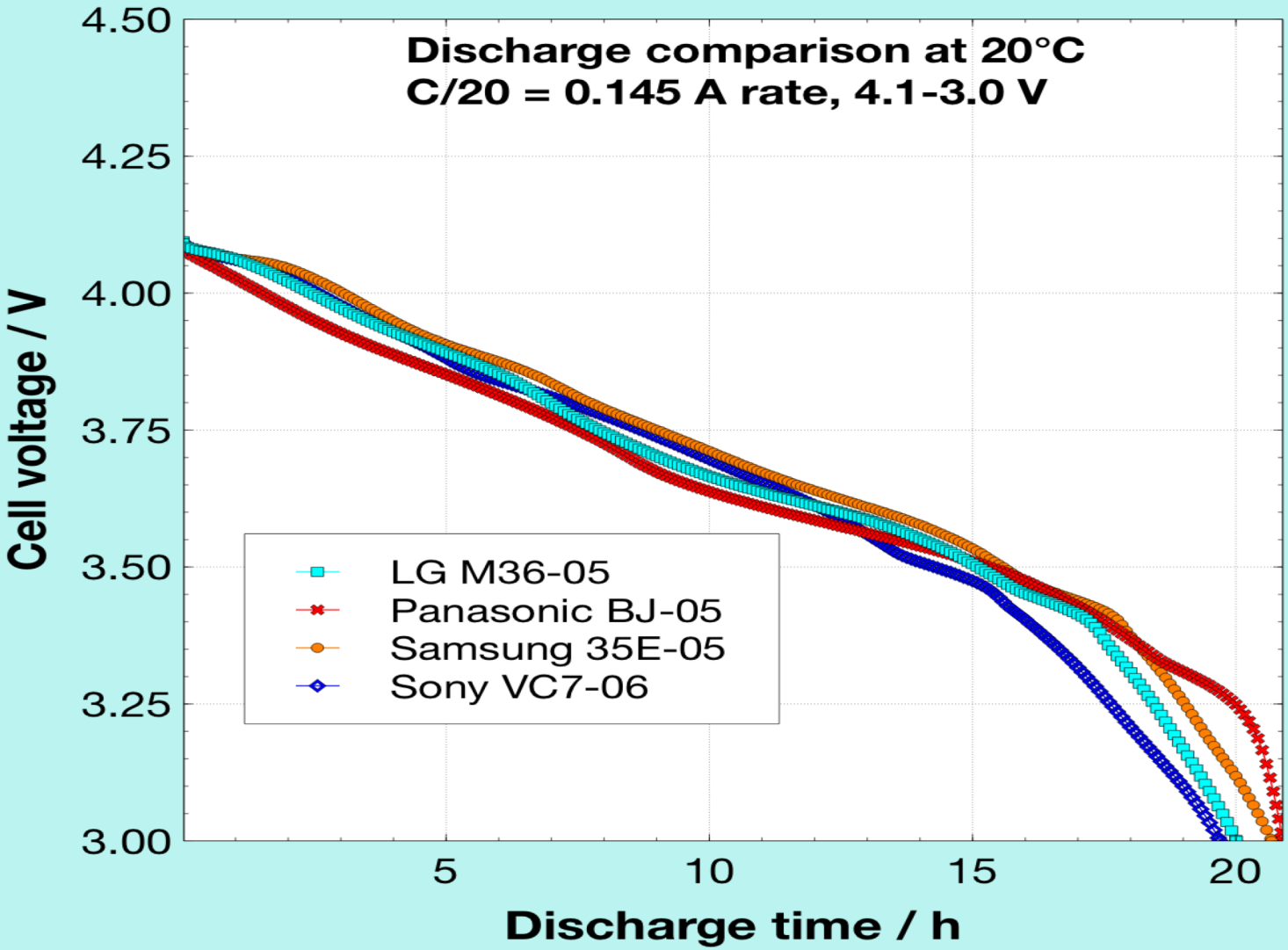
C/10 at RT	Panasonic NCR GA	Samsung 3.5E	Sony VC7	LG MJ1
Discharge Capacity (Ah)	3.34	3.49	3.5	3.41
Discharge Energy (Wh)	12.16	12.7	12.72	12.46
DC Internal Resistance (mohm)	38	35	31	33
Average Mass (g)	47	46	47.4	46.9
Average Volume (L)	0.0173	0.0173	0.0173	0.0173
Specific Energy (Wh/kg)	259	276	269	266
Energy Density (Wh/L)	704	733	735	720

18650 Cell Chemistries

Long-form name	Chemical abbreviation	Name format 1	Name format 2	Name format 3
Lithium manganese oxide	LiMn2O4	IMR	LMO	Li-manganese
Lithium manganese nickel	LiNiMnCoO2	INR	NMC	---
Lithium nickel cobalt aluminum oxide	LiNiCoAlO2	---	NCA	Li-aluminum
Lithium nickel cobalt oxide	LiNiCoO2	---	NCO	---
Lithium cobalt oxide	LiCoO2	ICR	LCO	Li-cobalt
Lithium iron phosphate	LiFePO4	IFR	LFP	Li-phosphate

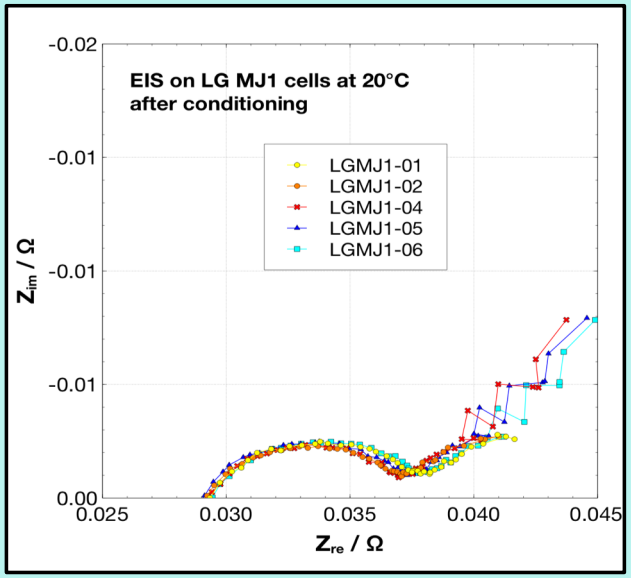
- Different cathodes, carbon anodes and may be electrolyte
- Planning to perform tear-down analysis for gathering information on these chemistries.

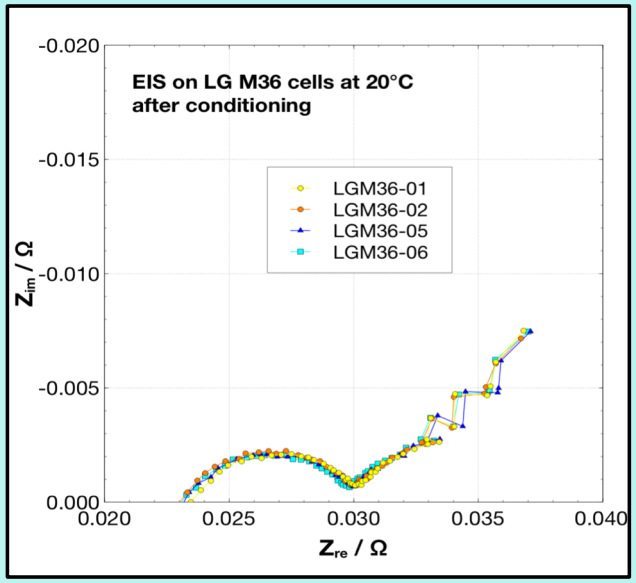
Comparison of Discharge profiles at +20 ºC

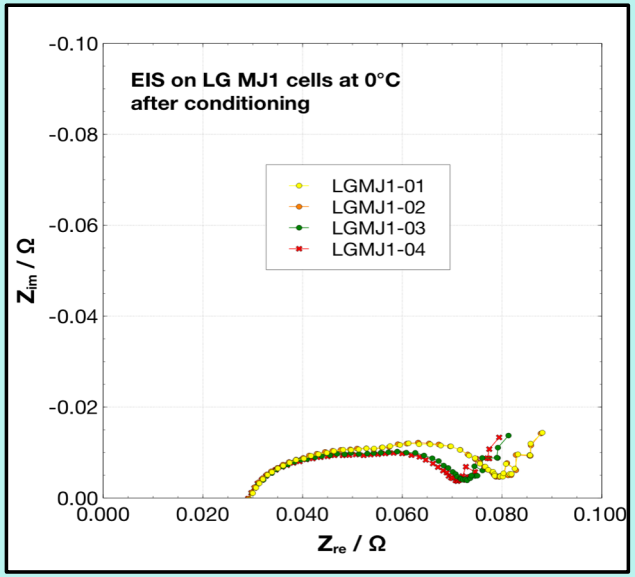


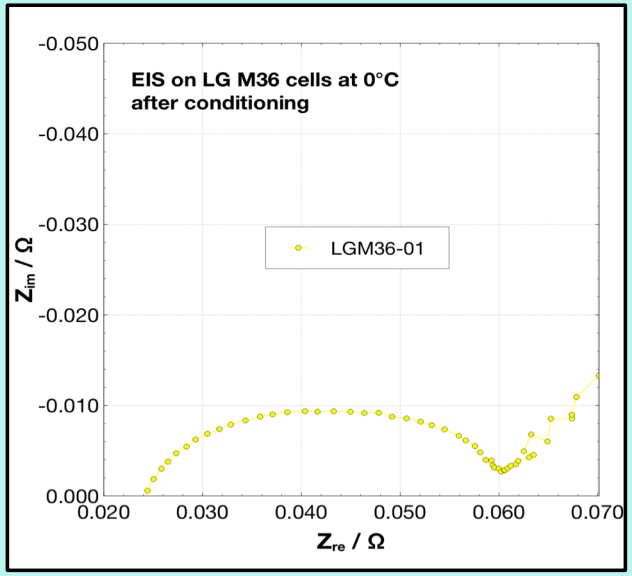
- PNs LG “INR18650MJ1” and Samsung “INR1865035E” suggest NMC cathode
- Panasonic BJ unique in lacking initial 4.10 – 4.05 V plateau (NCA?)

EIS of LG MJ1 and M36 cells after conditioning



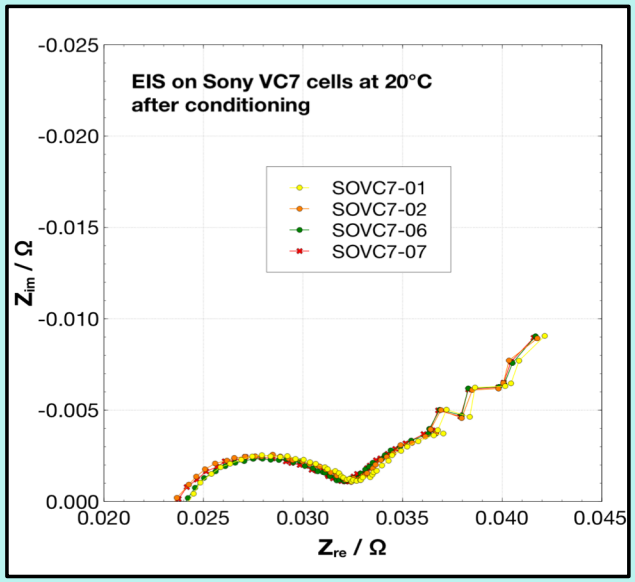


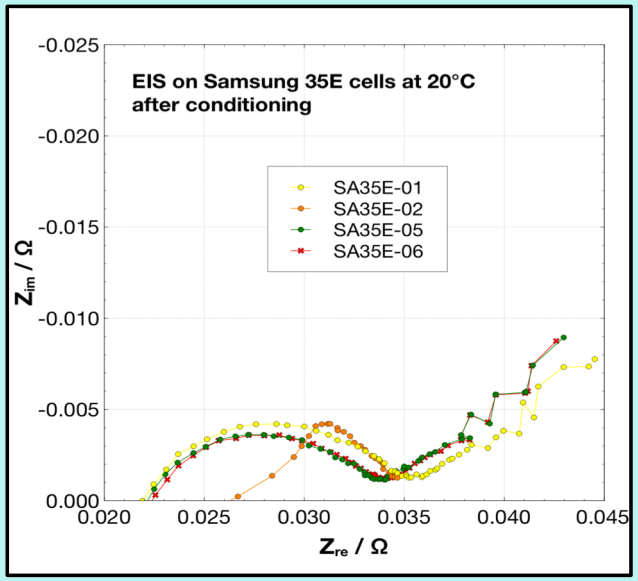


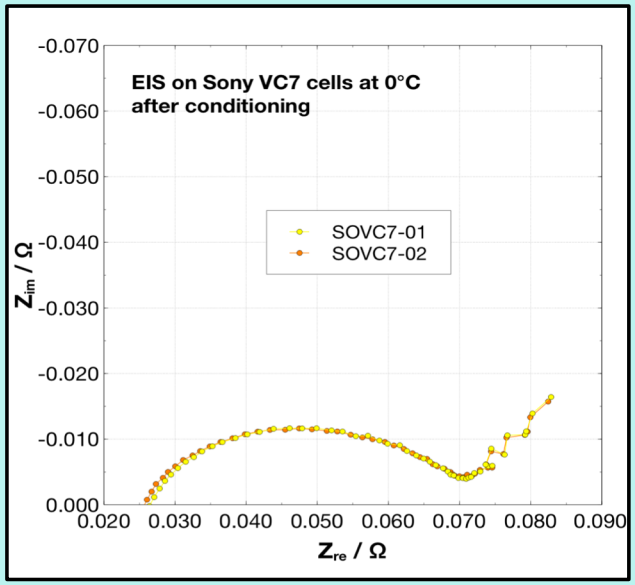


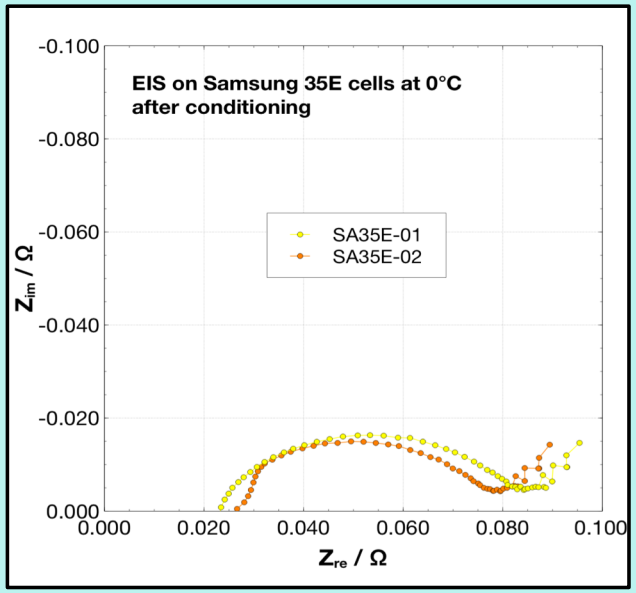
- Both LG MJ1 cells and M36 cells have very good cell-to-cell reproducibility in EIS spectra at +20°C
- Some variance in 0°C spectra between test batches

EIS of Sony VC7 and Samsung 35Ecells after conditioning



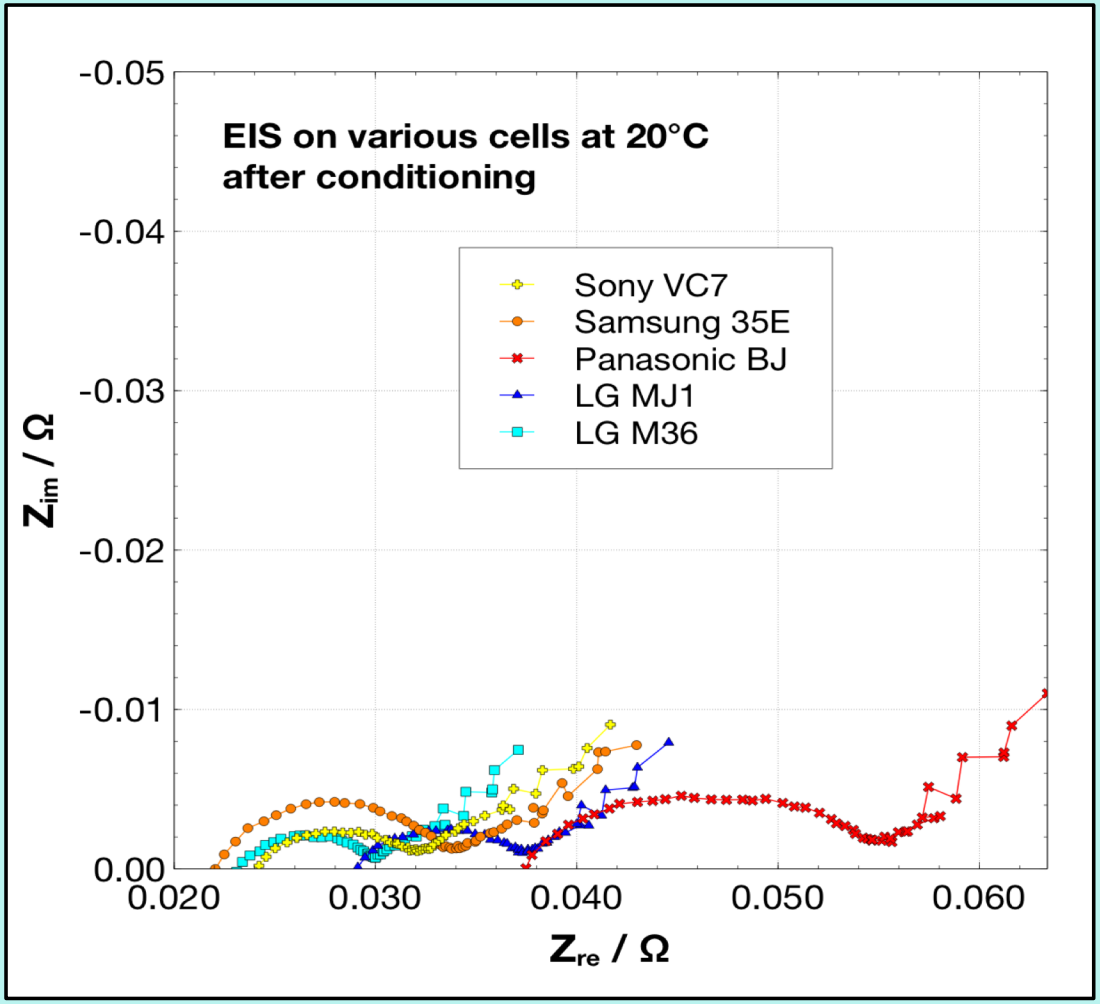






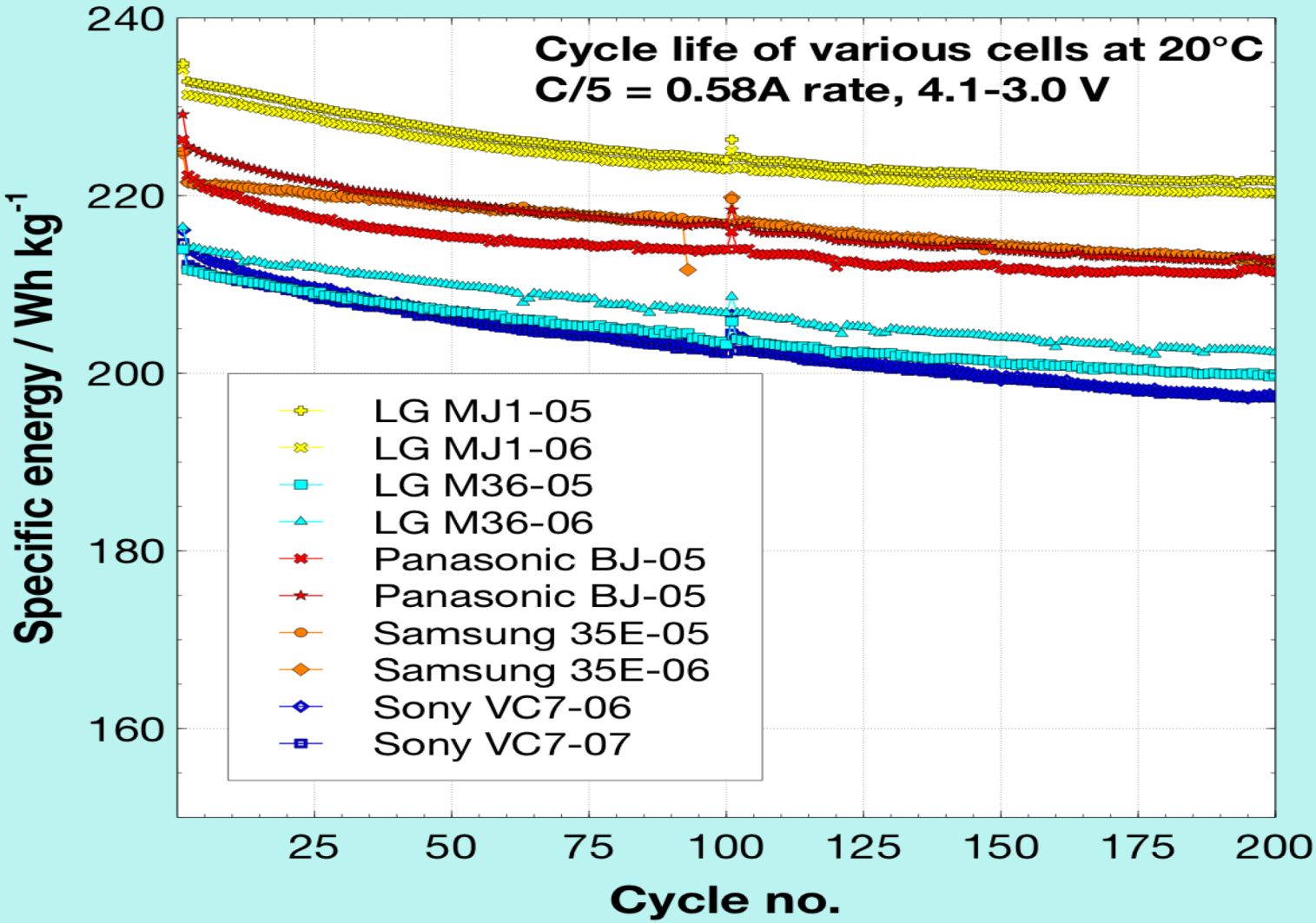
- Sony VC7 had very consistent spectra at both temperatures.
- For Samsung cells, one cells was outlier at both temperatures, despite changing connections and repeating testing.
- Less consistent overall than other designs.

Comparison of EIS of different cells +20 ºC



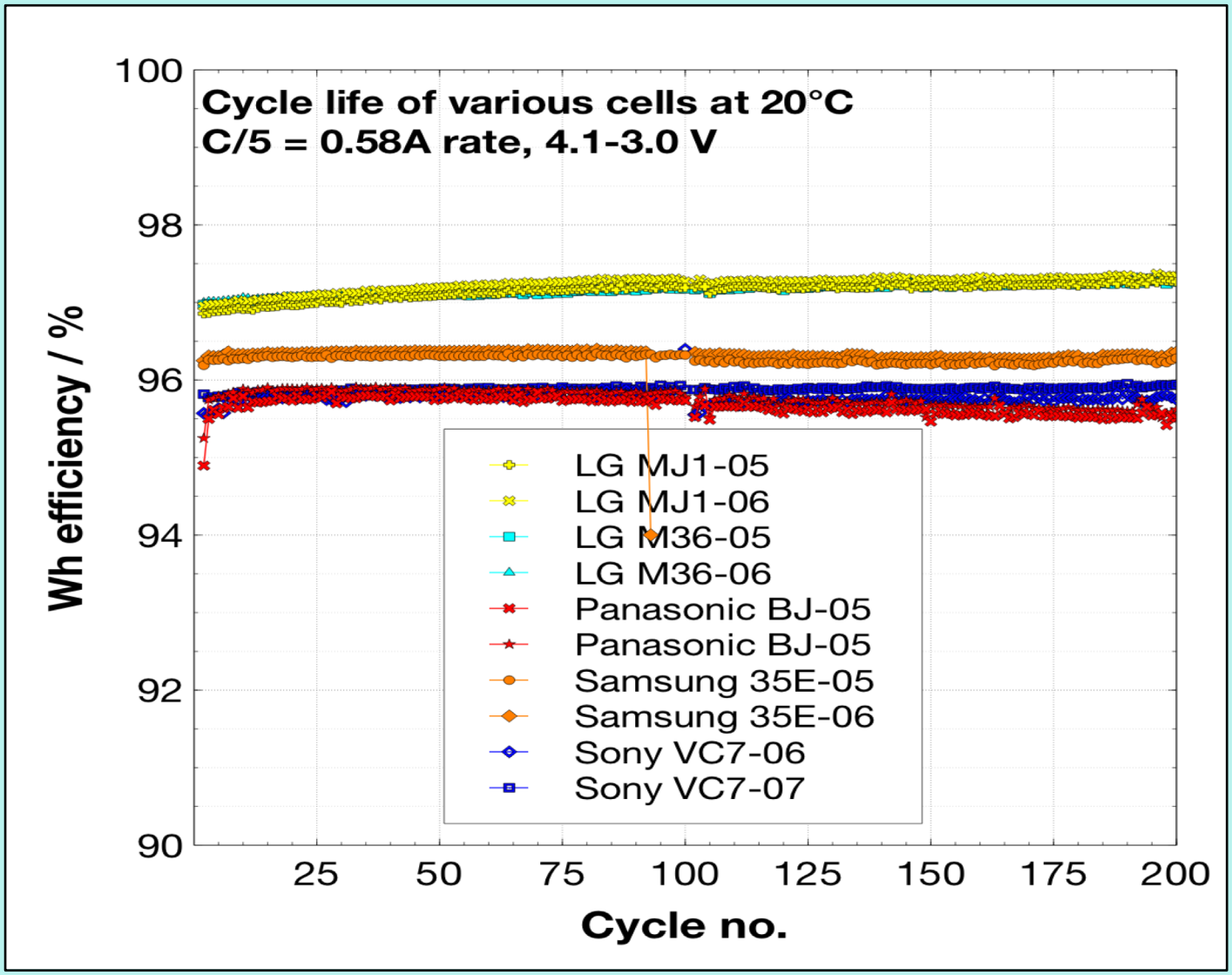
- Panasonic BJ cells appear to have greater film resistance, possibly due to suspected low-temperature optimized electrolyte
- LG M36 shows narrowest loop
- Series resistance values may also be affected by leads and/or small temperature gradients during testing

Comparison of Cycle life at +20 ºC



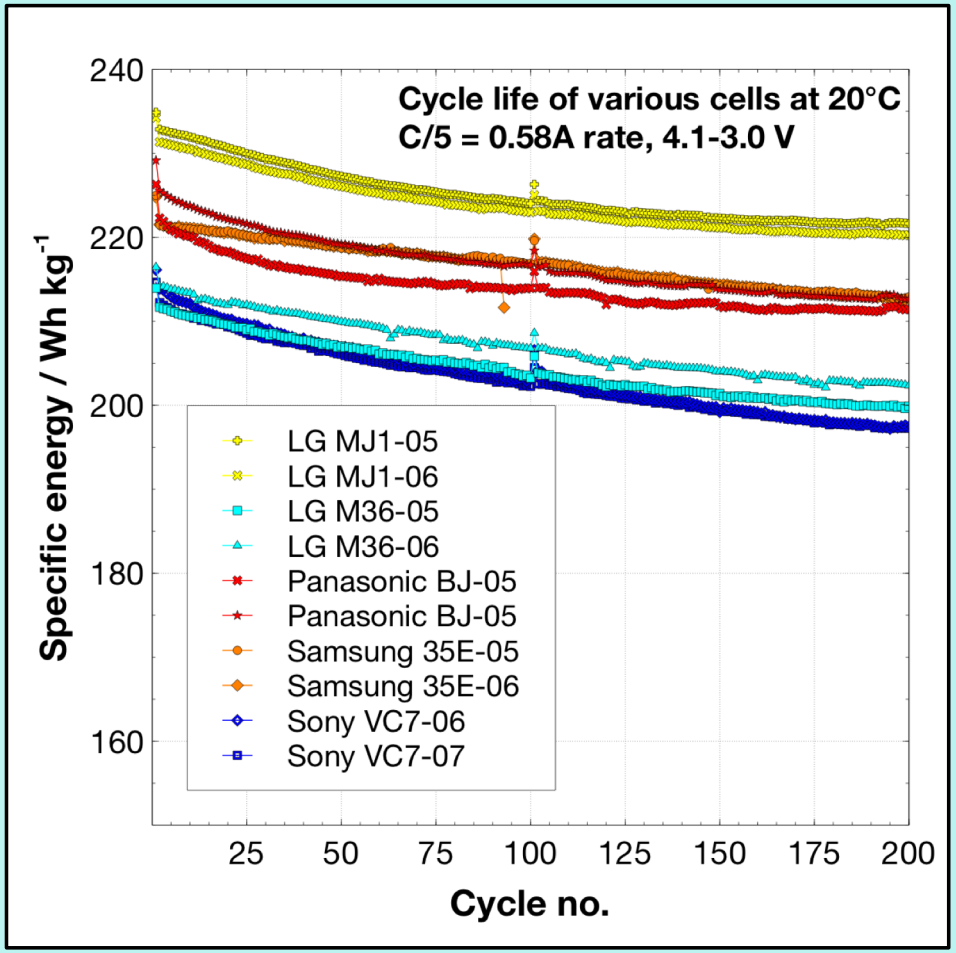
- All the cells display good capacity retention during cycling at 25ºC.
- LG cells have ~220 Wh/kg after 200 cycles.

Comparison of Cycle life at +20 ºC



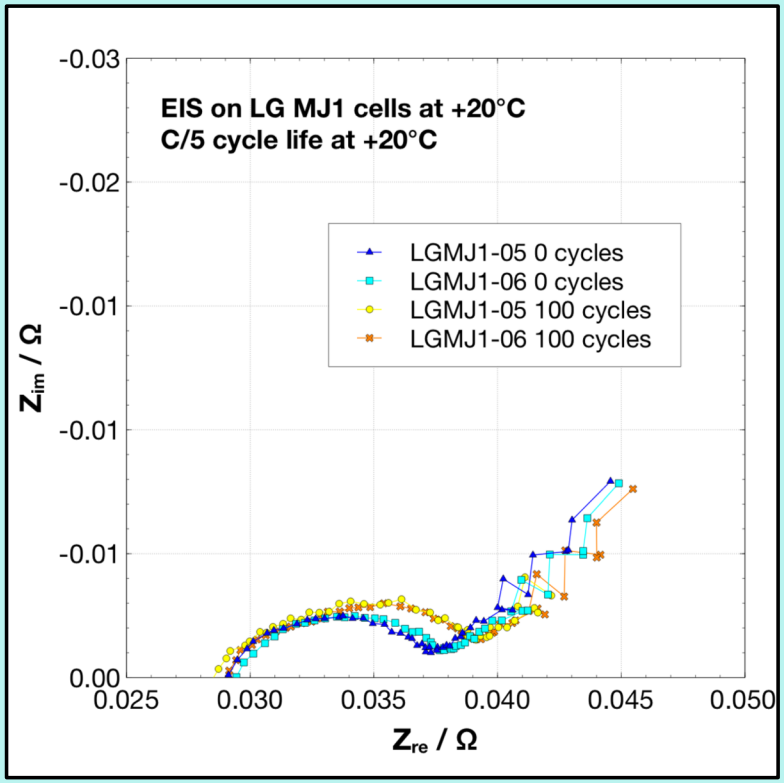
- High (>95%) Wh efficiency at C/5 in all the cells.
- LG cells show the highest efficiency of ~97%.

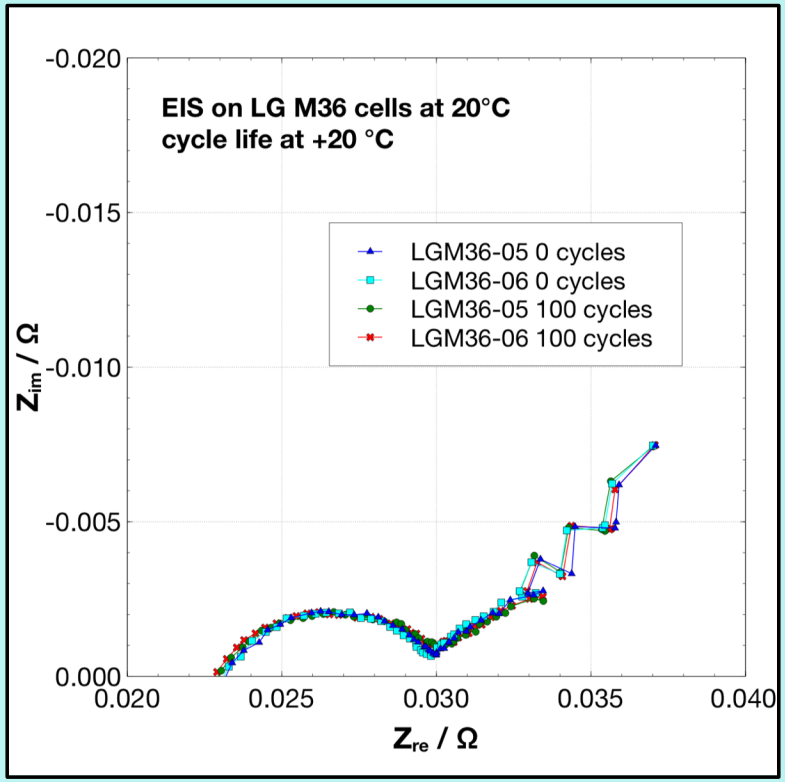
Cycle life at +20 °C Comparison of cells



Cell Type	Energy fade rate (mWh/kg/cycle, average of 2 cells)
LG MJ1	14
LG M36	29
Panasonic NCR-BJ	12
Samsung 35E	32
Sony VC7	47

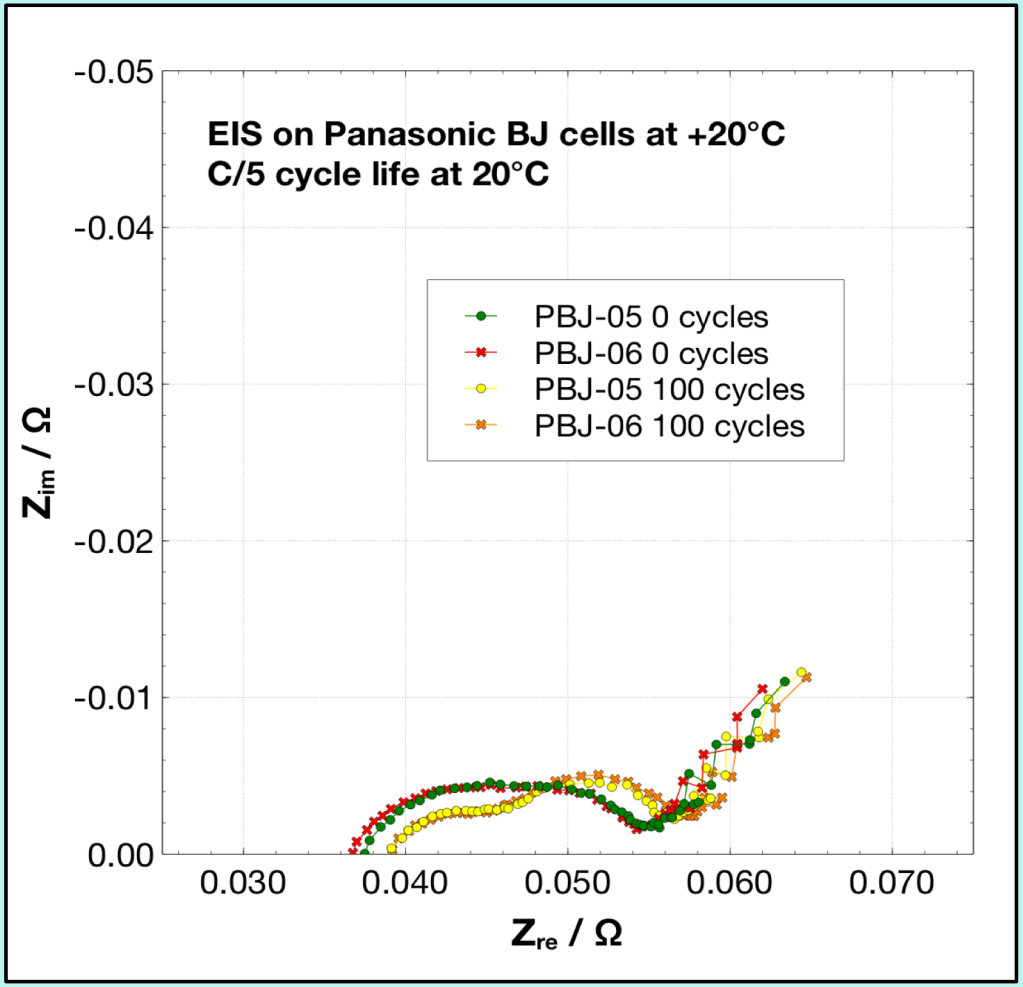
EIS vs. cycle life at +20 ºC - LG MJ1 and LG M36





- LG MJ1 show modest film impedance growth over 100 cycles at +20 ºC
- LG M36 cells show no difference in impedance spectrum

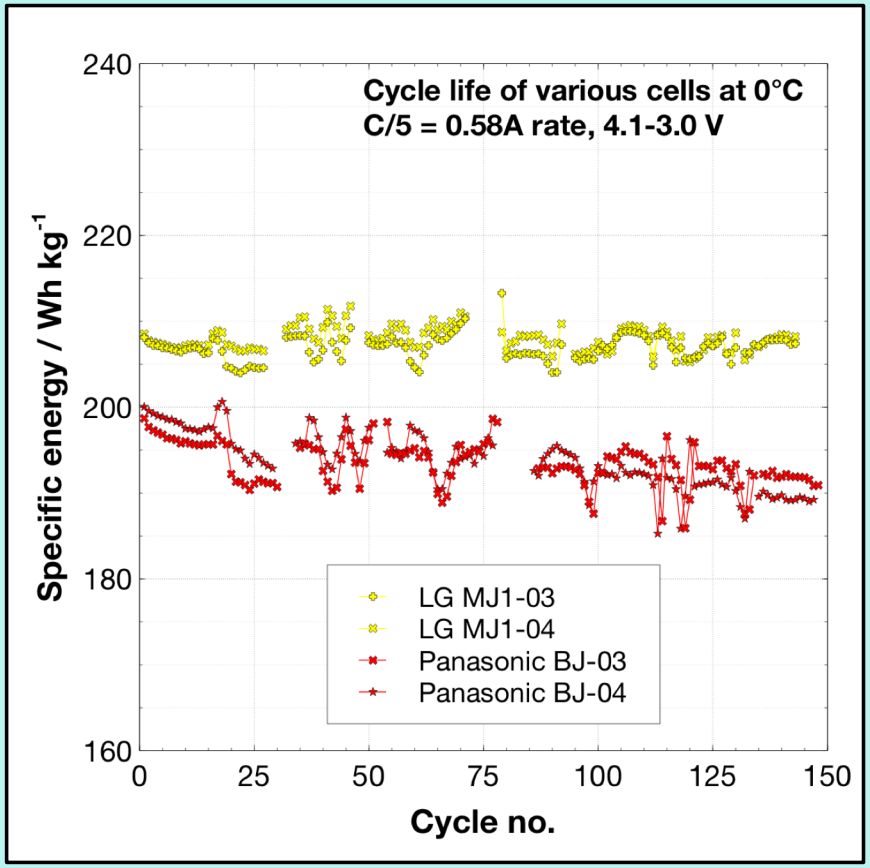
EIS vs. cycle life at +20 ºC Panasonic BJ

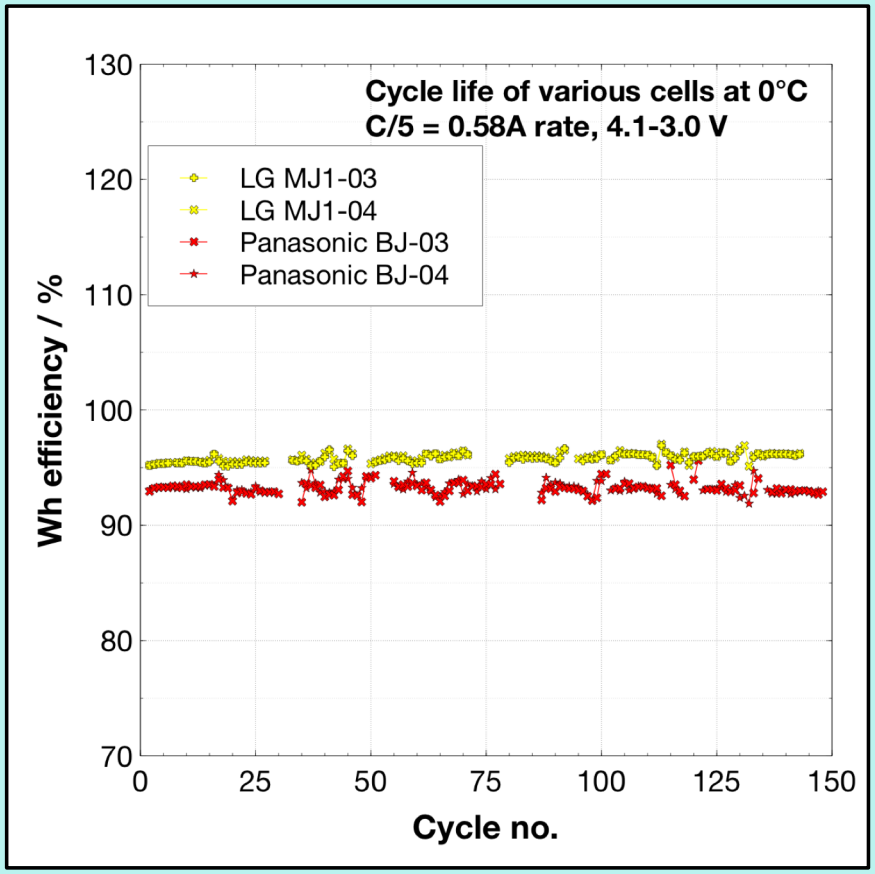


- Panasonic BJ spectrum suggests some modification of surface films over 100 cycles at +20 ºC
- EIS analysis of other cell types after cycling still in progress

Cycle life test at 0 °C - Comparison of cells

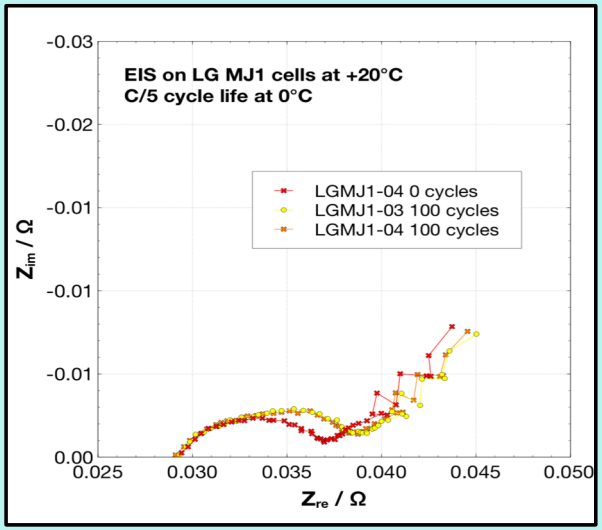
Cycle life at C/5 rate (0.58 A), 4.10 – 3.00 V

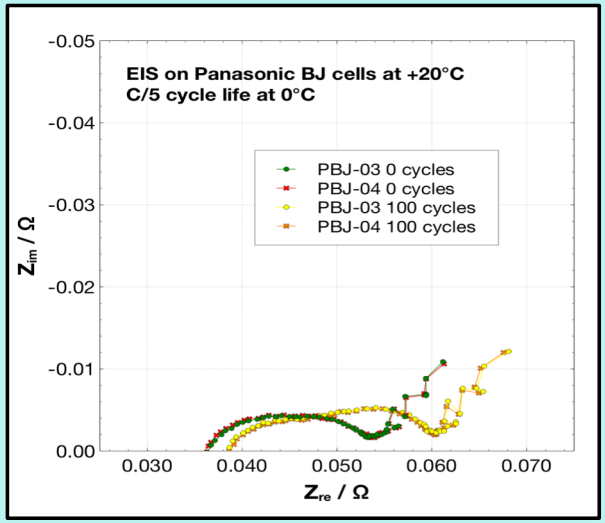


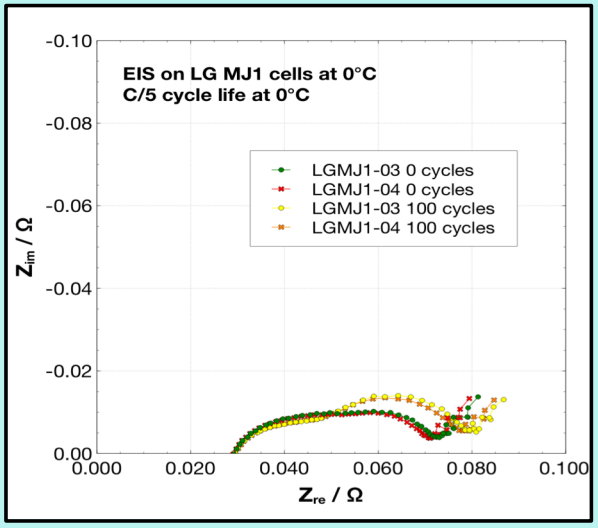


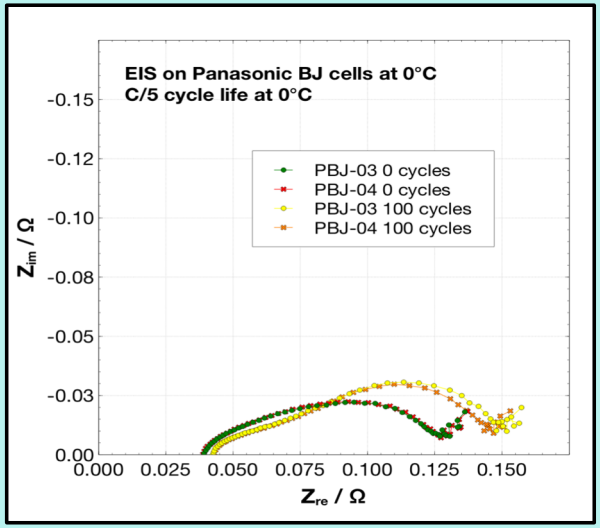
- Capacity fade is improved during low temperature cycling.
- Fluctuations are due to poor temperature control by the test chamber.
- Wh efficiency is still high at 0 °C (95% for LG Chem cells)

EIS at 25 °C and 0 °C vs. cycle life at 0 °C - LG MJ1 and Panasonic BJ





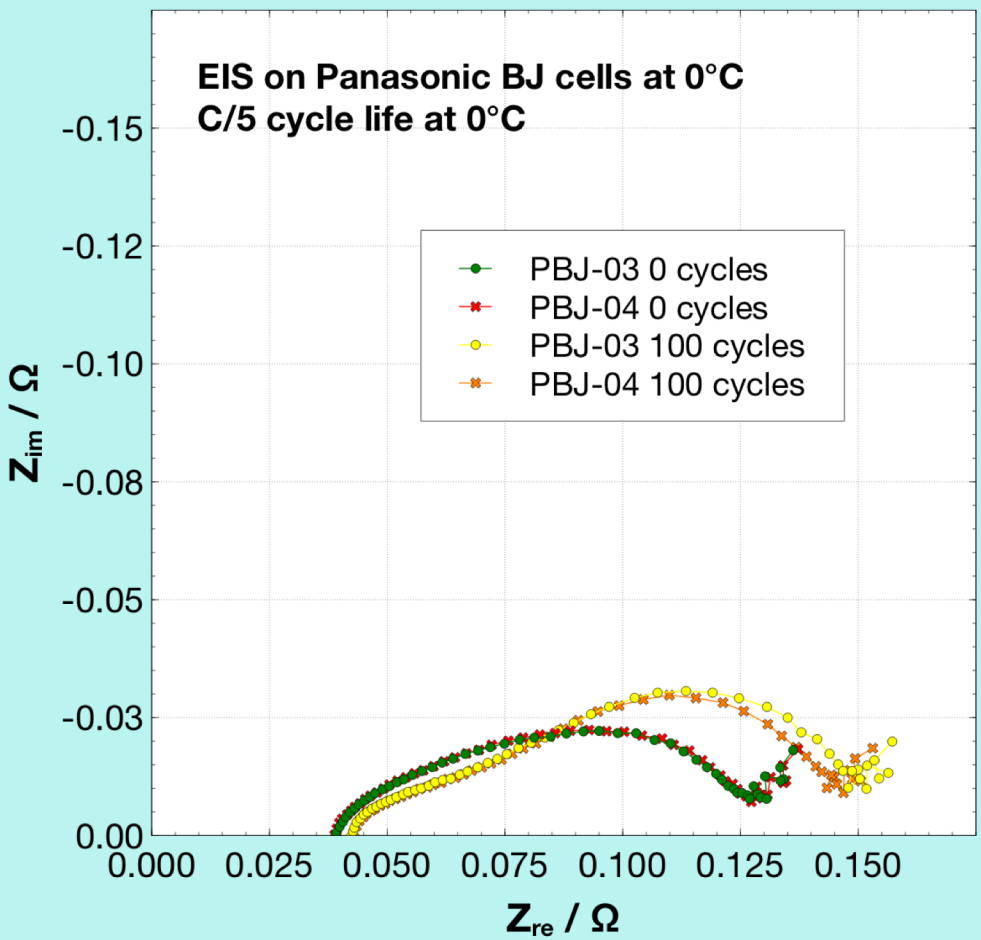


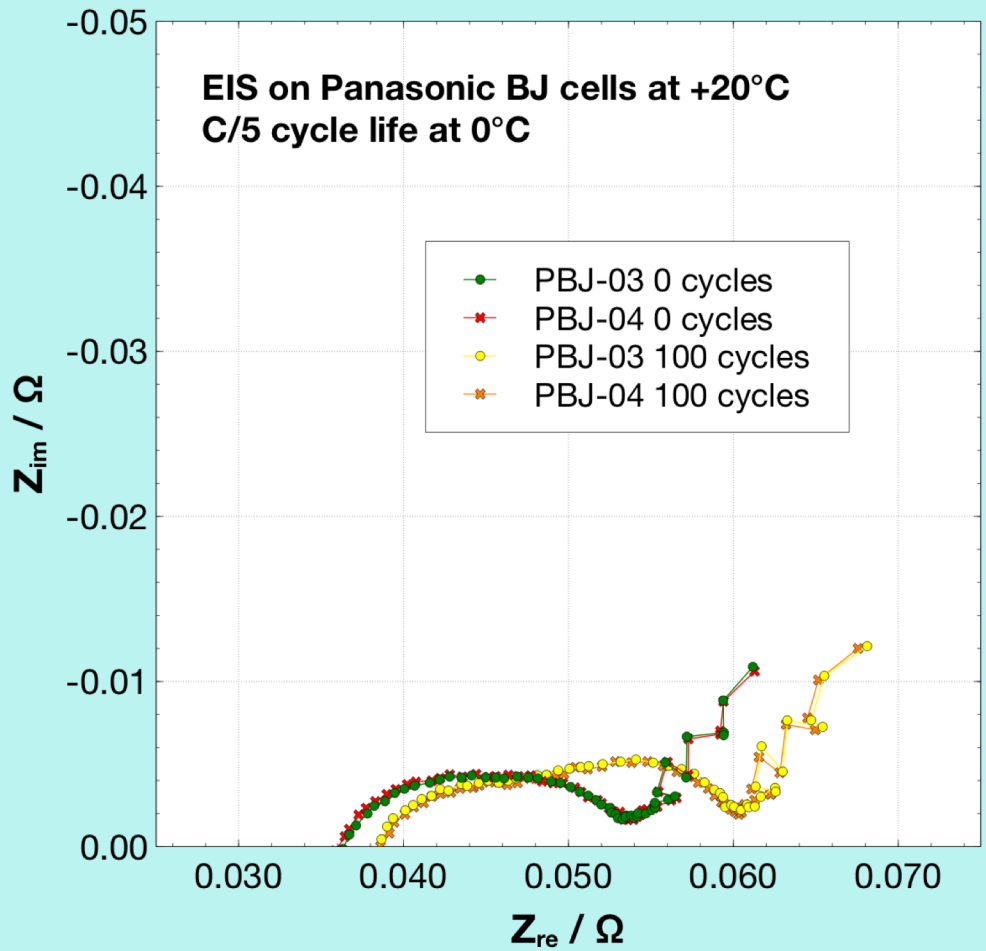


- In both LG and Panasonic cells, EIS shows an increase in low frequency loop after 100 cycles at 0 ºC, which suggests that the film impedance is unchanged, but but cathode kinetics may be hindered.

EIS vs. cycle life at 0 ºC

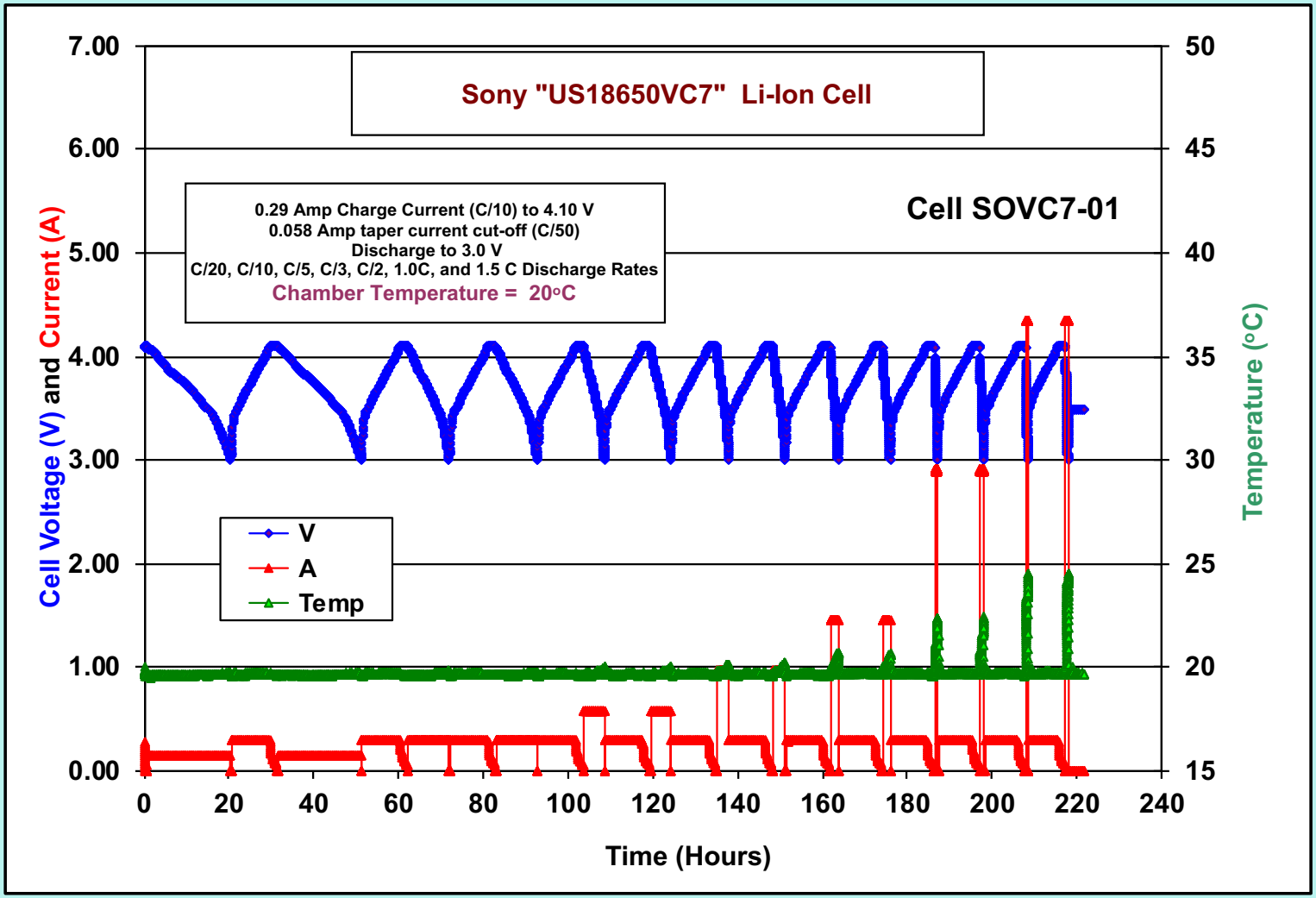
Panasonic BJ at 0 and 20 ºC





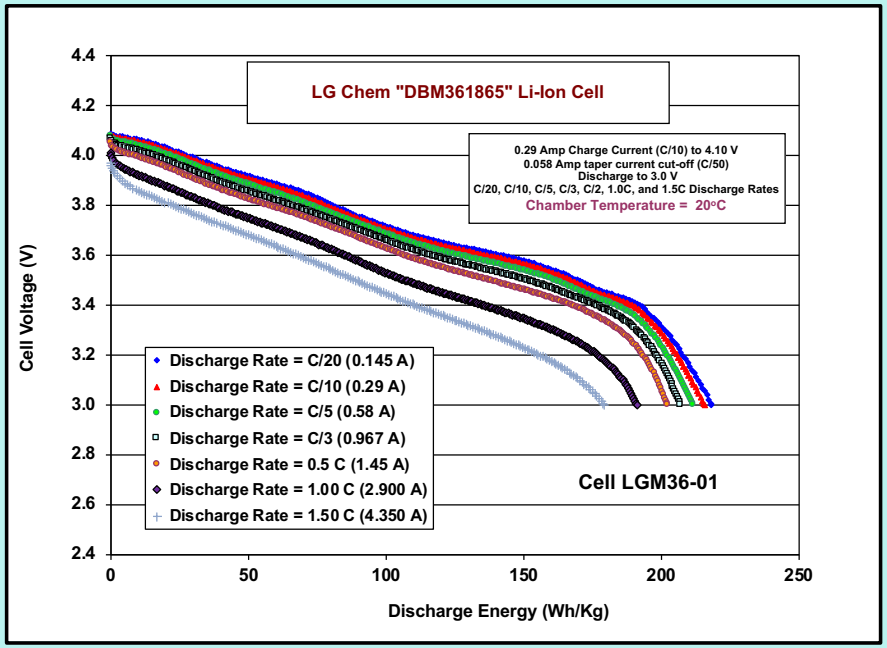
- PBJ show increase in low frequency loop over 100 cycles at 0 ºC
- May suggest film impedance is not changing, but charge transfer process is

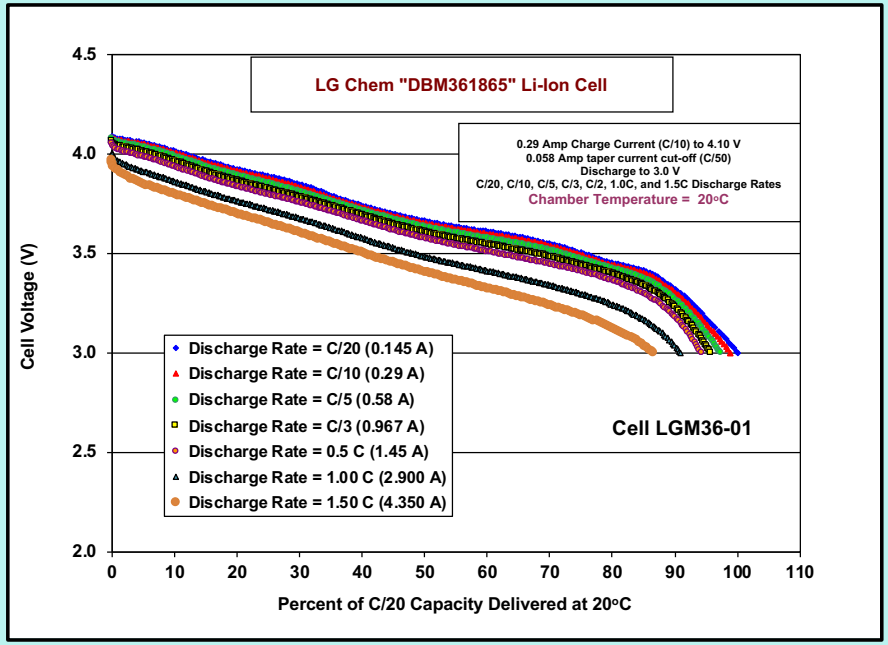
Discharge rate test at +20 °C



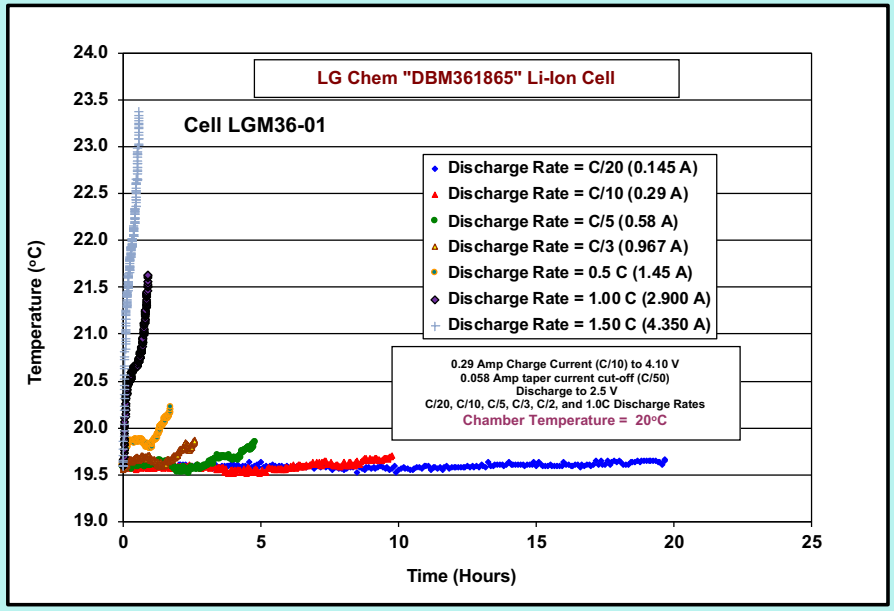
- Discharge rates from C/20 (0.145 A) to 1.5 C (4.35 A); charge at C/10 (0.29 A)
- Two cycles per rate, 4.10 – 3.00 V

Discharge rate test at +20 °C LG M36 – Specific energy vs. rate

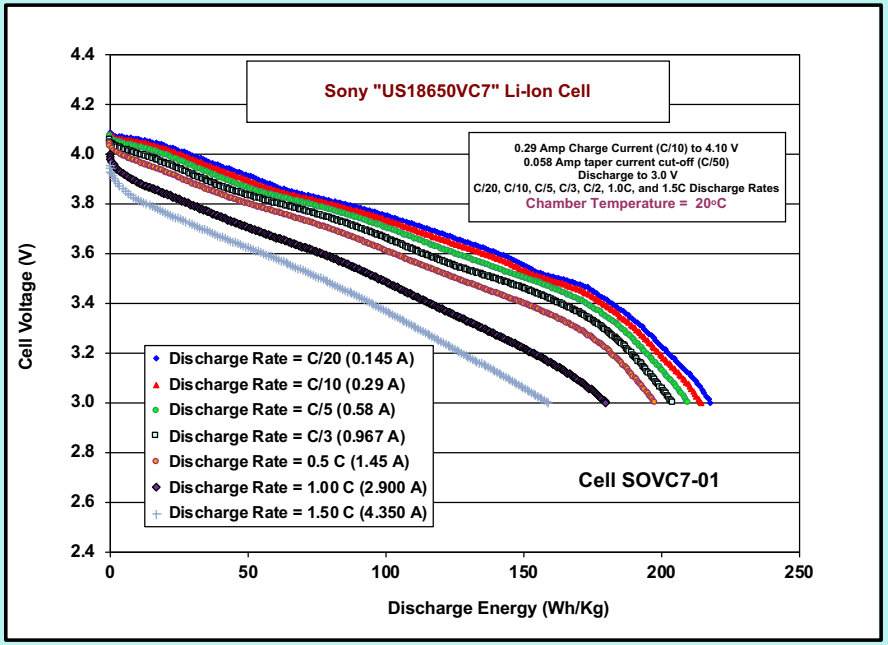


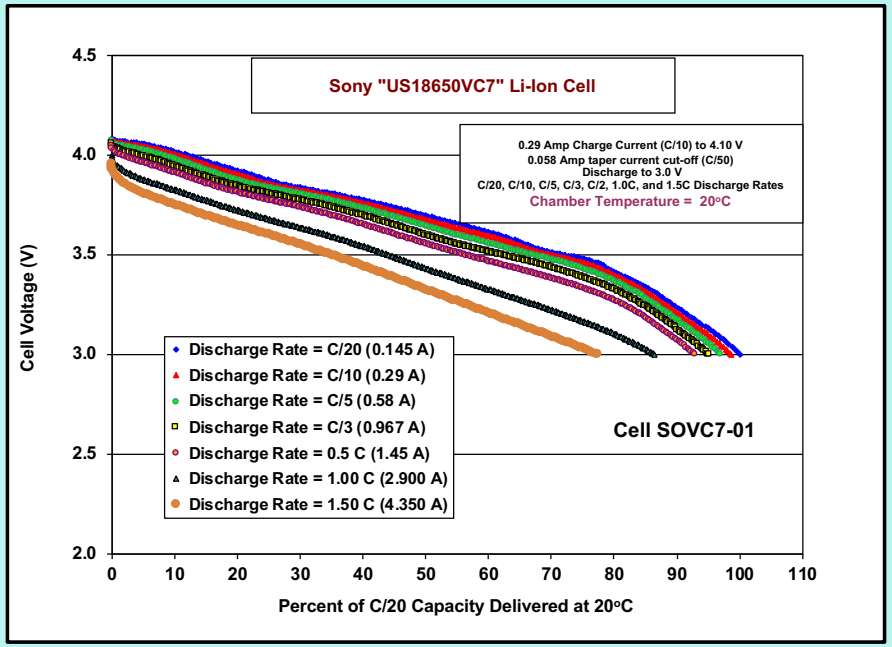


- Excellent rate capability (90% of the capacity, 190 Wh/kg at 1.5C rate
- Marginal self-heating (cell temperature: ~3 °C at 1.5 C rate

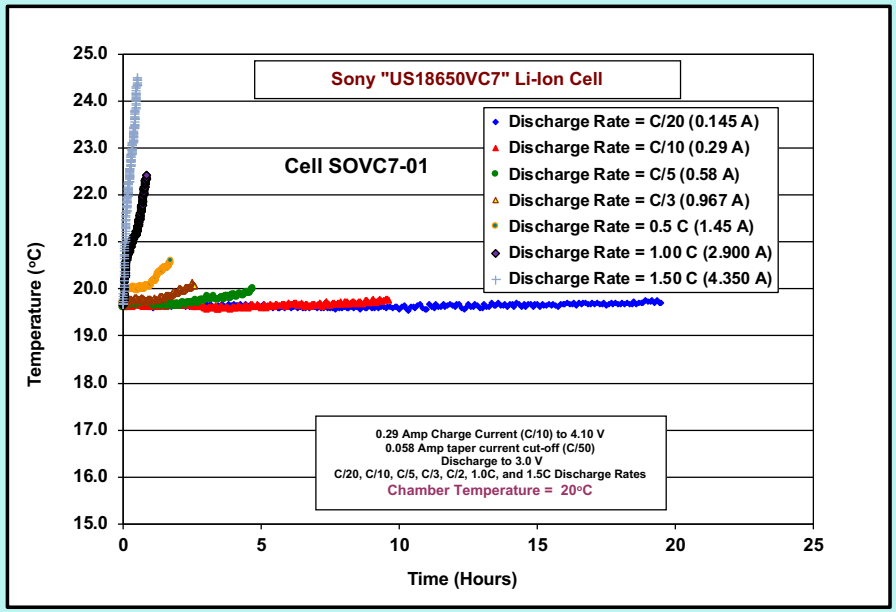


Discharge rate test at +20 °C Sony VC7 – Specific energy vs. rate

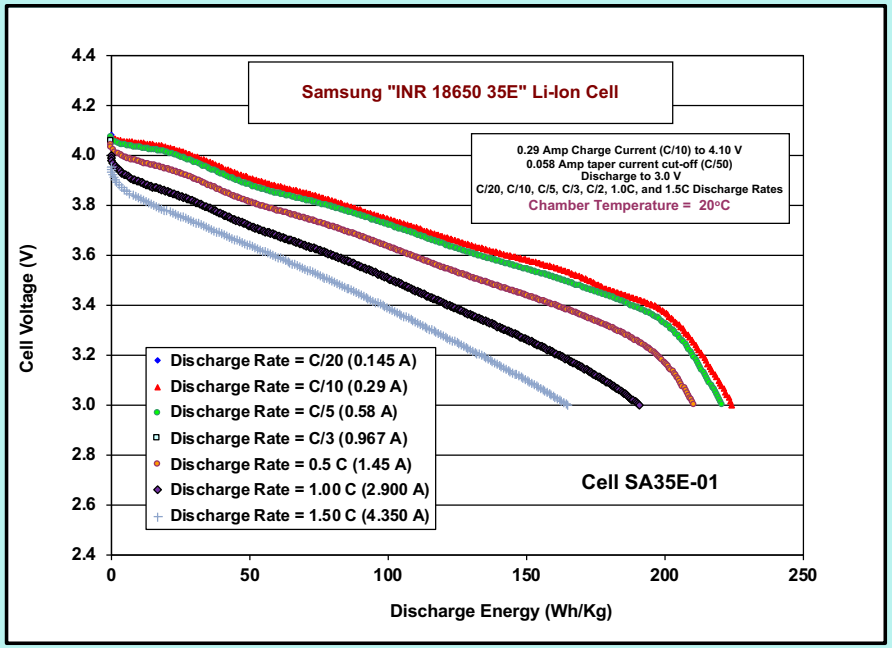


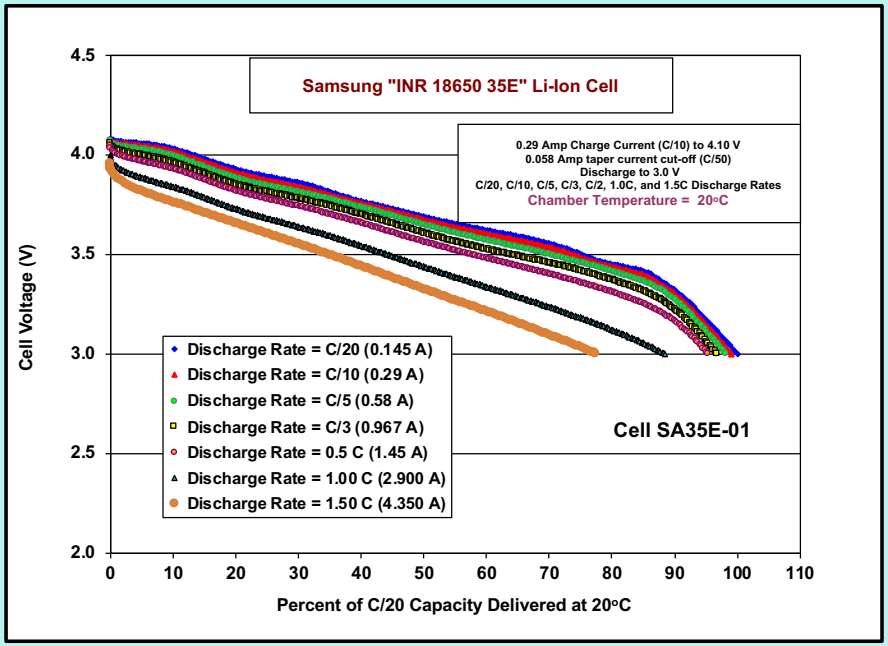


- Good rate capability (80% of the capacity, 160 Wh/kg at 1.5C rate
- Marginal self-heating (cell temperature: ~4.5 °C at 1.5 C rate

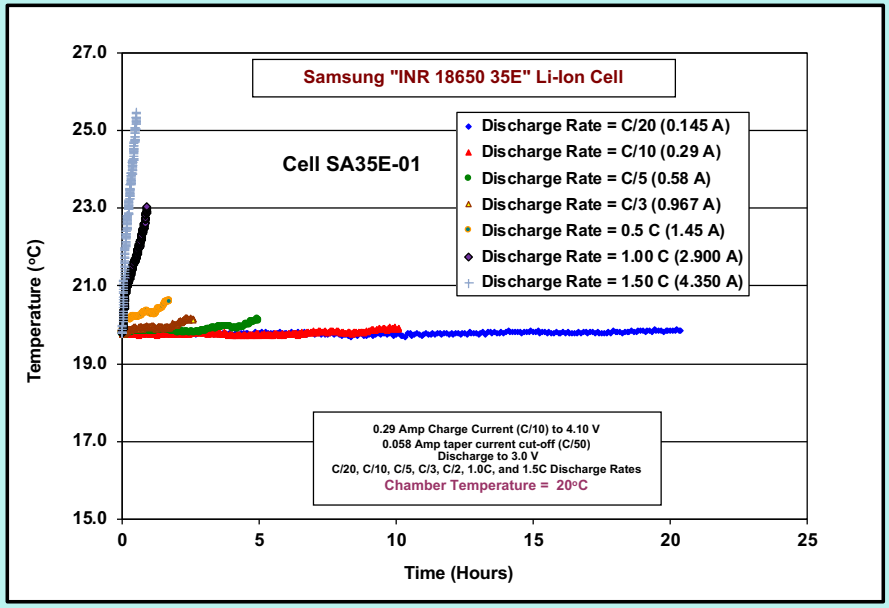


Discharge rate test at +20 °C Samsung 35E– Specific energy vs. rate

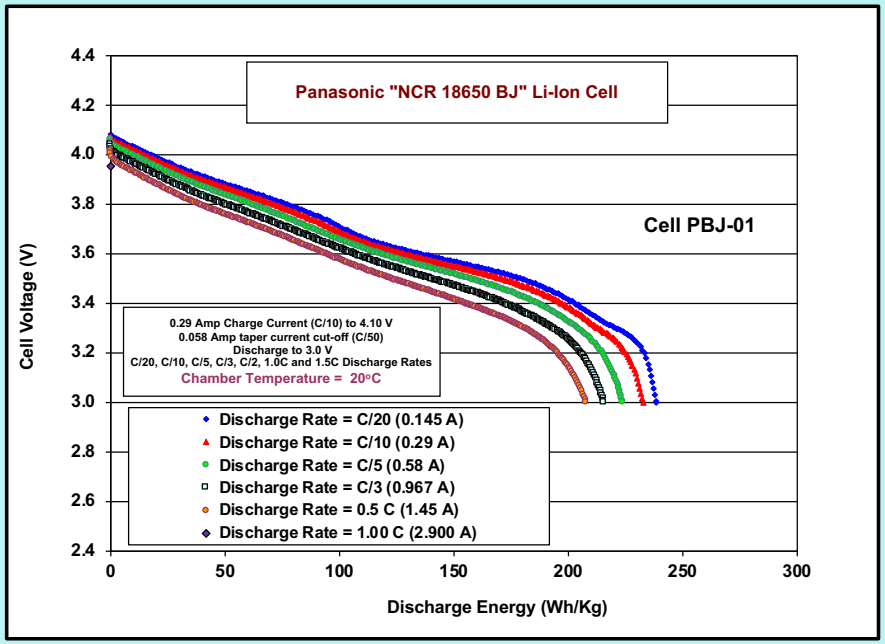


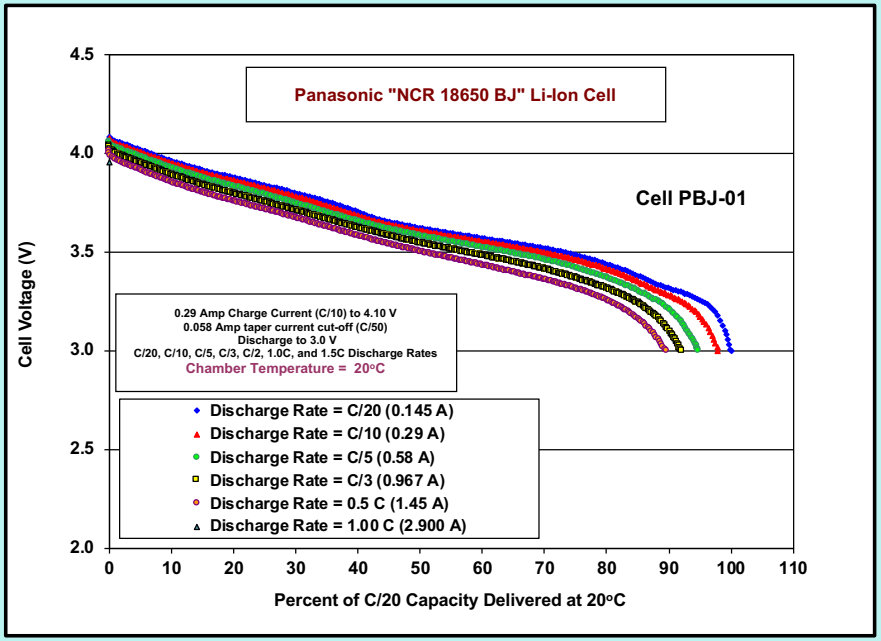


- Good rate capability (~80% of the capacity, 160 Wh/kg at 1.5C rate
- Marginal self-heating (cell temperature: ~5.5 °C at 1.5 C rate

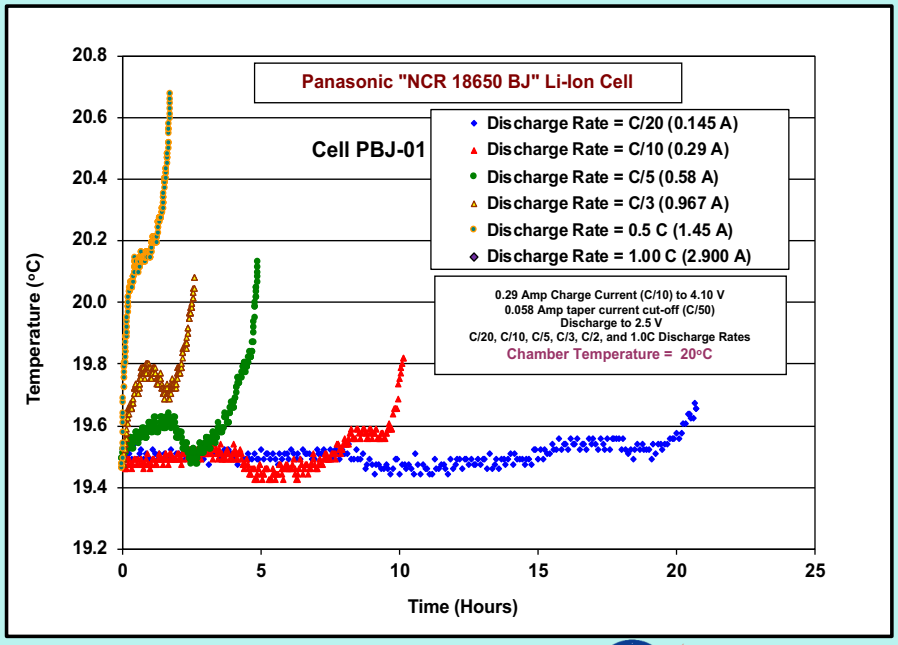


Discharge rate test at +20 °C Panasonic BJ Specific energy vs. rate

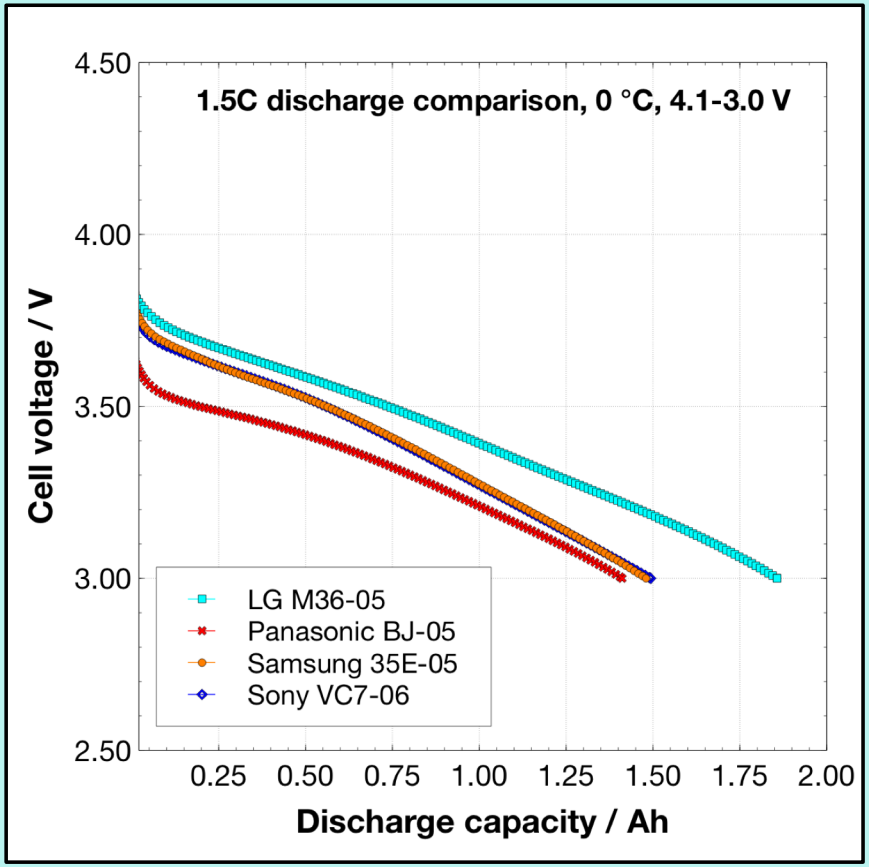


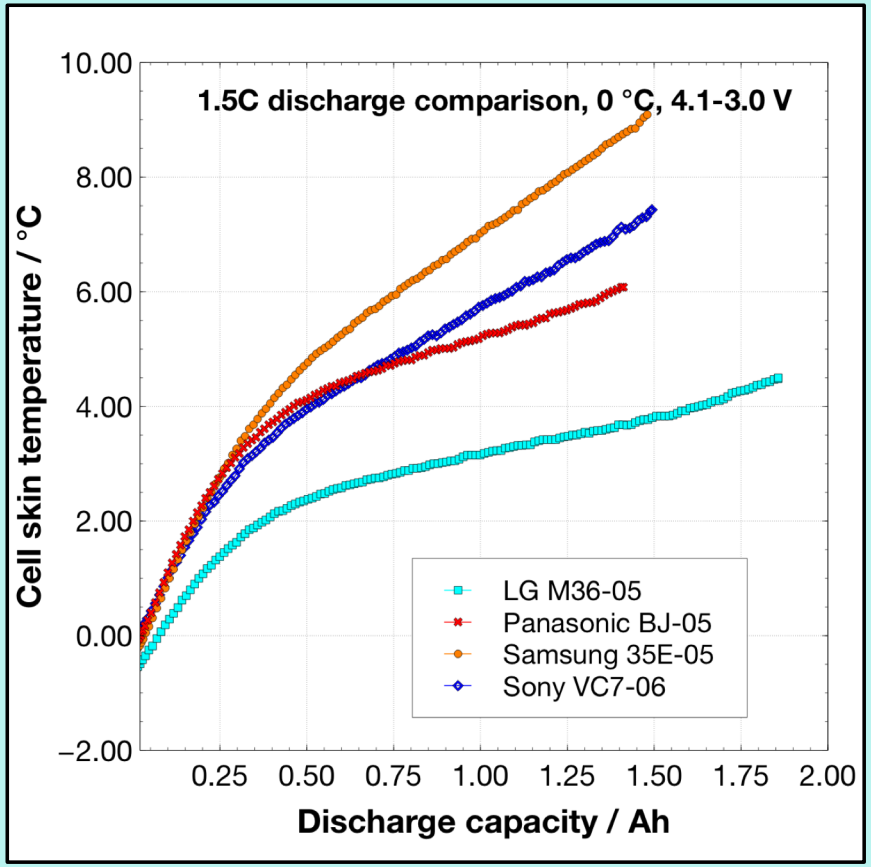


- Excellent rate capability (~90% of the capacity, 200 Wh/kg at 1.5C rate
- Little self-heating (cell temperature: ~1 °C at 1.5 C rate



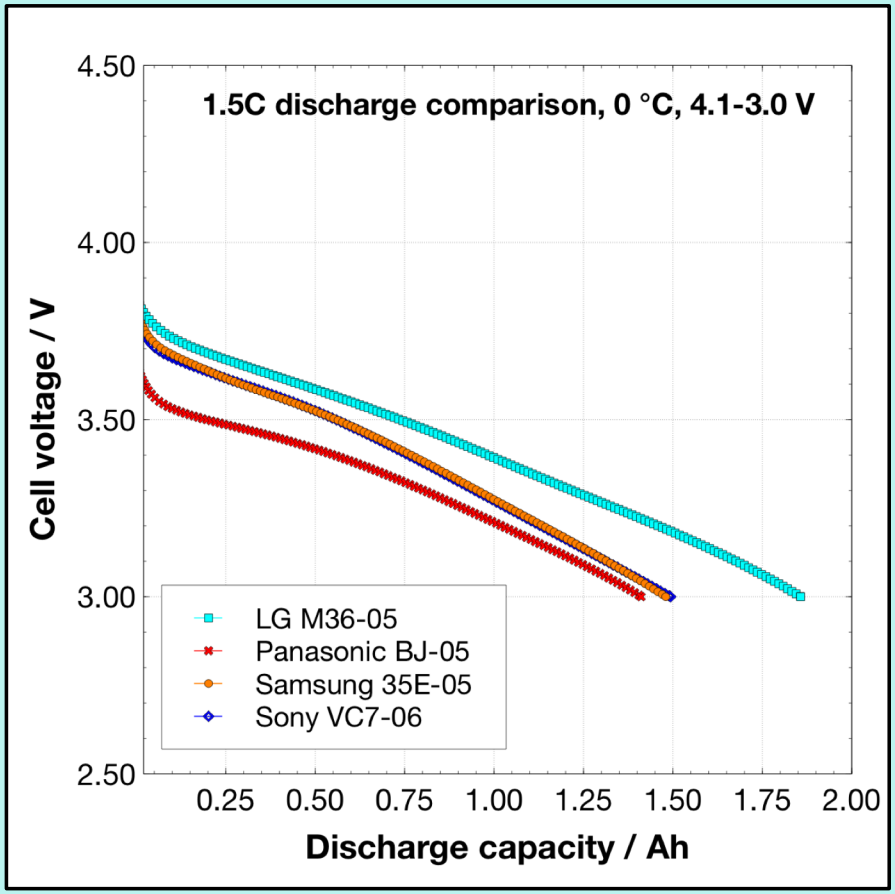
Discharge rate test at 0 °C Comparison at 1.5C

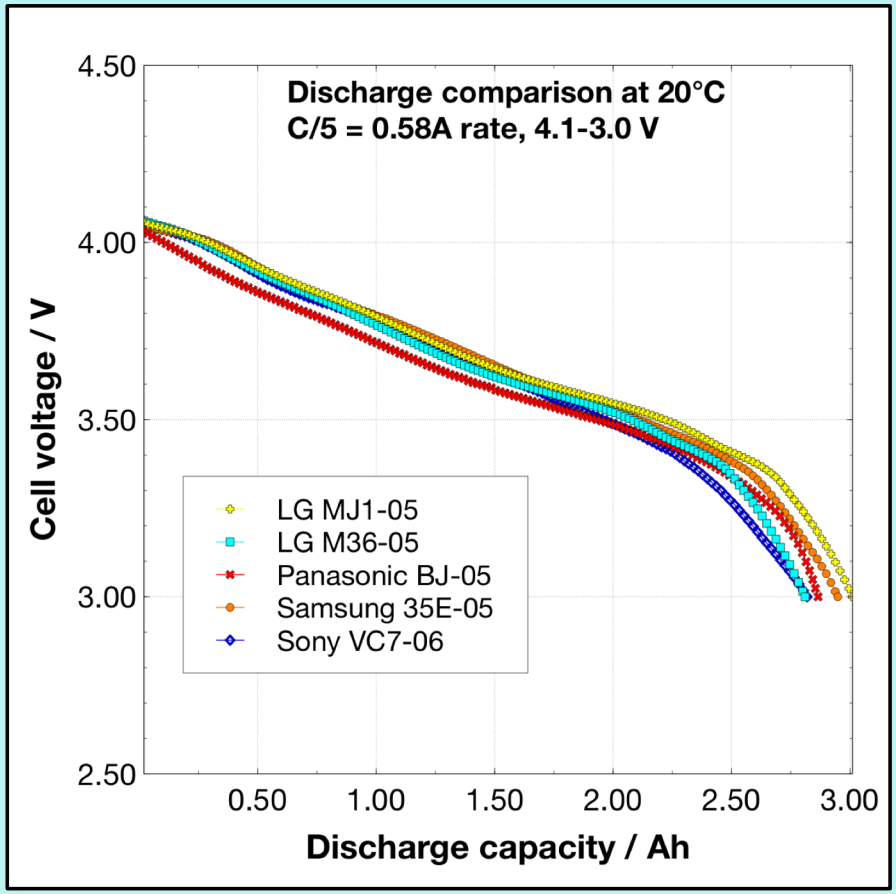




- LG M36 has highest capacity and voltage with least self-heating, suggesting a good low temperature performance.
- Plans are underway for testing at lower temperatures.

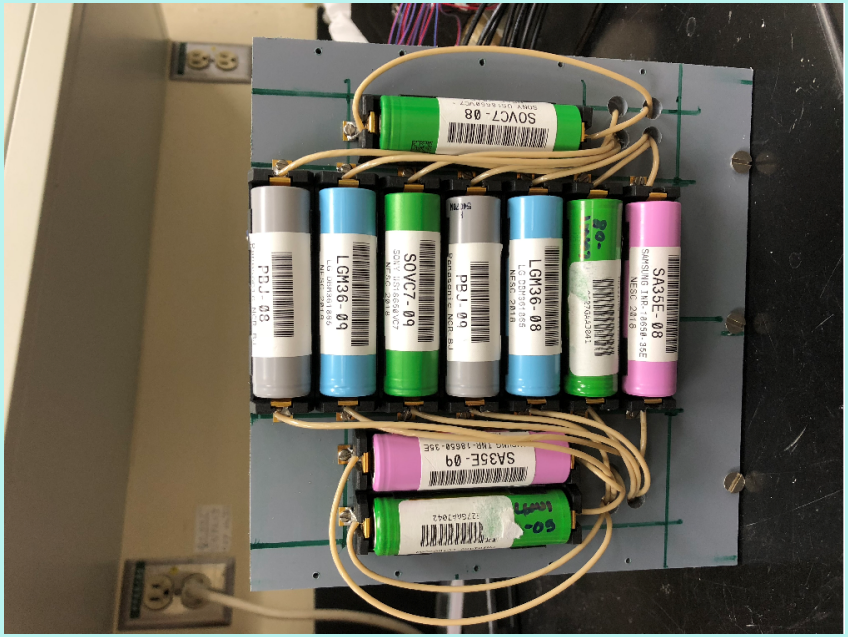
Discharge rate test 1.5C – Comparison between 25 °C and 0 °C

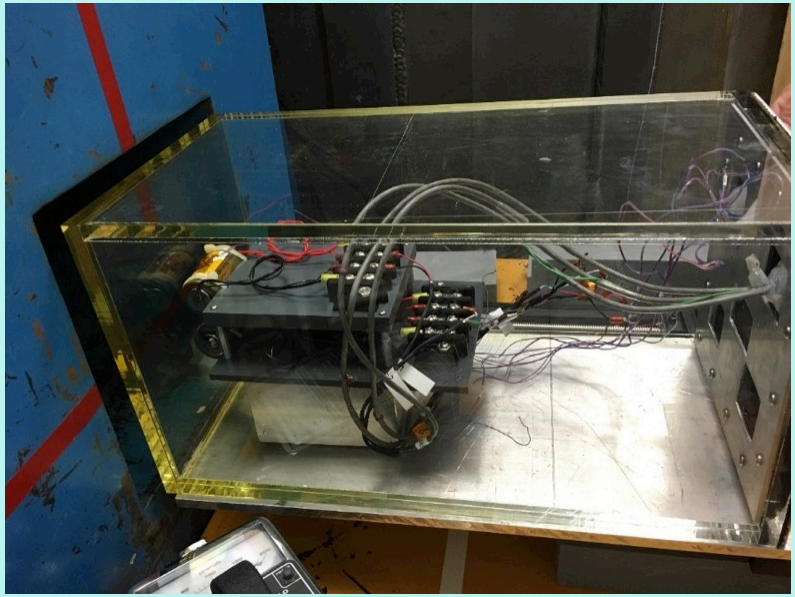




- LG M36 > Sony VC7 > Samsung 35E > Panasonic BJ
- LG M36 has highest capacity and voltage with least self-heating

Effect of ^{60}Co γ-radiation Testing at JPL





- Plans are to complete 20 MRad cumulative TID (Total Ionizing Dose) in steps
  - 12 MRad for planetary protection
  - 8 MRad from the Jupiter/Europa environment
- Completed 12 MRad on the cells

Effect of ^{60}Co γ-radiation - Capacity at +20 °C and 0 °C

	Capacity at 20 ºC, C/5 (Ah)			Capacity at 0 ºC, C/5 (Ah)		
Cell	0 Mrad	12 Mrad	% change	0 Mrad	12 Mrad	% change
LGM36-08	2.790	2.824	1.22	2.558	2.583	0.95
LGM36-09	2.788	2.765	-0.82	2.565	2.537	-1.09
LGMJ1-08	2.942	2.913	-0.99	2.668	2.655	-0.50
LGMJ1-09	2.944	2.893	-1.76	2.678	2.644	-1.29
PBJ-08	2.889	2.756	-4.61	2.537	2.324	-8.40
PBJ-09	2.831	2.858	0.98	2.403	2.483	3.31
SA35E-08	2.897	2.876	-0.73	2.626	2.623	-0.10
SA35E-09	2.912	2.901	-0.40	2.643	2.648	0.21
SOVC7-08	2.777	2.723	-1.95	2.532	2.482	-1.96
SOVC7-09	2.809	2.761	-1.70	2.570	2.525	-1.76

- Most cells have < 2% decrease in capacity after 12 Mrad exposure
- Some cells show small increases in capacity
- Changes in same order of magnitude of experimental variations
- One PBJ cell showed more dramatic performance decrease, but the second cell showed better performance after radiation

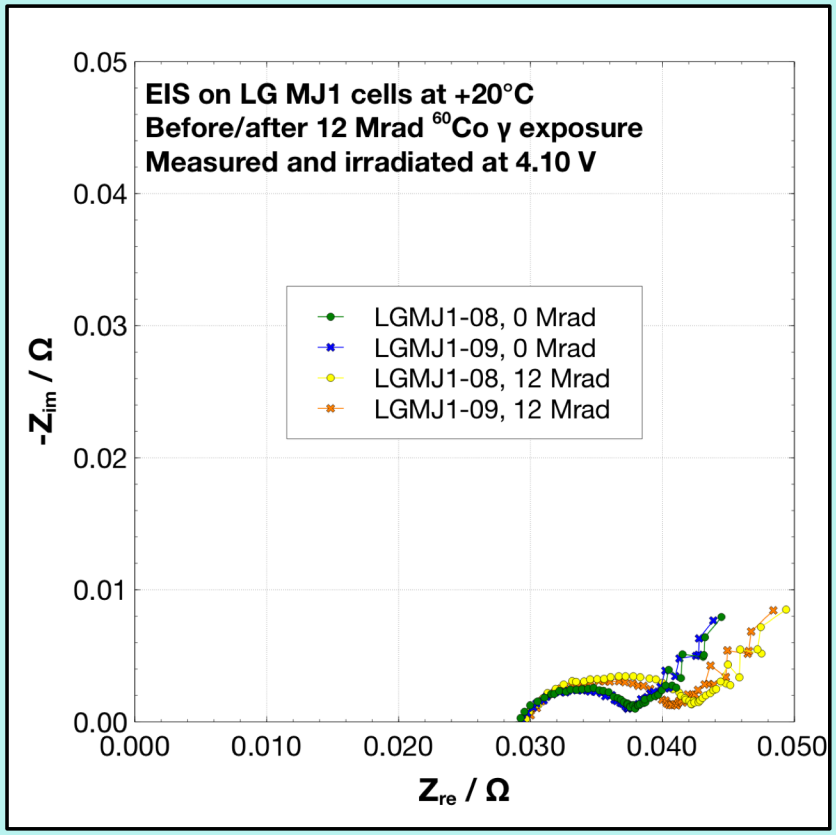
Effect of ^{60}Co γ-radiation- DC Impedance at +20 °C and 0 °C

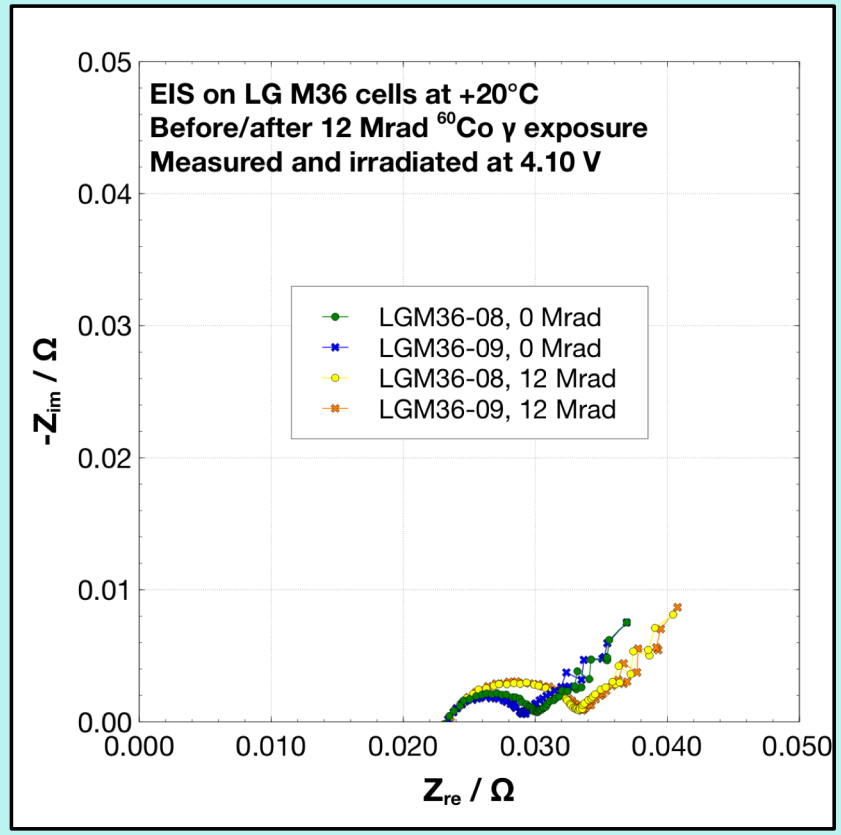
DC Impedance before and after Irradiation at 80% SOC

	dc impedance at 20 ºC, 80% SOC (mOhm)			dc impedance at 0 ºC, 80% SOC (mOhm)		
Cell	0 Mrad	12 Mrad	% change	0 Mrad	12 Mrad	% change
LGM36-08	41.0	38.1	-7.06	66.8	66.5	-0.46
LGM36-09	40.3	38.6	-4.17	65.3	65.3	0.00
LGMJ1-08	45.5	44.7	-1.68	75.4	74.3	-1.42
LGMJ1-09	44.7	45.6	2.05	73.1	74.0	1.25
PBJ-08	67.6	63.0	-6.77	128.5	124.4	-3.21
PBJ-09	65.9	64.2	-2.55	123.8	125.9	1.73
SA35E-08	49.4	45.9	-7.10	88.8	86.2	-2.92
SA35E-09	50.0	46.2	-7.62	90.2	87.7	-2.71
SOVC7-08	45.3	44.9	-1.01	77.4	81.9	5.92
SOVC7-09	43.5	43.6	0.35	73.1	77.7	6.26

- Most cells show decrease in dc impedance at 80% SOC after radiation

Effect of ^{60}Co γ-radiation EIS at +20 °C

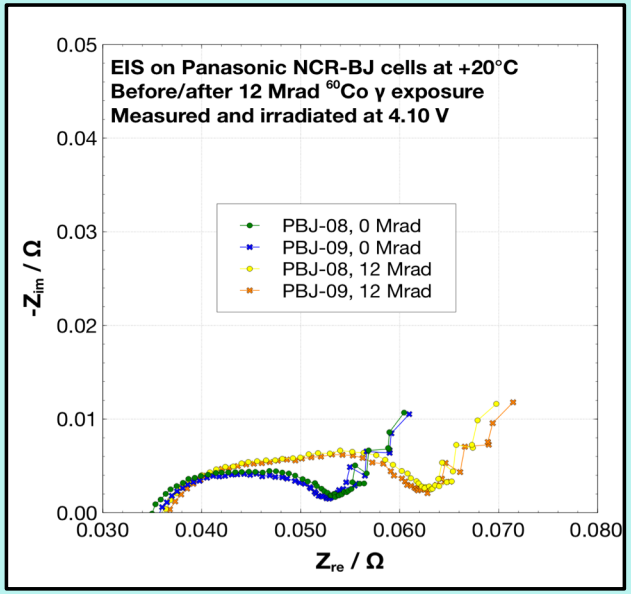


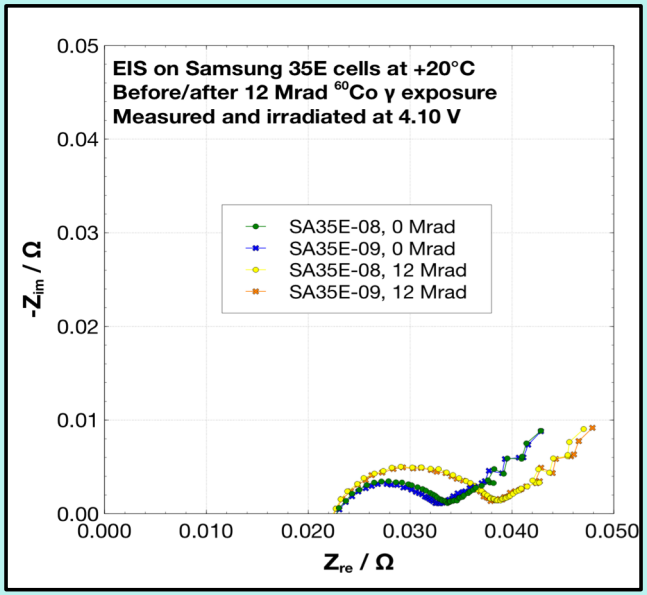


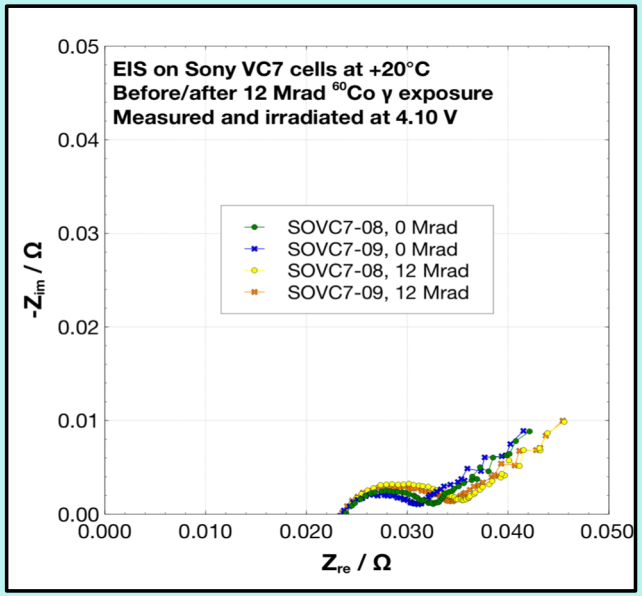
- Increase in breadth of impedance loop
- Possible resolution of two loops after radiation?
- Small increase in series resistance
- No noticeable change in slope of low frequency linear region

- Increase in breadth of impedance loop
- Only very small increase in series resistance
- No noticeable change in slope of low frequency linear region

Effect of ^{60}Co γ-radiation EIS at +20 °C







- Increase in impedance loop
- Further resolution of two loops after radiation
- Small increase in series resistance

- Increase in impedance loop
- No increase in series resistance
- Little change in slope of low frequency linear region

- Marginal increase in the impedance loop
- No increase in series resistance
- Little change in slope of low frequency linear region

Future Plans

- Complete performance testing at different (high) rates (up to 3C) and temperatures (-20°C to +40°C)
- Performance testing vs. evolving DS power requirements
- Cycling of cells at 100% and partial Depth of Discharge
- Capacity retention during storage at 100% State of Charge
- Capacity retention during cruise
- Radiation testing of cells at JPL at 12 M Rad (planetary protection) and 8 Mrad (on-tour) and performance testing (including cycle life) before and after the radiation exposure
- Destructive Physical Analysis for a preliminary understanding of radiation effects
- Testing of multi-cell modules (8s5P) for cell divergence during cycling and storage

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