

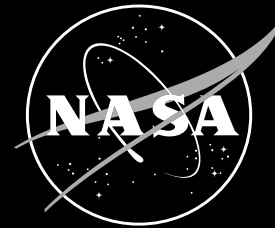
# New Electrolytes for High Temperature 18650 Cells

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Jet Propulsion Laboratory, California Institute of Technology  
2026 Space Power Workshop

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acknowledged.

*Does Not Contain CUI.*



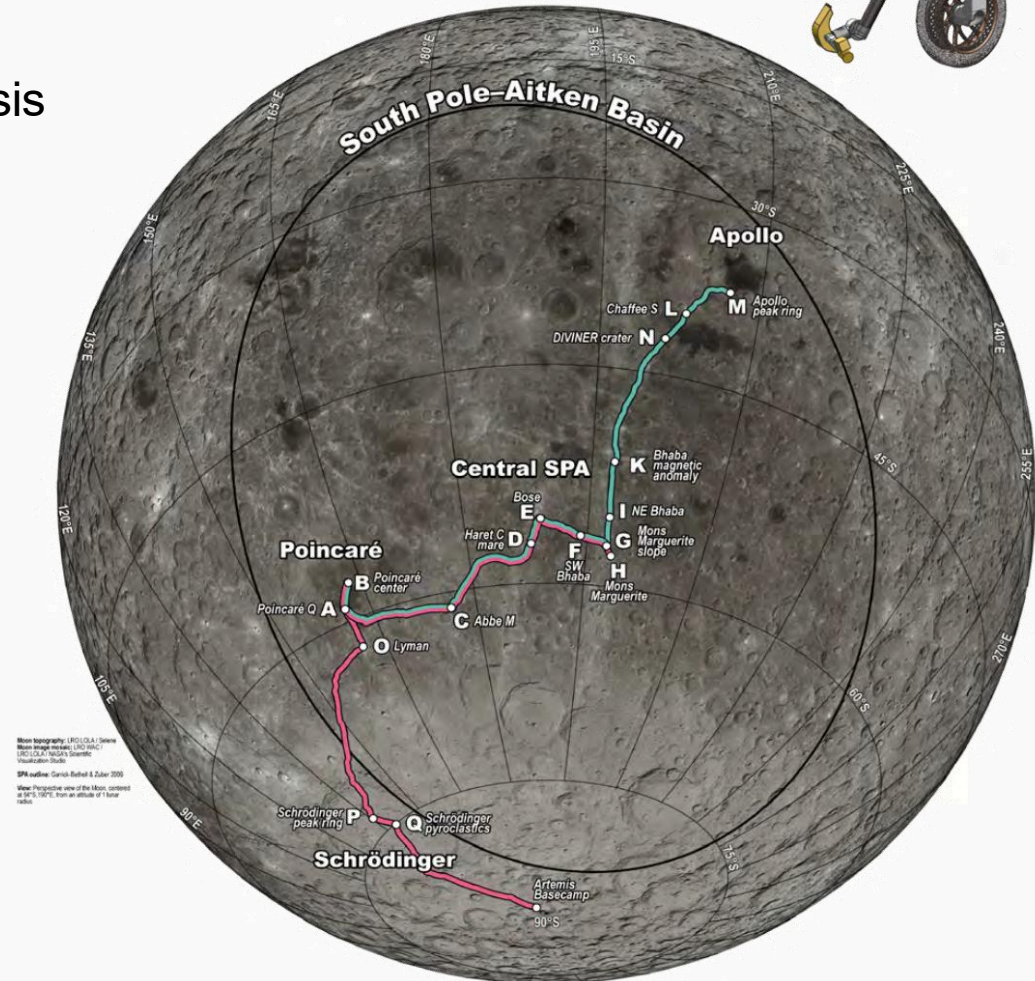
**Jet Propulsion Laboratory**  
California Institute of Technology

# Motivation – Endurance Mission Concept

- Long-range lunar rover concept to travel **~2,000 km** over **~5 years**
- Collect kgs of lunar samples for rendezvous with a return vehicle to carry samples back to Earth for analysis
- RTG-powered, relies on a battery for load leveling, similar to how Curiosity and Perseverance operate
- Big difference between this and prior missions is the vast distance the rover must drive
  - Perseverance was designed for **20 km**
- Autonomy is a big part of the mission concept (not covered here)
- Two main battery-specific challenges:
- **Extended 50 °C operation** (RTG coupled with high lunar daytime temps)
- **~1,500 cycles** due to high use to operate above RTG power limitations



GLOBAL MAP SET 1: Color and albedo



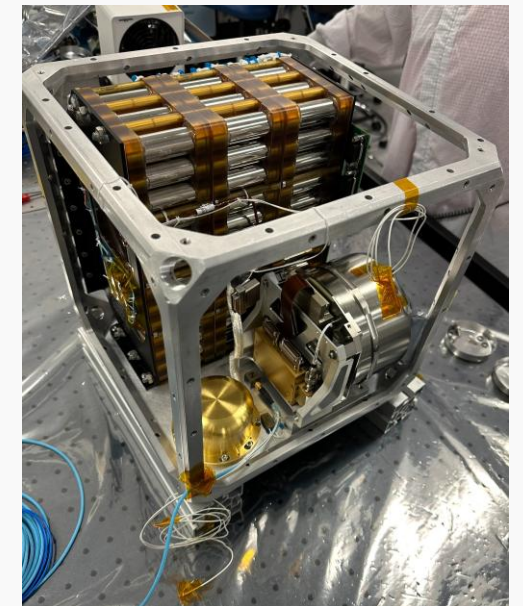
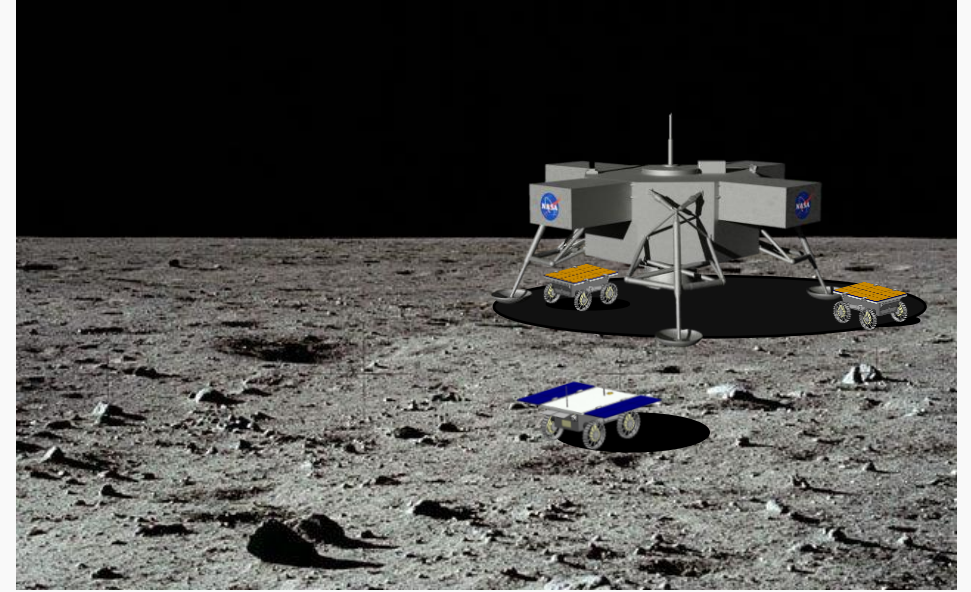
Moon topography: LPSC/OLA / Science  
Moon magnetic field: LPSC/OLA / Science  
LRO/LOREX/MAGS Scientific  
Characterization Study  
SPA outline: Garick, Ruffel & Zuber 2009  
View: Perspective view of the Moon, centered  
at 0°N, 0°E, from an altitude of 1 lunar  
radius.

<https://science.nasa.gov/wp-content/uploads/2023/11/endurance-spa-traverse-and-sample-return.pdf>

# What about other lunar missions?

- Cooperative Autonomous Distributed Robotic Exploration (CADRE)
  - Allowable flight temperature (AFT) on the battery of -20 to +75 °C
  - Only designed to survive one lunar day (~14 Earth days)
  - Used Saft MP-xtd cells in 4s1p battery
  - MP-xtd cells are rated to +85 °C, but only for “short” periods of time
  - Cells are ~150 Wh/kg
- Farside Seismic Suite (FSS)
  - Max allowable battery temperature 35 °C
  - Stationary lander design allows for a more controlled thermal environment
  - Relatively low number of cycles because battery is mostly to survive the lunar night
- **Most prior lunar missions have been relatively short duration**

## Cooperative Autonomous Distributed Robotic Exploration (CADRE)



Farside Seismic Suite (FSS)

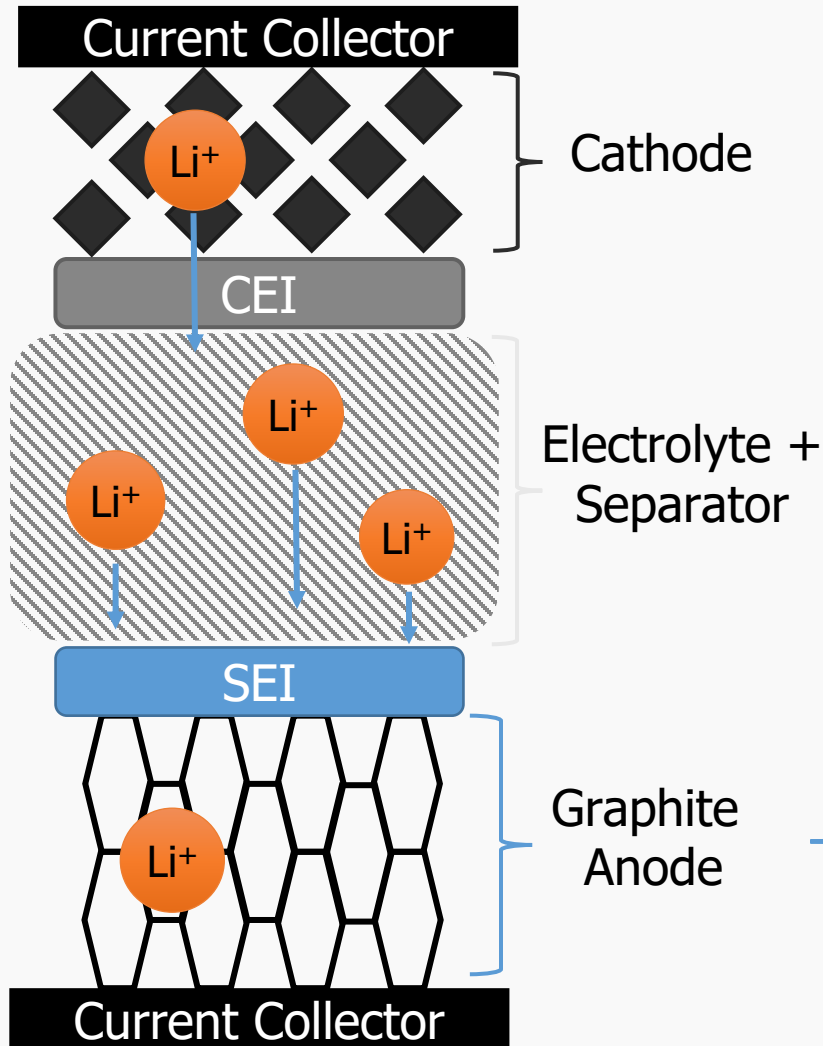
# What is the Failure Mechanism at High Temp?

- Electrode replacement studies indicated that the electrodes are stable<sup>1</sup>
- Time at temperature is generally more difficult to achieve than high cycle life
- None of the other components in the cell decompose at <100 °C
- The cathode electrolyte interphase (CEI) and solid electrolyte interphase (SEI) are two prime candidates for instability
- Both are formed by breakdown products from the electrolyte and serve to stabilize the cell over hundreds-thousands of cycles
- Prior lab studies have shown more effect on the CEI than SEI<sup>2</sup>

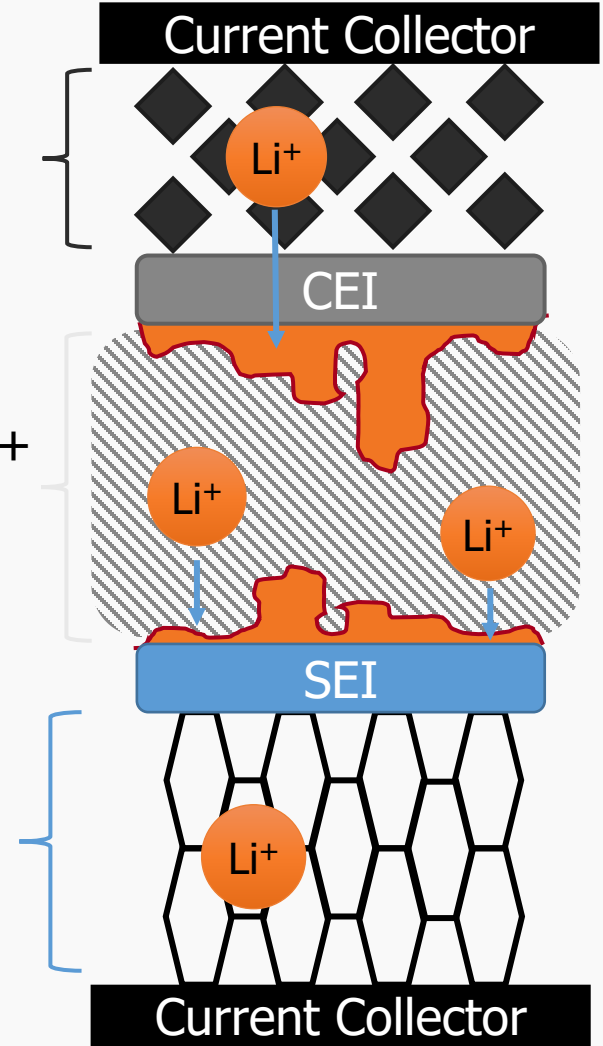
<sup>1</sup>Hawkins et al. *Journal of The Electrochemical Society*, 2023 170 100522. <https://doi.org/10.1149/1945-7111/acfc36>

<sup>2</sup>Wang et al. *Journal of The Electrochemical Society*, 2024, 171, 120517, <https://doi.org/10.1149/1945-7111/ad9b52>

## Normal Li-ion cell



## Degraded Li-ion cell



# Objective of Battery Effort

- 1-year funded effort
- Identify high energy ( $\sim 250$  Wh/kg) cell which can support a 5-year mission with a **0-50 °C AFT** and **1,000-1,500** cycles
  - 0-50 °C AFT allows the battery to share the same thermal zone with electronics boxes
  - Qual temp range of -10 °C to +60 °C
  - No high-power phases anticipated
- Generate data to support battery life projections
  - Capacity fade and impedance growth are key metrics
  - Set operational voltage limits
  - Compare baseline commercial cells to custom, high specific energy cells

# COTS Baseline Cell Selection Rationale

- LG MJ1 control cell (18650)
  - High-energy / long cycle life
    - 10 A max current / 35 mΩ impedance
  - 3.5 Ah cell / 260 Wh/kg
  - Data sheet temperature limit: 45 °C
- Sony/Murata VTC6 (18650 format)
  - High-power/high-energy cell with very low impedance
    - 20 A max current / 18 mΩ impedance
  - 3 Ah cell / 230 Wh/kg
  - High data sheet temperature tolerance (60 °C)
- Molicel P30B (18650 format)
  - High-power/high-energy cell with very low impedance
  - 3 Ah cell / 230 Wh/kg
    - 30 A max current / 17 mΩ impedance
  - High data sheet temperature tolerance (60 °C)
- Saft MP176065-xtd (small prismatic format)
  - Wide temperature range (-30 to +85 °C)
  - 5.6 Ah cell / 150 Wh/kg
  - Cells swell at elevated temperature

Cells selected to provide a wide range of realistic options in the space given limited resources

High-rate cells were selected as a comparison point to see if their initial low impedance and high data sheet temperature limits could achieve our targets

# Electrolyte Selection for Custom Cells

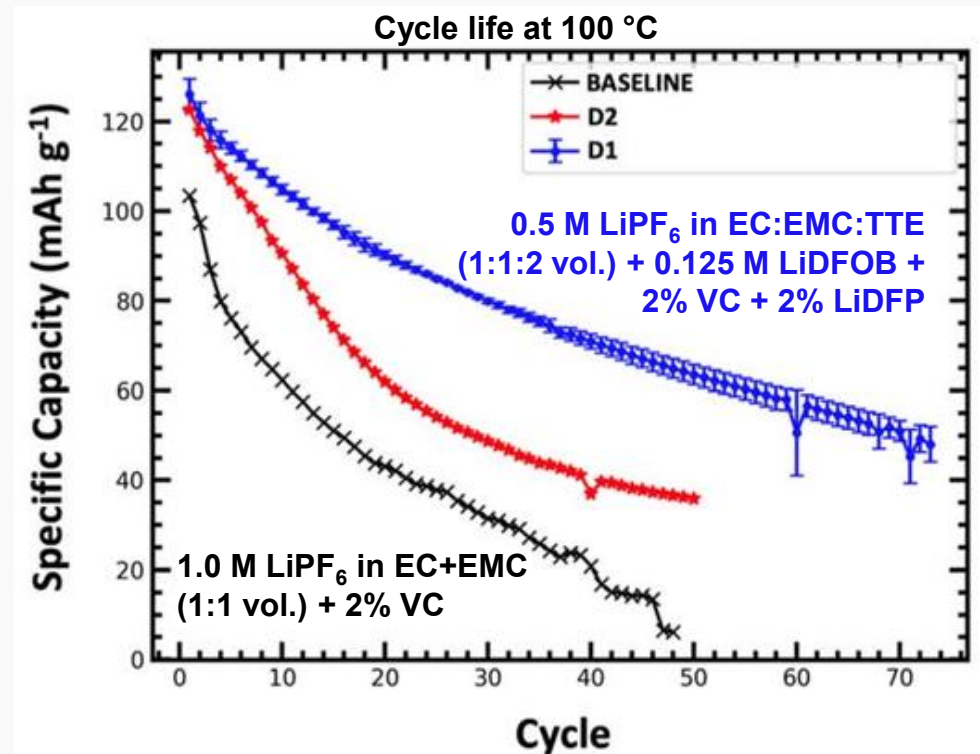
- E-one Moli prepared 100x 2.8 Ah 18650 cells with four different electrolyte formulations:
  - 2x electrolytes based on Moli's current best guess based on our requirements
    - **RNP2** and **RNP3**
  - 2x electrolytes will be based on our prior work:
    - **RNP4**: 1.0 M LiPF<sub>6</sub> in EC+EMC (1:1 vol.) + 2% VC<sup>1</sup>
      - JPL baseline high temp formulation
    - **RNP5**: 0.5 M LiPF<sub>6</sub> in EC:EMC:TTE (1:1:2 vol.) + 0.125 M LiDFOB + 2% VC + 2% LiDFP<sup>2</sup>
      - Optimized for 100 °C cycling

<sup>1</sup>M. C. Smart et al., *ECS Trans.*, **2010**, 25, 37, <https://dx.doi.org/10.1149/1.3393838>

<sup>2</sup>Wang et al. *J Electrochem. Soc.*, **2024**, 171, 120517, <https://doi.org/10.1149/1945-7111/ad9b52>

EC: ethylene carbonate  
EMC: ethyl methyl carbonate  
VC: vinylene carbonate  
FEC: fluoroethylene carbonate  
TTE: 1,1,2,2-tetrafluoroethyl-2,2,3,3-tetrafluoropropyl ether  
LiDFOB: lithium difluoro(oxalato)borate  
LiDFP: lithium difluorophosphate

- TTE-containing electrolyte selected due to excellent performance relative to the JPL baseline in coin cells<sup>2</sup>
- LiDFP and DFOB are to improve CEI formation
- TTE is thought to suppress SEI dissolution



# Outline of Cell Test Plan

1. Procure cells
2. Check-in testing on all cells
  - 20 °C, 3x C/5 cycles followed by DCIR every 20% capacity
3. Exploratory cycles at 50 and 60 °C to determine V vs. SOC
4. Split cells into groups for:
  1. RT reduced DoD cycle life testing
    - 4.1 to 3.6 V C/2 charge and discharge x2 cells
  2. 50 °C reduced DoD cycle life testing
    - 4.1 to 3.6 V C/2 charge and discharge x2 cells
    - 4.0 to 3.6 V C/2 charge and discharge x2 cells
  3. 60 °C reduced DoD cycle life testing
    - 4.1 to 3.6 V C/2 charge and discharge x2 cells
    - 4.0 to 3.6 V C/2 charge and discharge x2 cells
  4. 40, 50, 60, 70 °C aging storage x2 cells per condition
    - Charged to 3.9 V (~70% SOC)
    - Check-in test after 3 months of storage



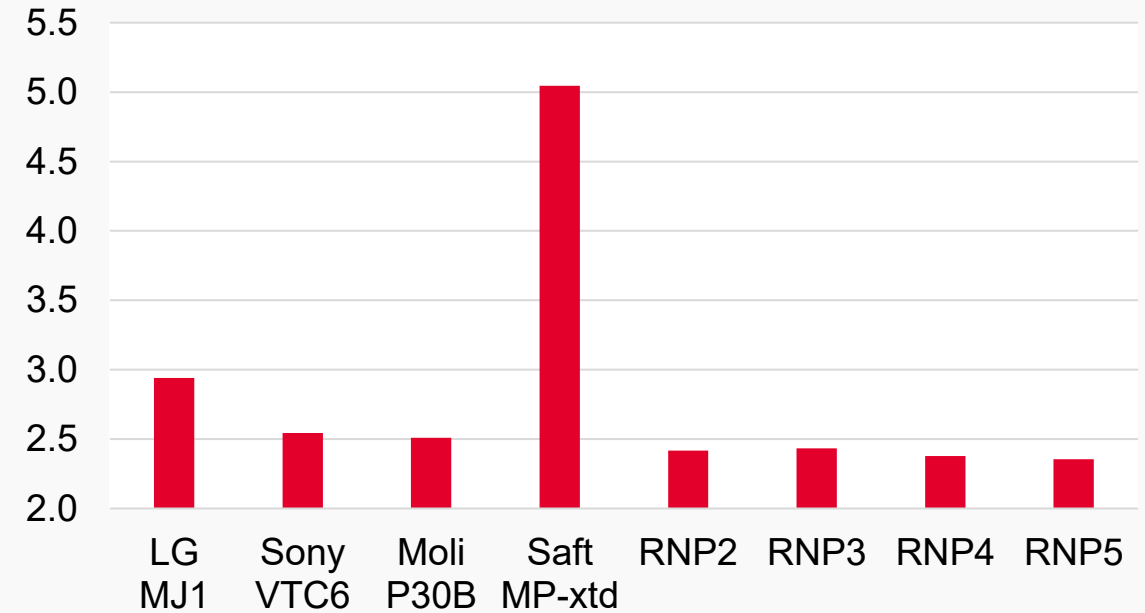
Cycle life testing demonstrates mission electrical profile, with 60% DoD maximum allowed value

Storage testing helps predict and understand calendar aging

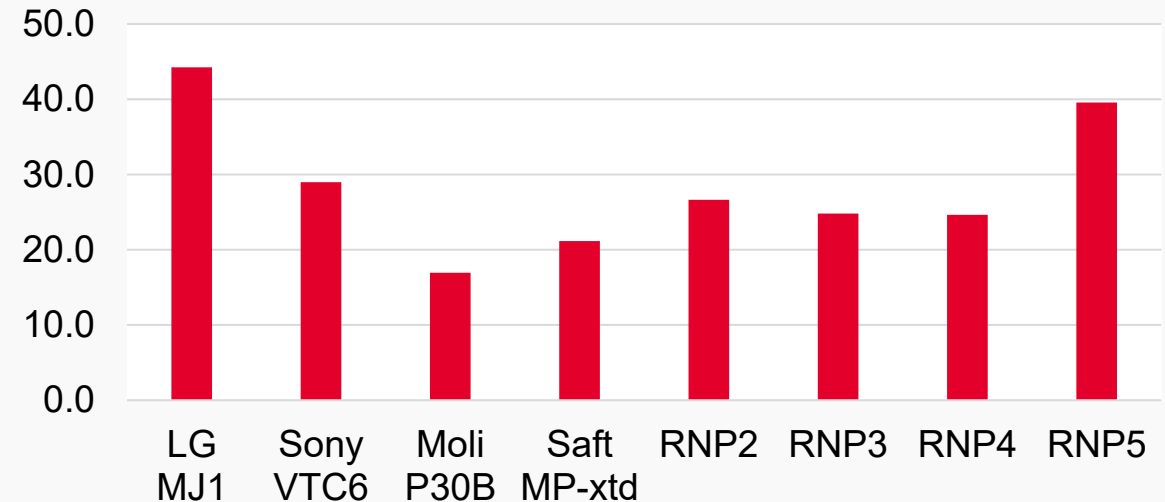
# Initial Cell Screening

- Cells checked in with 3x C/5 cycles from 4.1 to 3.0 V
- DCIR measured every 20% capacity with C/2 pulses
- Saft MP-xtd is a much larger (5.6 Ah nameplate, NP) prismatic cell than the rest
- LG MJ1 is highest specific energy cell with 3.5 Ah NP capacity
- Sony VTC6 and Moli P30B represent high specific energy “power” 18650s with 3.0 Ah NP capacity
- The RNP cells are all built on the 2.8 Ah Moli P28A platform, so have a little less capacity than the rest
- Initial DCIR reveals that RNP5 has very high initial DCIR for the format, likely due to the high TTE content

Initial Capacity at C/5, 4.1 to 3.0 V, 20 °C



DCIR at 80% SOC, 20 °C

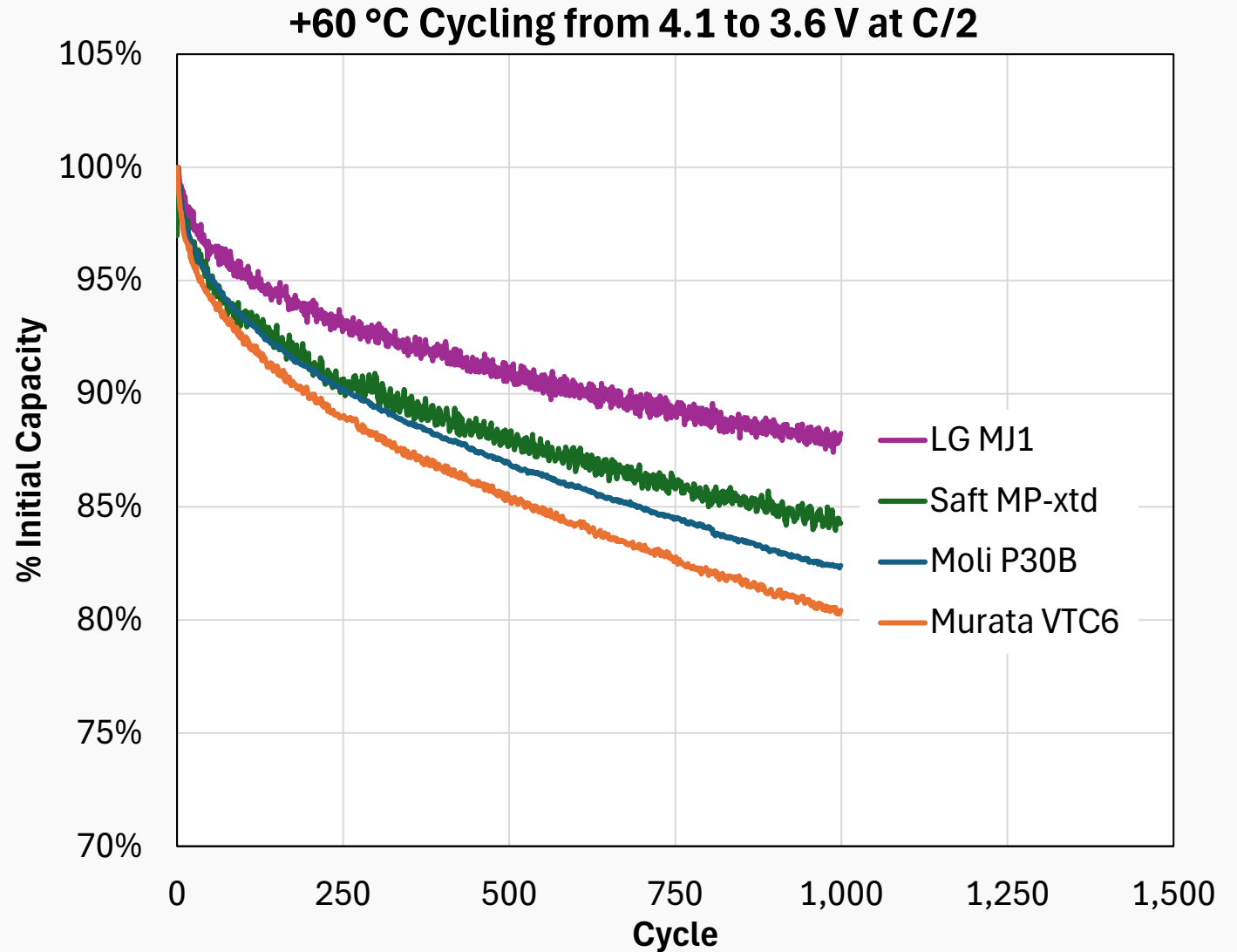


■ Initial DCIR

Does Not Contain CUI.

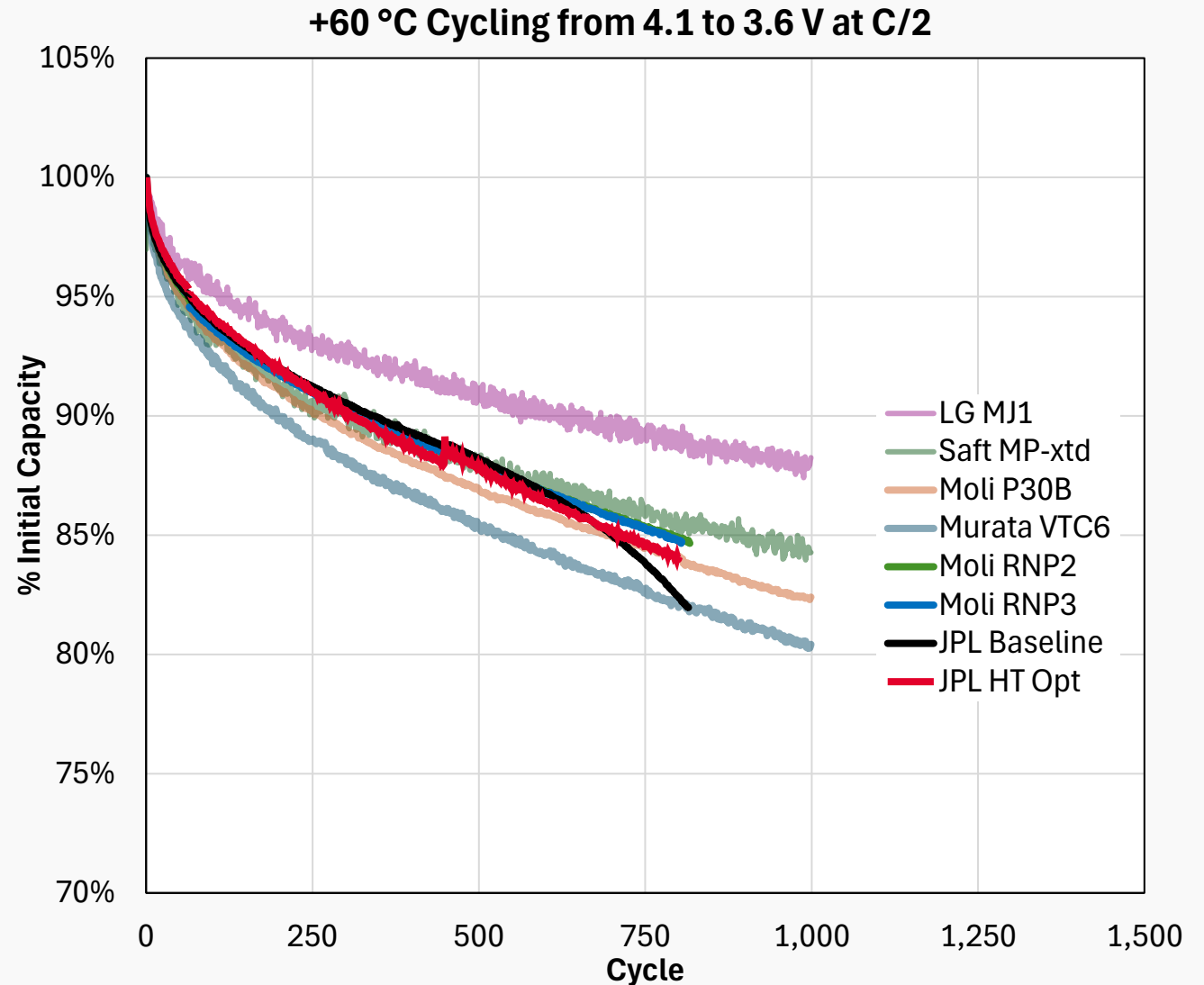
# COTS Cycle Life

- All COTS cells survived even the most stressful cycling condition
- Defying initial expectations, the LG MJ1 retained the most capacity after 1,000 cycles
- Max charge temp on data sheet:
  - LG MJ1: **45 °C**
  - Saft MP-xtd: 85 °C
  - Moli P30B: 60 °C
  - Murata VTC6: 60 °C
- MJ1 wins COTS comparison despite having highest initial capacity and highest initial impedance
- After ~200 cycles, fade rate is reasonably linear across all cells



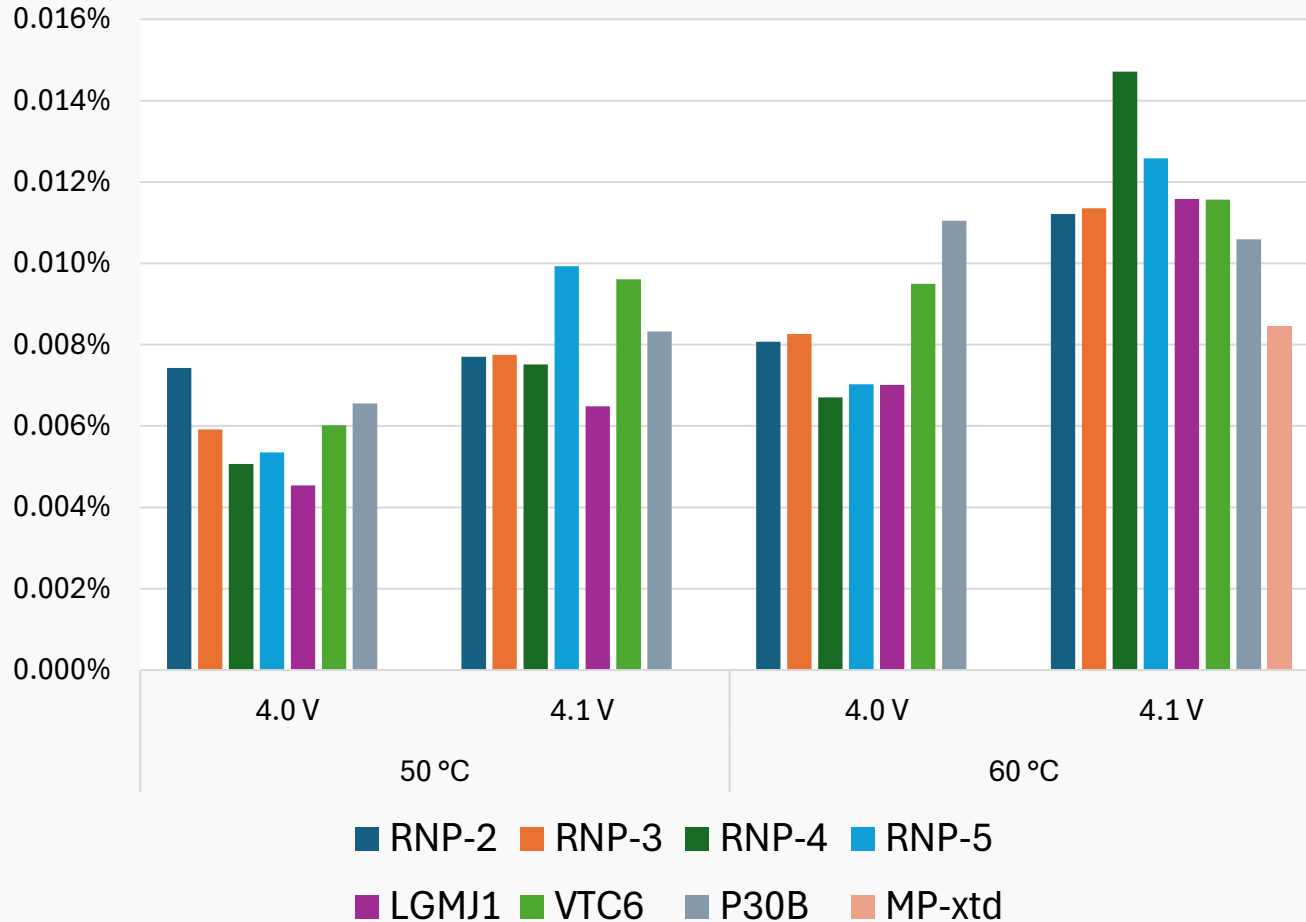
# Custom Life Data

- Cycle life for custom cells is all virtually identical
- Also very similar to Moli P30B, which is perhaps unsurprising given that the P30B is closely related to the cell that Moli used for our custom electrolytes
- JPL HT baseline (1.0 M LiPF<sub>6</sub> in EC+EMC 1:1 vol. + 2% VC) is exception, which rapid capacity fade starting at ~600 cycles
  - This behavior was only observed at +60 °C and 4.1 V, the cell behaved normally at all other conditions
- Most COTS cells probably use far more additives than in the JPL HT baseline
- **We cannot affect cycle life much with electrolyte changes**



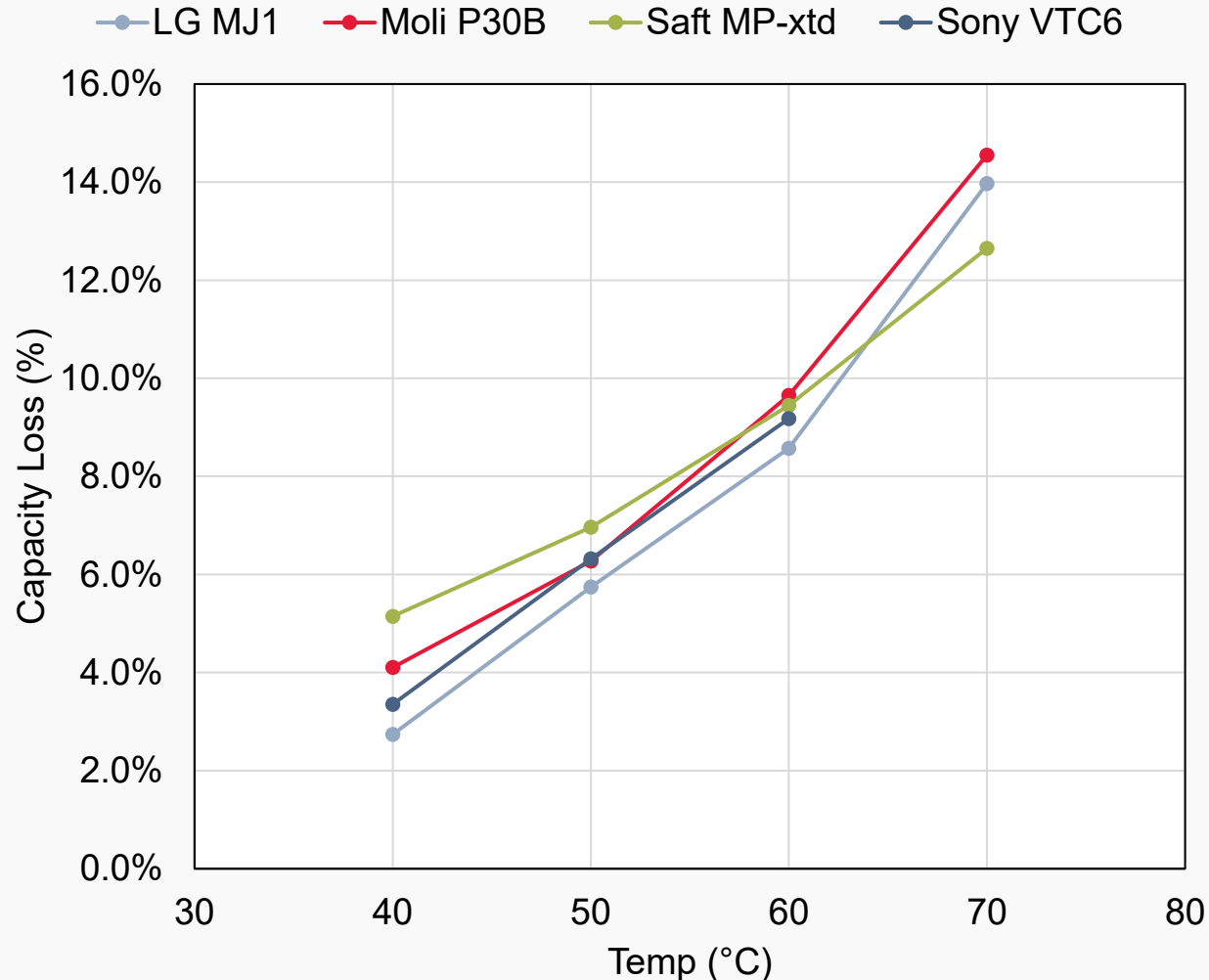
# Compiled Cycle Life Data

200+ Per Cycle Fade Rate



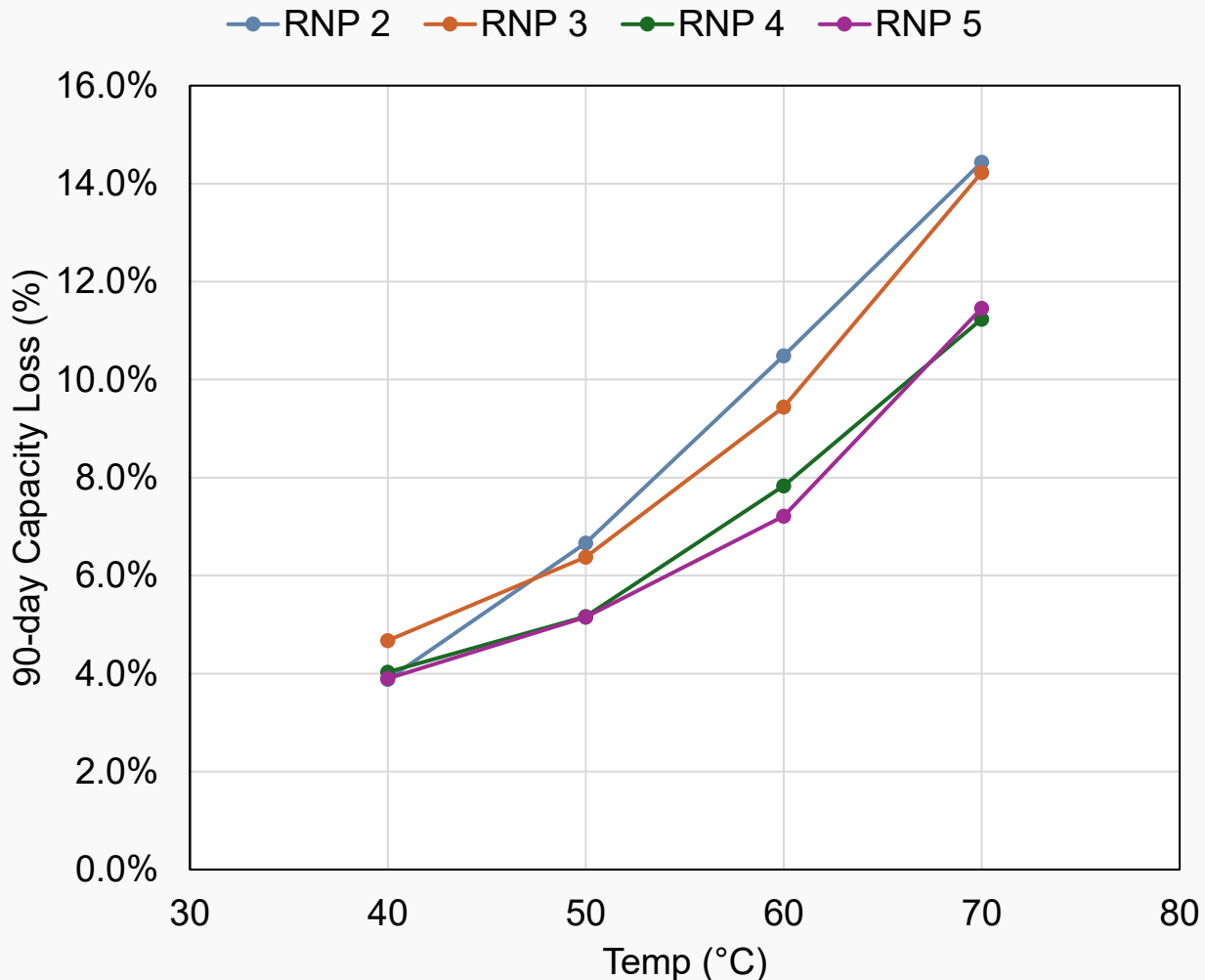
- Slope starting after first 200 cycles, to capture steady state fade
- Trends reveal that MJ1 is primarily better at holding initial capacity, but its cycle life slope after 200 cycles is not that much better than other cells
- Capping charge voltage to 4.0 V is beneficial for most cells, particularly at 60 °C
- Exception is P30B which actually fares better at 4.1 vs. 4.0 V when cycled at 60 °C
- JPL electrolytes RNP4 and RNP5 are clearly better at 4.0 V rather than 4.1 V, particularly at 60 °C
- Other cells do not suffer as much when pushed to 4.1 V
- Saft MP-xtd performs very well at 60 °C and 4.1 V in terms of steady-state cycle life

# COTS Cell Storage



- Cells stored for 90 days at indicated temperatures
- Charged to 3.9 V (~70% SOC) prior to storage
- Only failure was a Sony VTC6 cell stored at 70 °C
- MJ1 performs very well between 40-60 °C, but then rapidly declines at higher temp
- Saft MP-xtd is clearly optimized for higher temperature, with the best performance at 70 °C

# Custom Cell Storage



- Custom cells stored for 90 days at indicated temperatures
- Charged to 3.9 V (~70% SOC) prior to storage
- Testing indicates that **RNP 4** and **RNP 5** are superior to all other cells at temperatures >50 °C
  - **RNP-4:** 1.0 M LiPF<sub>6</sub> in EC+EMC (1:1 vol.) + 2 wt% VC
  - **RNP-5:** 0.5 M LiPF<sub>6</sub> + 0.125 M LiDFOB in EC+EMC+TTE (1:1:2 vol.) + 2 wt% VC + 2 wt% LiDFP
- JPL electrolytes are very similar when looking at calendar life at 3.9 V exclusively
- Suggests that high EC content and VC to shore up anode SEI are key ingredients in high temperature stability
- Additives included in RNP-5 were focused on CEI
- TTE in RNP-5 likely reduces SEI dissolution, but perhaps at <3.9 V this is not an issue

# Arrhenius Analysis

- If we plot the capacity fade over time data from the previous slide differently, we can solve the Arrhenius equation:

$$k = Ae^{\frac{-E_a}{RT}}$$

- When data can be connected via a straight line ( $R^2$  close to 1), then there is no change in mechanism over the investigated temperature range
  - This means that an accelerated aging protocol is valid
- Solving for  $E_a$  (activation energy) allows us to calculate any combination of temperature and time with reasonable accuracy
- Activation energies match reasonably well with literature values

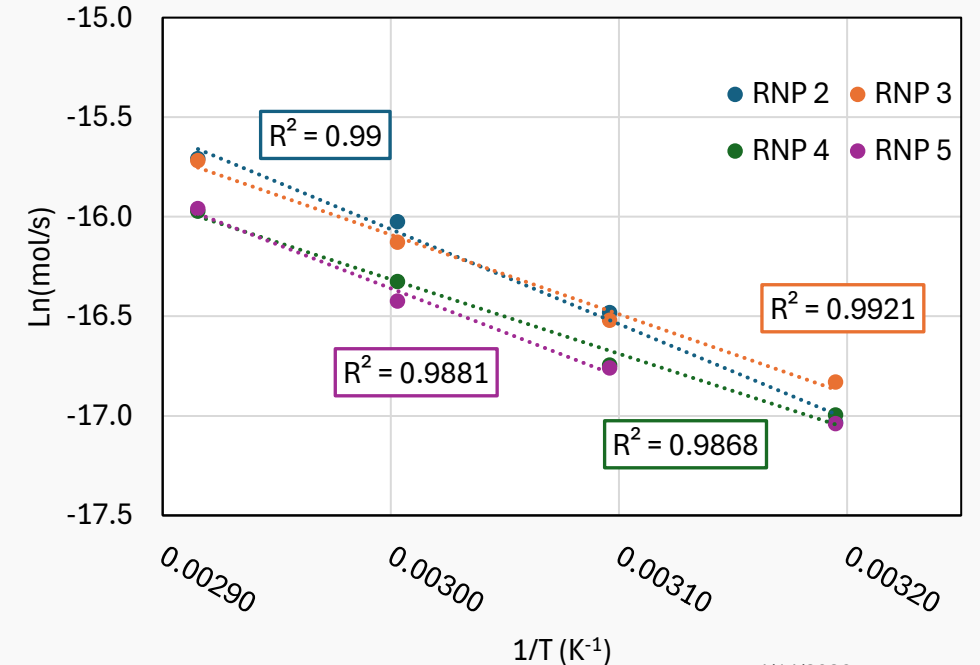
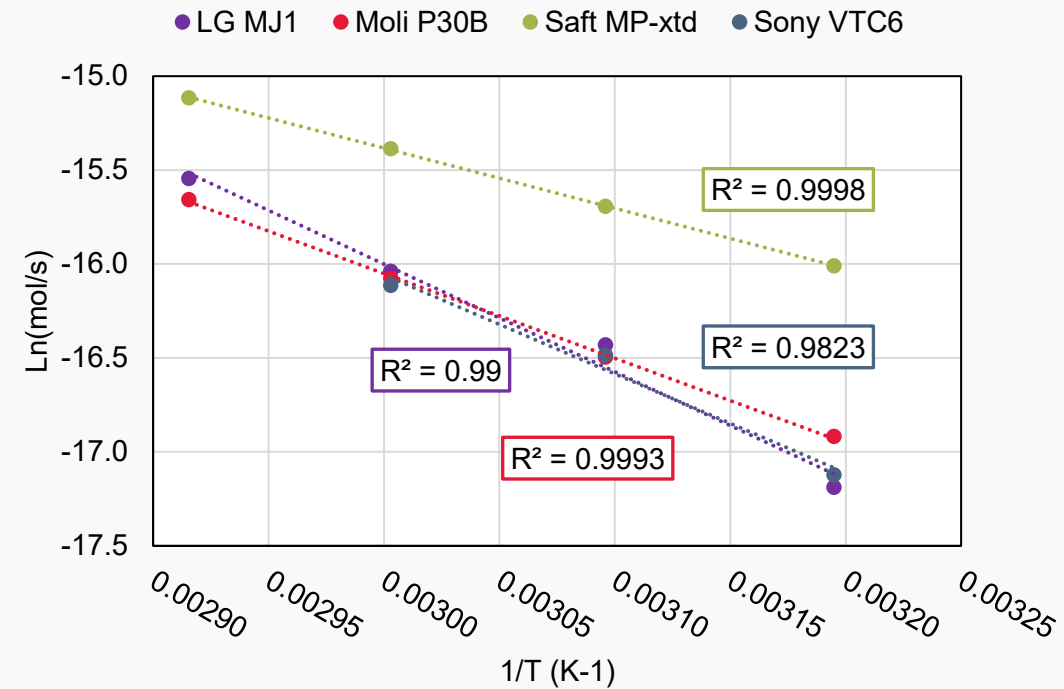
- 40.5 kJ/mol calculated from Sony US18650 data sheet by Sponitz<sup>1</sup>
- 29-32 kJ/mol measured on custom 18650s by Dhan's group<sup>2</sup>

<sup>1</sup>R. Sponitz, *J. Power Sources*, **2003**, 113, 72.

<sup>2</sup>C. Floras et al., *J ECS*, **2025**, 172, 020514.

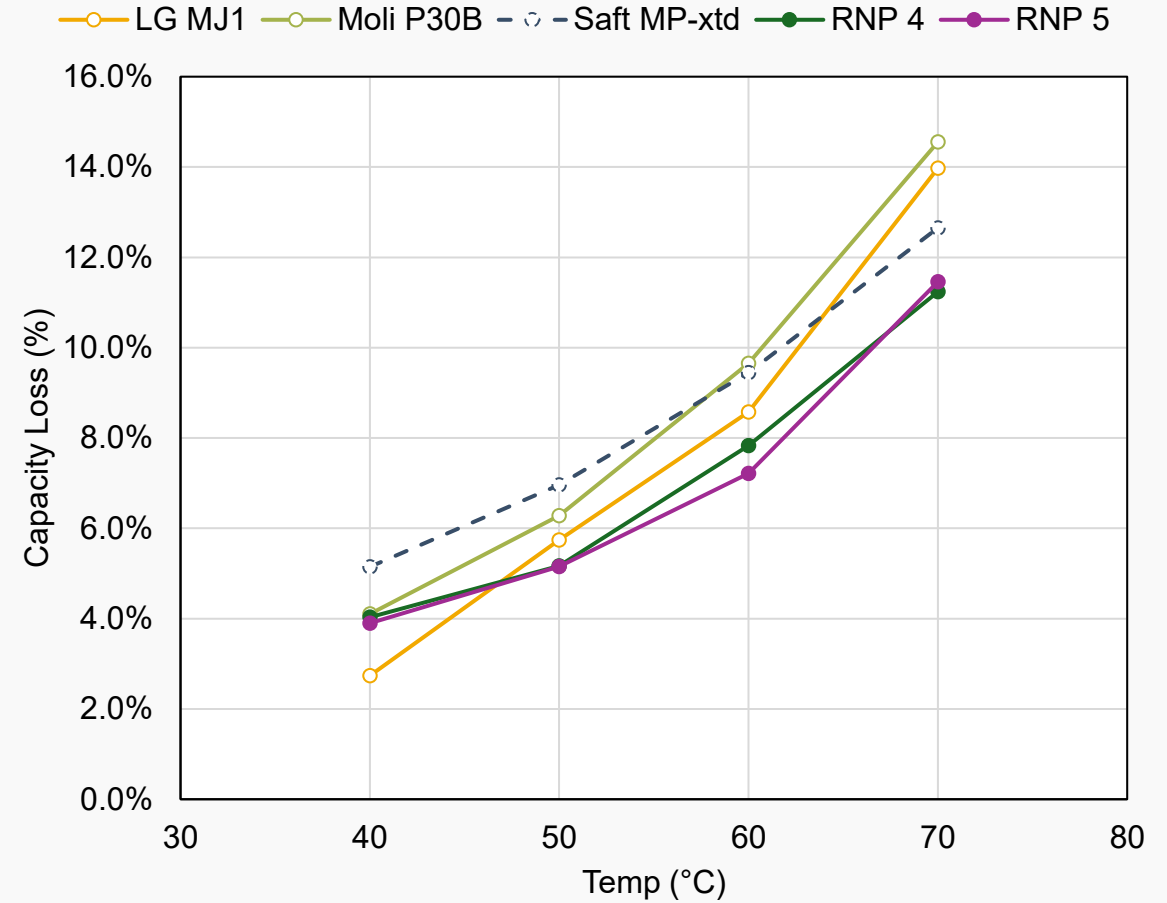
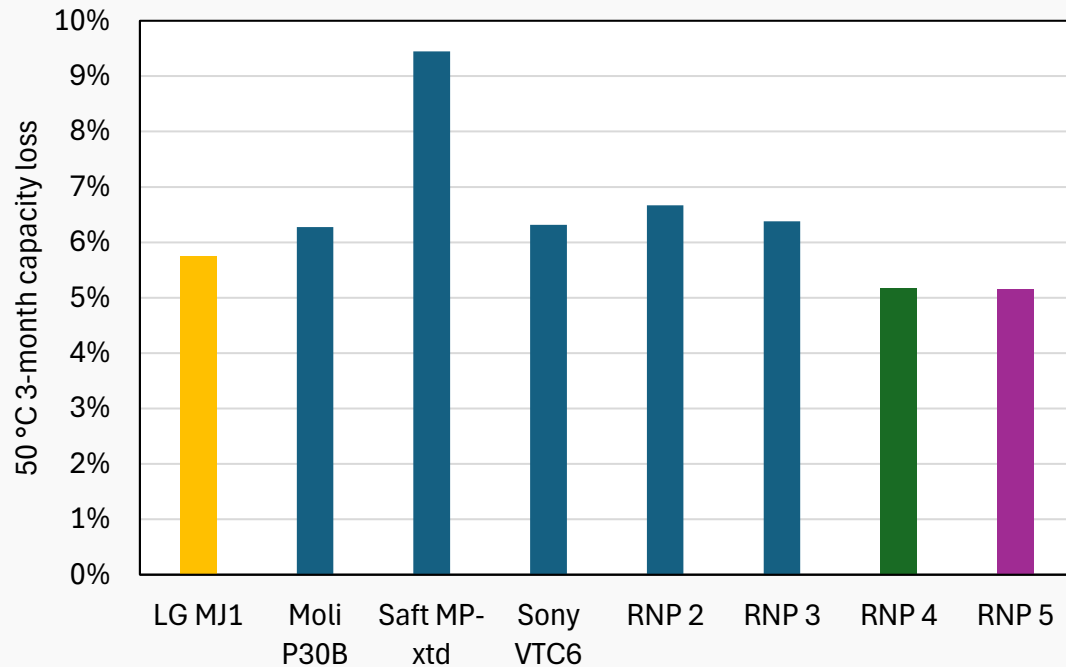
<https://doi.org/10.1149/1945-7111/adb184>

	$E_a$ (kJ/mol):
LGMJ1	47.6
Moli P30B	37.5
Saft MP-xtd	26.7
Sony VTC6	43.8
RNP 2	39.6
RNP 3	33.2
RNP 4	31.1
RNP 5	36.8



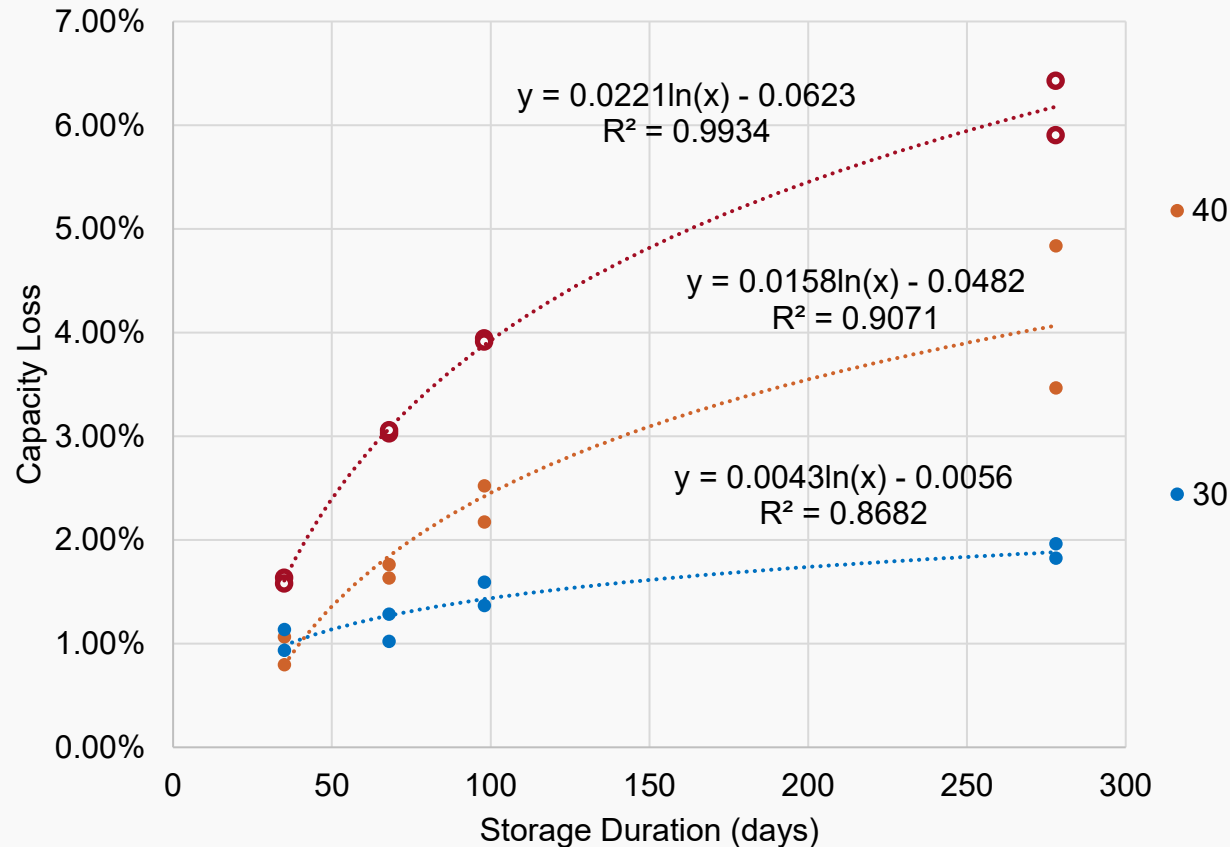
# Custom vs. COTS Cell Storage

- JPL-developed electrolytes are better than COTS options for every case  $\geq 50\text{ }^{\circ}\text{C}$
- Direct scaling of these values would mean that RNP 5 slightly edges out RNP 4, and both beat MJ1



# Long Term MJ1 Storage Data

LG MJ1 Storage at 3.8 V



- In a different project, MJ1 cells were stored for nine months and checked at regular intervals
- Storage temperatures lower overall (30-50 °C)
- Not directly comparable to prior data because the storage voltage was 3.8 V rather than 3.9 V
- These data demonstrate that at least MJ1 cells age mostly during the first three months of storage at 40 and 50 °C, and then level out
- If this holds for other cell types, then a 5-year mission with a +50 °C AFT may be achievable
- Unfortunately, this behavior cannot be predicted by Arrhenius analysis because we assume 0<sup>th</sup> order reaction to complete the analysis

# Conclusion

- Continuous operation at 50 °C is well within the capabilities of COTS 18650s
- Cycle life is primarily determined by the cell design, rather than electrolyte
- MJ1 provides unmatched cycle life characteristics (within this test group)
- MJ1 also provides expanded temperature range operation up to 60 °C continuous, but starts to fall apart at 70 °C storage
- COTS 18650 cells tested are generally ok up to ~60 °C, but begin to fall apart beyond that
- JPL electrolytes based on 1.0 M LiPF<sub>6</sub> in EC+EMC (1:1 vol.) + 2% VC provide the best calendar life characteristics ≥50 °C, with <12% capacity fade at 70 °C over three months

# Acknowledgements

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