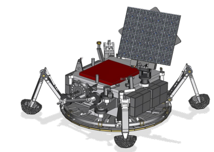
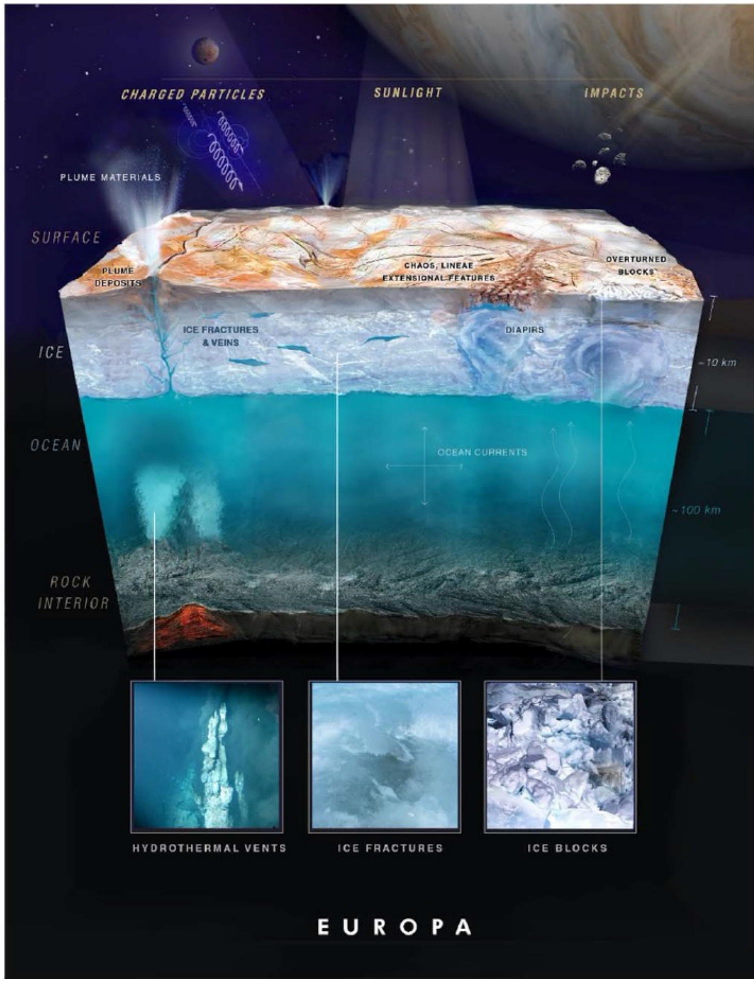


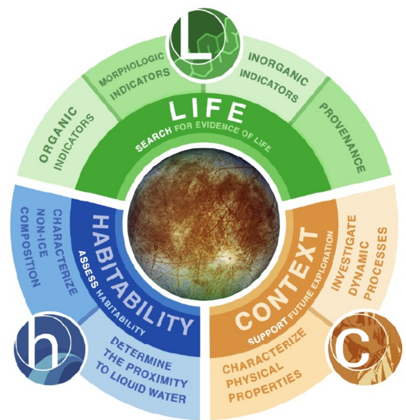
Development and Evaluation of Li/CF_x Primary Batteries for Deep Space Missions

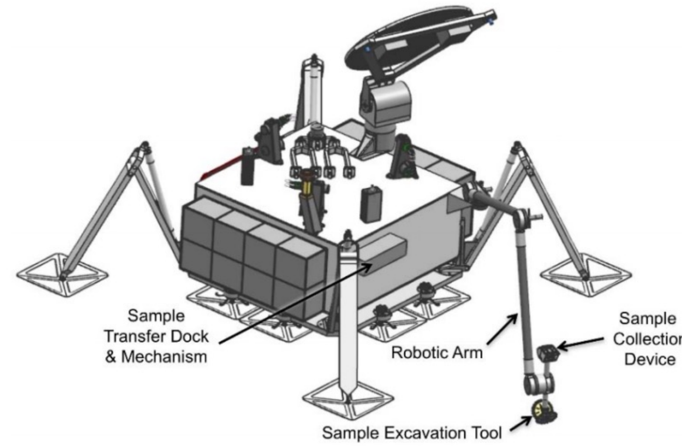
E.J. Brandon*, H.L. Seong, K. Billings, J. Pasalic, J.P. Ruiz, J.-P. Jones, R. Lin and E. Wood
Jet Propulsion Laboratory, California Institute of Technology
Pasadena, CA

NASA Aerospace Battery Workshop
November 16, 2022

Europa Lander Mission Concept

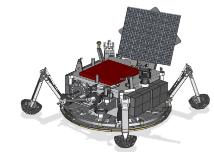


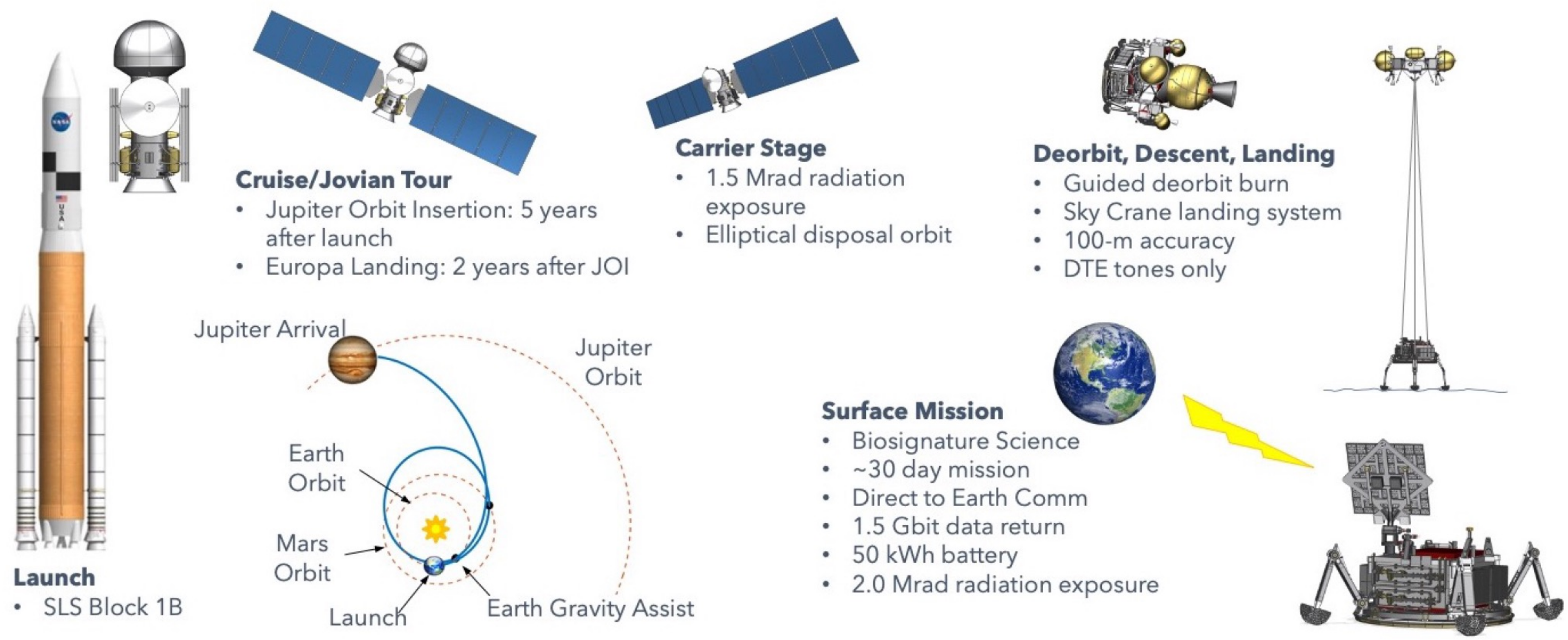




- A mission concept to land on Europa
- Europa is an ocean world within our solar system, believed to harbor significant liquid water under an icy shell
- Mission objectives:
  - Assess habitability
  - Search for evidence of life
  - Characterize the surface to support future exploration
- “Civilization-scale science mission”

Europa Lander Mission Timeline

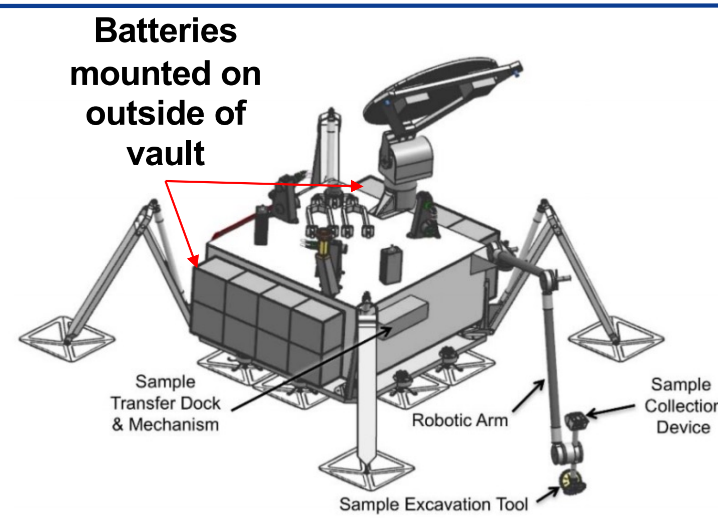




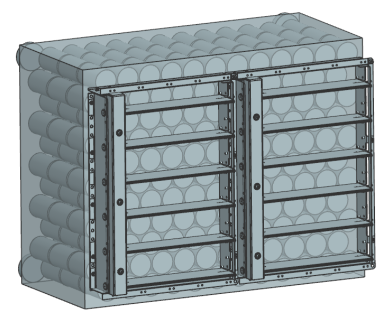
- **5+ year cruise time** after launch to reach Jupiter Orbital Insertion (JOI)
- Europa landing **two years after JOI**
- **20-30 day mission**

Europa Lander Primary Battery Mission

- **Primary battery only mission**
  - 50 kWh total energy
  - ~100 kg battery mass
  - 20-30 day mission to achieve primary science objectives
- **Initial target of 500 Wh/kg battery**
  - 4X battery modules
  - ~12.5 kWh each
- **Estimate ~700 Wh/kg required for the cell specific energy**
  - 75% allocated for cell mass
  - 25% overhead for battery packaging/structure
- **Must also consider de-ratings for losses and design principles**
- **Identify opportunities to increase specific energy**
  - Provide extra margin on the mission timeline
  - Extend timeline on the surface for additional science activities

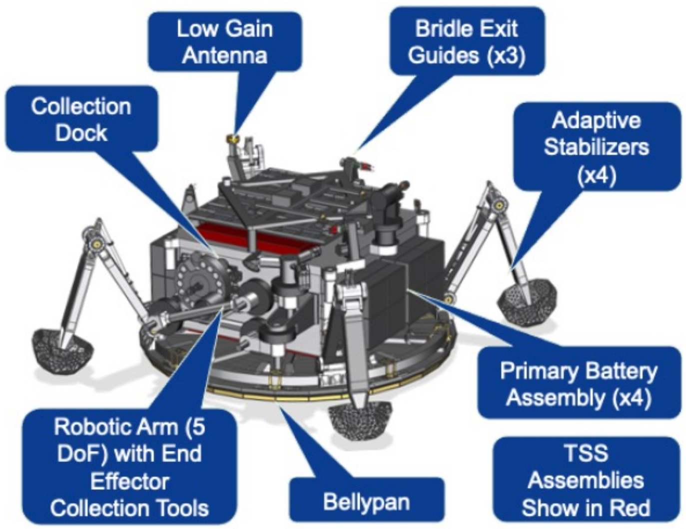


Notional Lander Concept



Initial battery module design (~12.5 kWh)

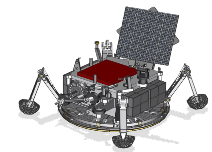
Defining Europa Lander Battery Needs



Parameter	Values	Comments
Operational temperature	0 to +70°C	Significant waste heat from avionics and cells
Non-operational temperature	-40 to +70°C	During cruise stored at 0ºC
Peak power	~510 W	Sampling
Average power	~50 W	20 W sleep mode
Radiation tolerance	2-3 Mrad	JOI and Landing
Storage Duration	7-11 years	Pre-launch, cruise and JOI

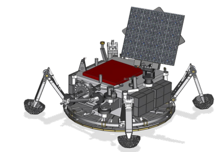
- Initially assume 12s26p module design operating over 24 – 31V
- Max. power is 510W / 24V = 21A / 26p strings = **800 mA / cell** (sampling warm-up power mode)
- Min. power is 20W / 31.2V = 0.640 A / 26p strings = **25 mA / cell** (sleep mode)
- Currents may be <25 mA, due to a lower sleep power mode, use of more strings or both

Initial Consideration of Battery Deratings



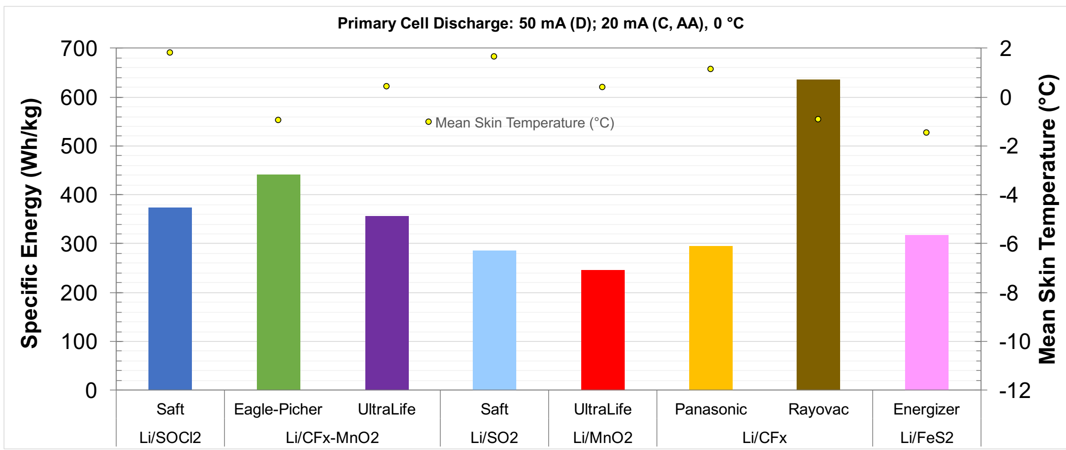
Loss Factor	Value	Comments
Depassivation Requirement	-3%	JPL Design Principle
80% Depth of Discharge Requirement	-20%	JPL Design Principle
Loss of string	~500 Wh (-1%)	JPL Design Principle
Storage Losses	-16%	Estimate based on 2% annual loss at 20ºC
Other losses	-5%	Estimate based on 10 Mrad radiation testing

- What can we do to address deratings of nearly -45%?
- First: target maximum initial cell specific energy

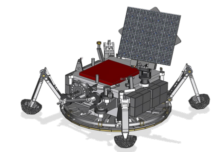


Initial COTS Screening for High Specific Energy Options (ca. 2018)

Specific Energy at ~C/300 and 0 ºC



- Li/CF_x only realistic option to meet mission requirements (>700 Wh/kg target)
- Enabled by moderate temperature and low rate conditions
  - Highest current well within Li/CF_x limits
  - *Low currents may actually pose challenges*
- Radiation tolerance largely unknown at the time

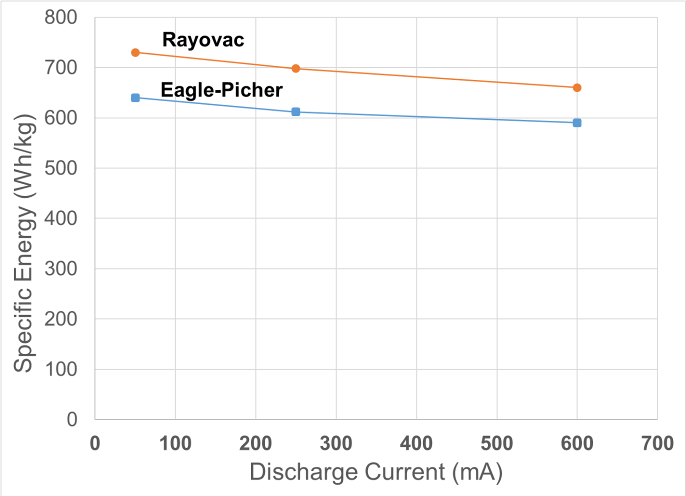


Li/CF$_x$ D-Cell Datasheet Values (2018)

	EaglePicher	Rayovac
Part #	LCF-129	Developmental D
Nominal Voltage (V)	2.6	2.5
Capacity (Ah)	**16** **(25ºC, 2 A, 2V cut-off)**	**19** **(22ºC, 50 mA, 2V cut-off)**
Maximum Current (A)	4	3
Height (mm)	54.88	56.9
Diameter (mm)	33.3	33.2
Mass (g)	**85**	**69**
Operating temperature range (ºC)	-40 to +85	-20 to +90
Self Discharge (%/year)	1	2
Specific Energy (Wh/kg)	**471* (2 A)**	**716** (50 mA)**
Case	**Steel**	**Aluminum**
*Evaluated at 25ºC, 2 A to 2V cut-off **Evaluated at 22ºC, 50 mA to 2V cut-off		

Initial JPL Li/CF_x D-Cell Screening (Aluminum Packaging)

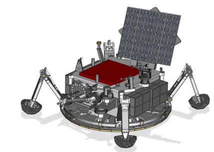
	1.5V cut-off (50 mA, 20ºC)		2.0V cut-off (50 mA, 20ºC)	
	Capacity (Ah)	Specific Energy (Wh/kg)	Capacity (Ah)	Specific Energy (Wh/kg)
Eagle-Picher	17.5	641	17.39	640
Rayovac	19.5	729	19.2	724



Specific Energy vs. Discharge Current (20ºC)

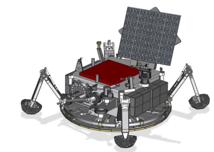
- Represented "off-the-shelf" cells that were available from the vendors
- Both featured developmental aluminum packaging
- Not yet optimized for Europa Lander

Europa Lander Battery Development Task



- In 2018, the Europa Lander project embarked on a major effort to develop and test improved Li/CF_x cells that could meet the aggressive mission targets
- JPL engaged two vendors to support three generations of Li/CF_x cell "builds" to demonstrate >700 Wh/kg
  - Rayovac
  - EaglePicher Technologies
- Focus on increasing specific energy through cell process improvements
  - Low mass aluminum can design
  - Increase active material loadings
  - Evaluate alternative electrolytes
- Designed and implemented extensive test campaign to evaluate suitability for Europa Lander mission concept
- Following Build 1, Rayovac exited the Li/CF_x business
- Executed three total cell builds with EaglePicher
  - Final cells will be delivered in late 2022
  - This talk will focus on preliminary Build 3 results, for cell testing completed to date

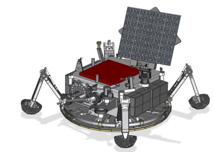
EaglePicher Cell Improvements



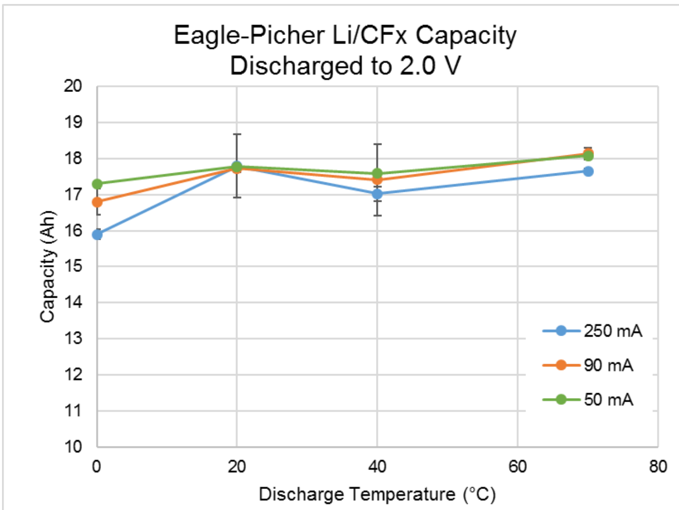
- Use of commercially available carbon fluoride (CF_x) powder
- EPT manufactured cells in D-size form factor using aluminum cases
- Advanced web coating process similar to that used in lithium ion technology
- Cathode composition / formulation optimized for high electrode density
  - Foil current collector
  - 50-60 micron thickness electrodes
- Baseline electrolyte: $LiBF_4$ salt in a solvent blend of propylene carbonate and 1,2-dimethoxyethane (PC:DME)
  - Incorporated JPL modified electrolytes in a sub-set of cells

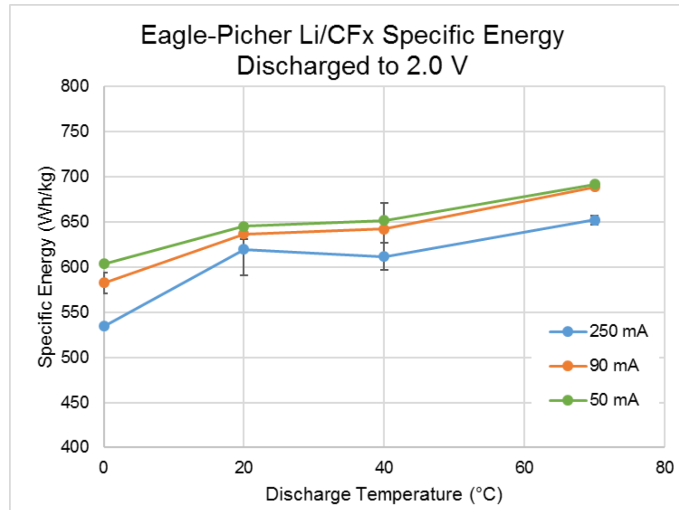
References

1. "Advanced Li-CFx Technologies for Space Application," Mario Destephen, Eivind Listerud, Ernest Ndzebet, and Dong Zhang, AIAA Propulsion and Energy Forum 10-12 July 2017, Atlanta, GA, 15th International Energy Conversion Engineering Conference.
2. "Advances in Lithium Carbon Monofluoride (Li/CFx) Technologies," Mario Destephen, 2022 Advanced Power Systems for Deep Space Exploration Conference, Aug. 30 to Sept. 1, 2022 (Virtual).



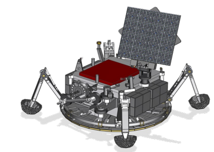
Build 1 EaglePicher Li/CF_x D-Cell Performance Recap (2018)





- **Capacity:** Between ~16-18 Ah
- **Specific Energy:** Between ~525 and 700 Wh/kg
- Fell short of >700 Wh/kg target at all rates and temperatures
- Targeted improvement with higher energy cathodes in Builds 2 and 3

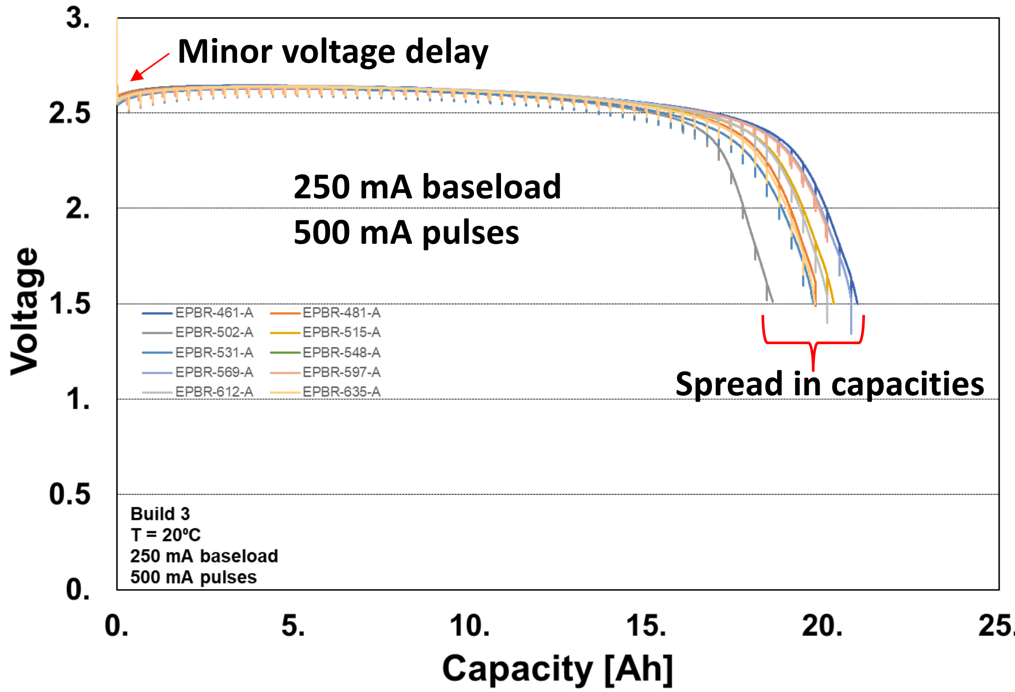
Build 3 Li/CF$_x$ Cell Test Campaign

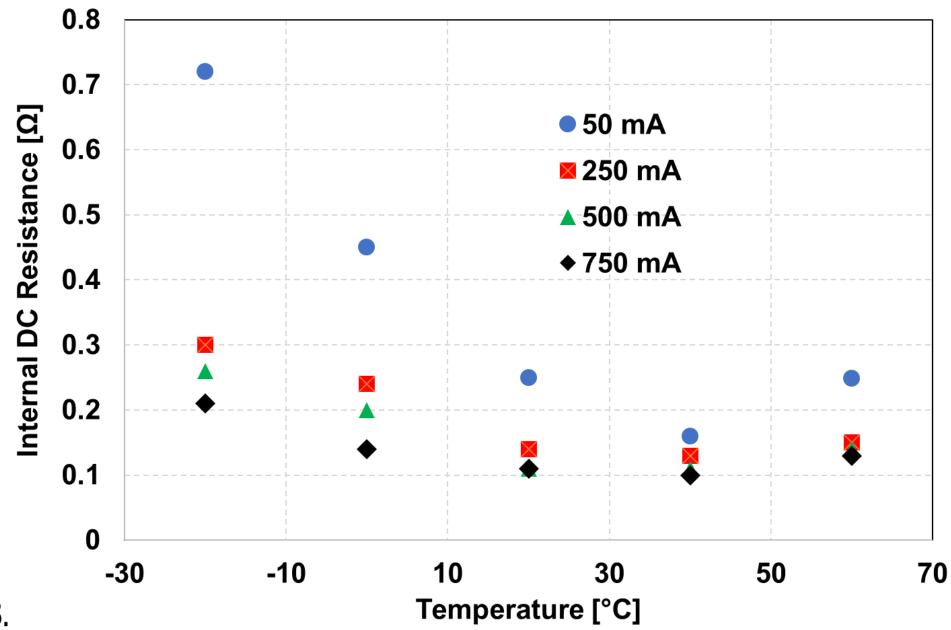


- Receive 200 baseline cells total
- Cell Dispersion Testing
- Beginning-of-life (BOL) Performance Testing
- Irradiated and Aged Performance Testing
- Storage Testing
- Voltage Delay / Depassivation Testing
- Heat Evolution Testing
- Gas Sampling of Irradiated Cells

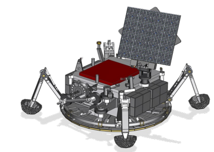
Test	Number of Cells
Cell Dispersion Testing	10
BOL Pristine Performance Testing	72
Aged Irradiated Performance Testing	24
Self Discharge Testing	60
Depassivation / Voltage Delay Test	6
Heat Evolution	9
Control Cells (irradiation)	6
Gas sampling irradiated cells	13
Total	**200**

Li/CF$_x$ D-Cell Build 3
Dispersion Testing at 250 mA and 20°C (2022)

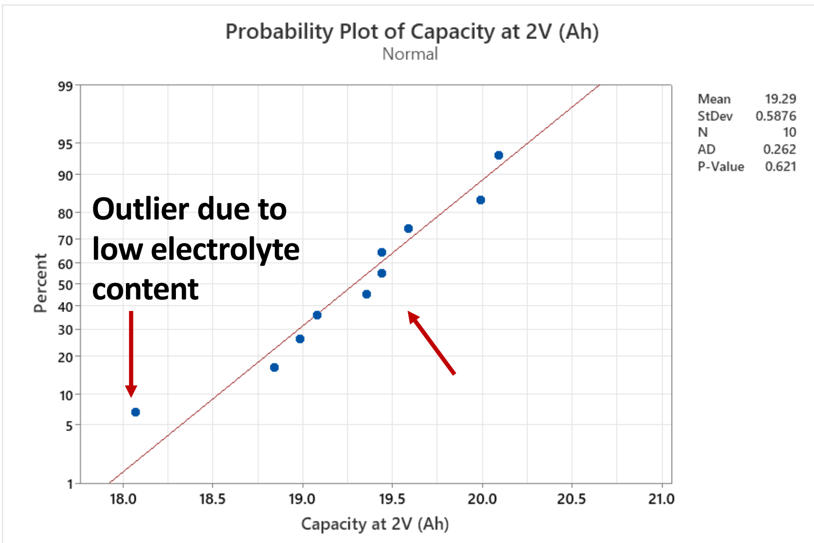


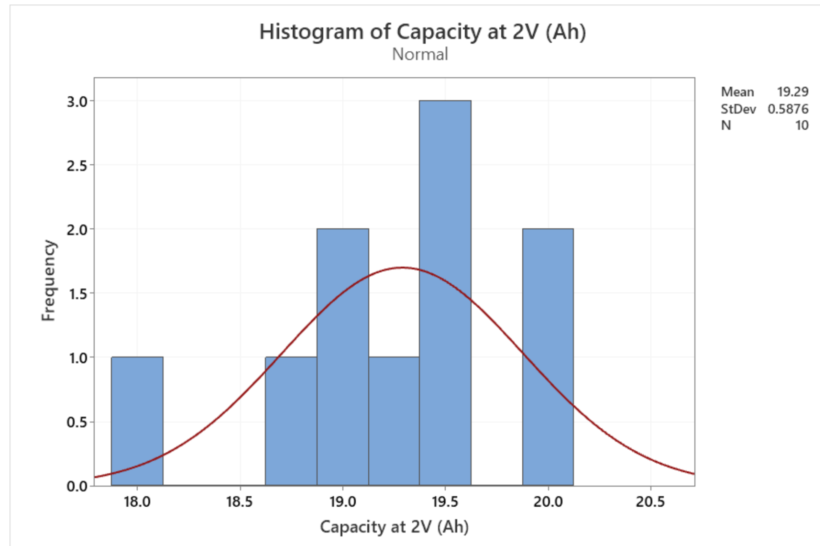


- Initial voltage delay settling in to discharge voltage of 2.6V
- Evaluate spread in capacities to better inform deratings
- Superimposed 500 mA pulses on 250 mA baseload, to extract internal cell resistance



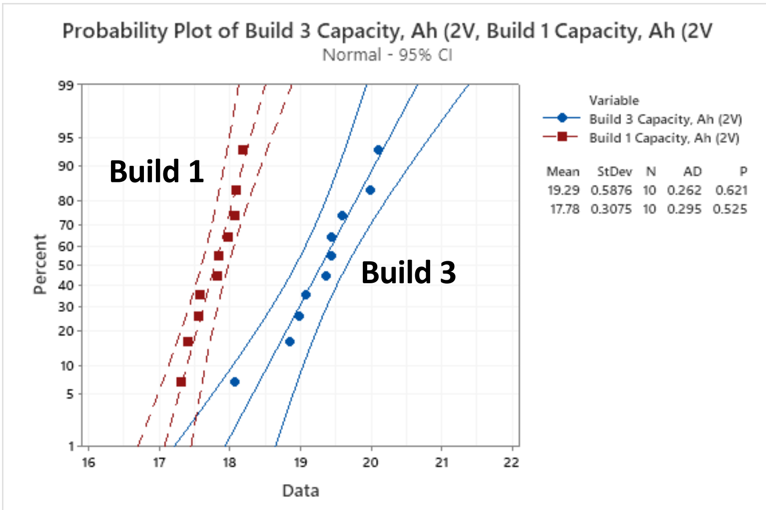
Build 3 Capacity Dispersion Data
Li/CF_x D-Cells

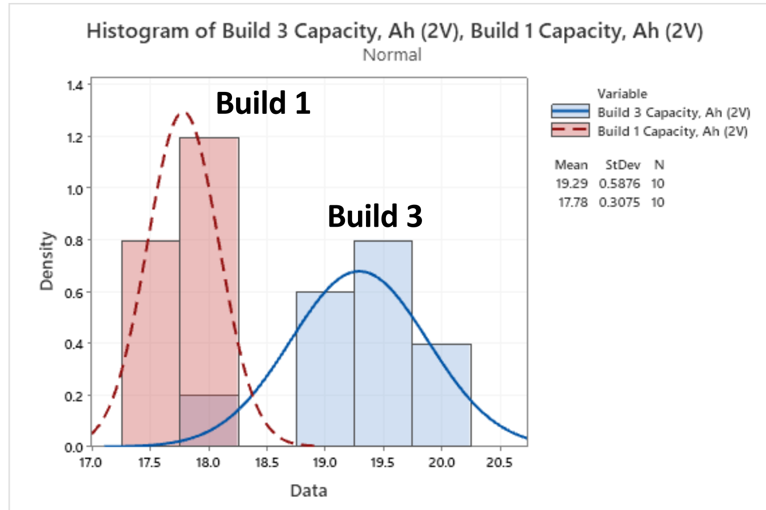




- Test 10 cells at 250 mA and 20ºC to evaluate capacity dispersion
- Monitor manufacturing process
- Use to re-consider 80% DOD battery requirement, by better understanding cell-to-cell variances
- Outlier later identified with low electrolyte content

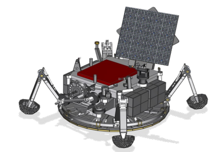
Li/CF$_x$ D-Cell Capacity Dispersion
Build 1 vs. Build 3 (2018 vs. 2022)



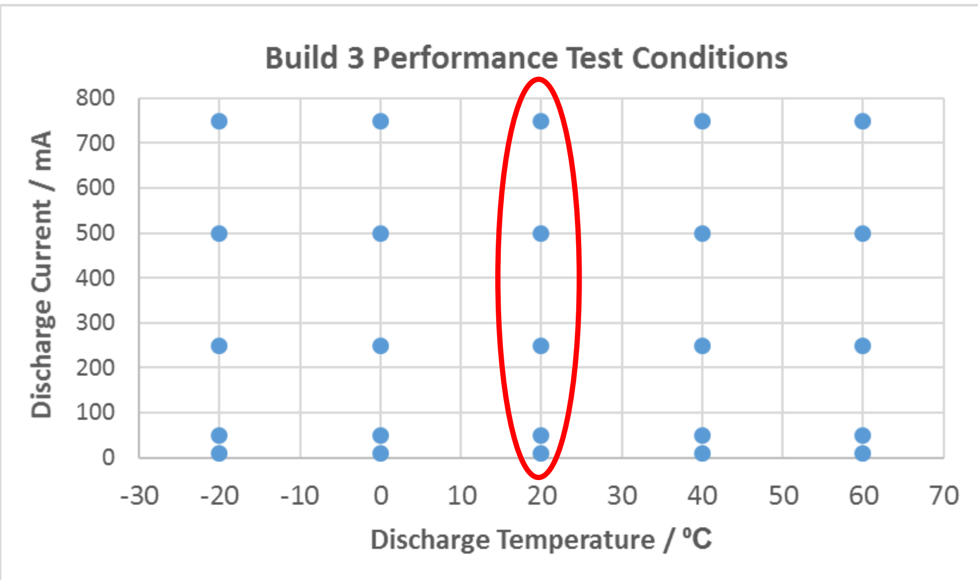


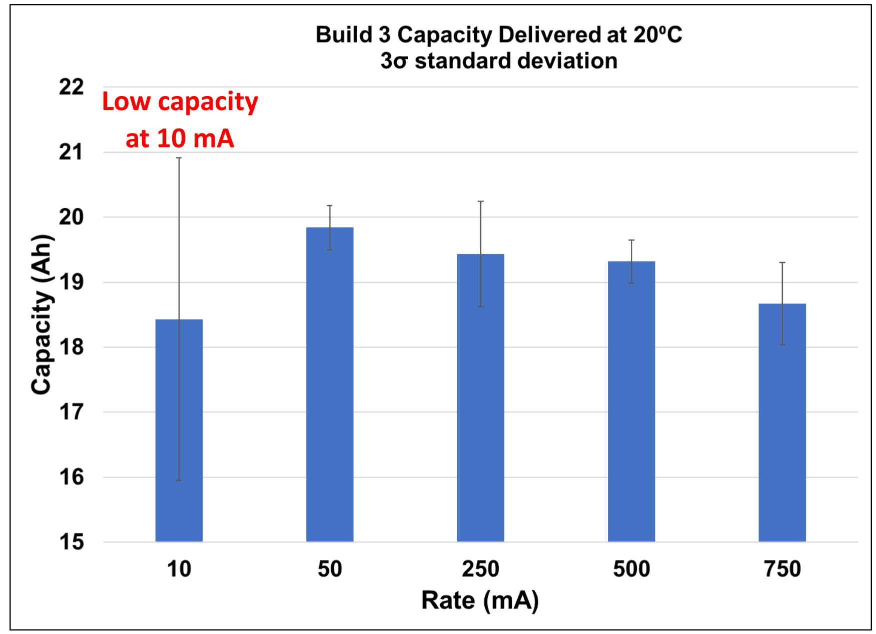
ID	Mean Capacity (Ah)	Standard Dev.
Build 1	17.78	0.3075
Build 3	19.29	0.5876

- Improved capacity for Build 3 vs. Build 1, but with wider spread in mean values
- Still a developmental cell, can improve dispersion with improved manufacturing controls following scale-up

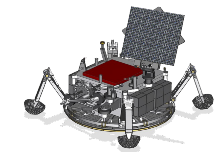


Build 3 Multi-Rate Testing at 20⁰C

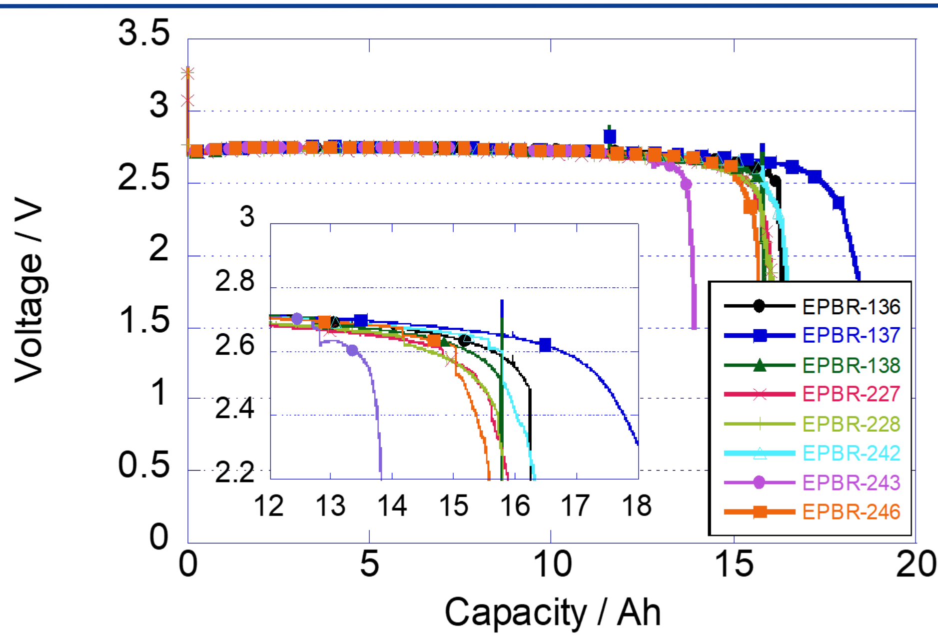


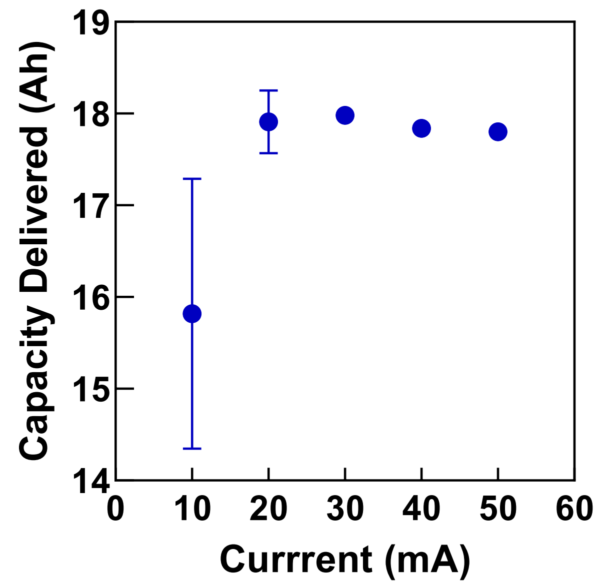


- Unusual trend first observed in Build 1 and again confirmed in Build 3
- Very low rate (10 mA) discharge results in anomalously low capacity delivery
- Low mean value relative to 50 mA condition, and much larger dispersion in values



Unexpected Low Capacity Delivered at Very Low Rates in Builds 1 and 2

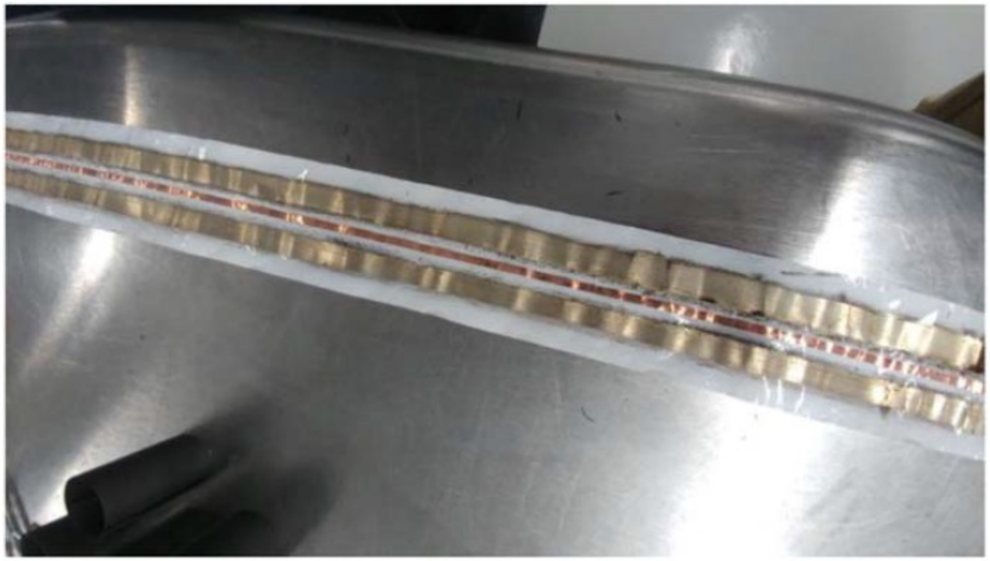




- 10 mA discharge at 20ºC resulted in capacities in 14-19 Ah range
- Converges to high capacity with little spread at currents ≥20 mA

"Anomalous Behavior During Low Rate Discharge of Li/CF_X Cells," Hui Li Seong et al 2022 J. Electrochem. Soc. 169 060550

Rate Dependent Li Anode Utilization

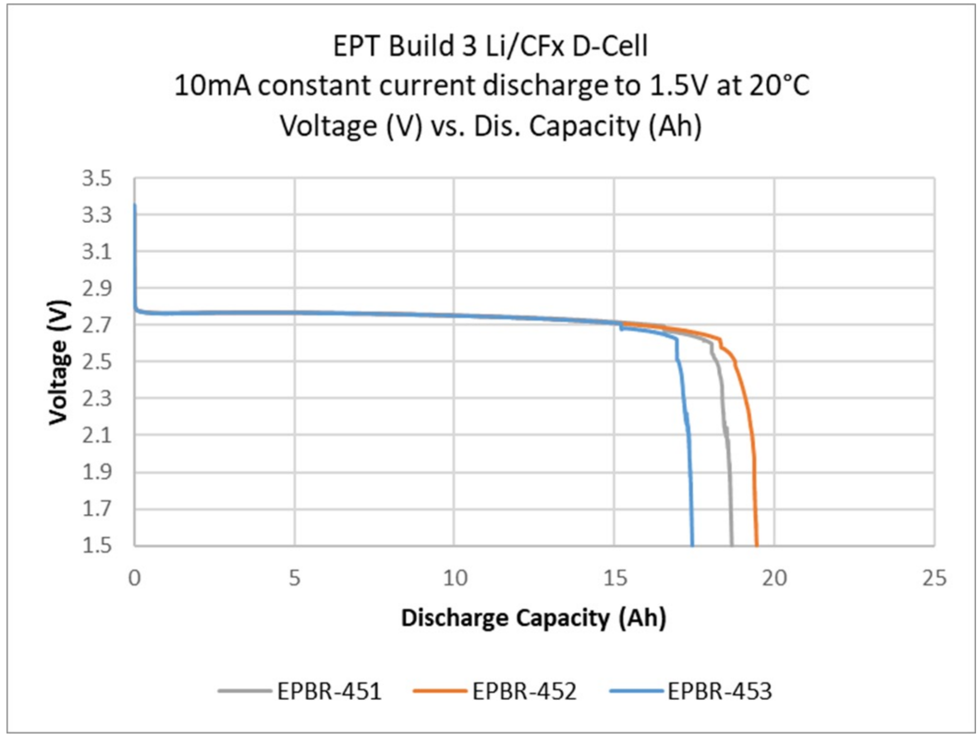


Discharged at 10 mA and 20°C (~13.25 Ah)

Discharged at 250 mA and 20°C (~19 Ah)

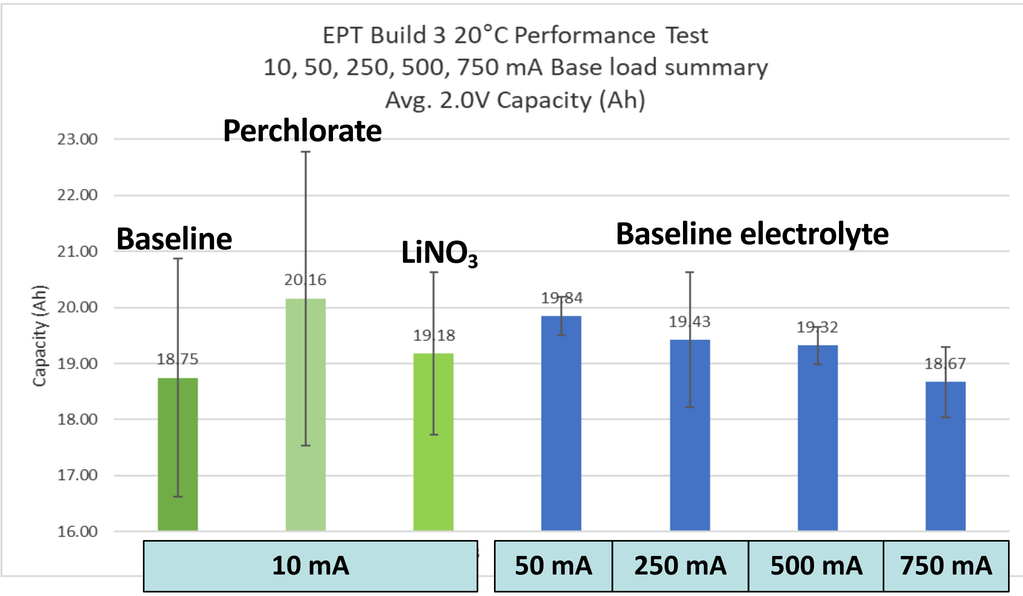
Li anode utilization is poor at very low rates

Similar Observation with Build 3 Cells at 10 mA



- Spread not as large relative to Build 1 and 2 cells
- Still spans from ~17–19 Ah with low mean value

Evaluating Alternative Electrolytes

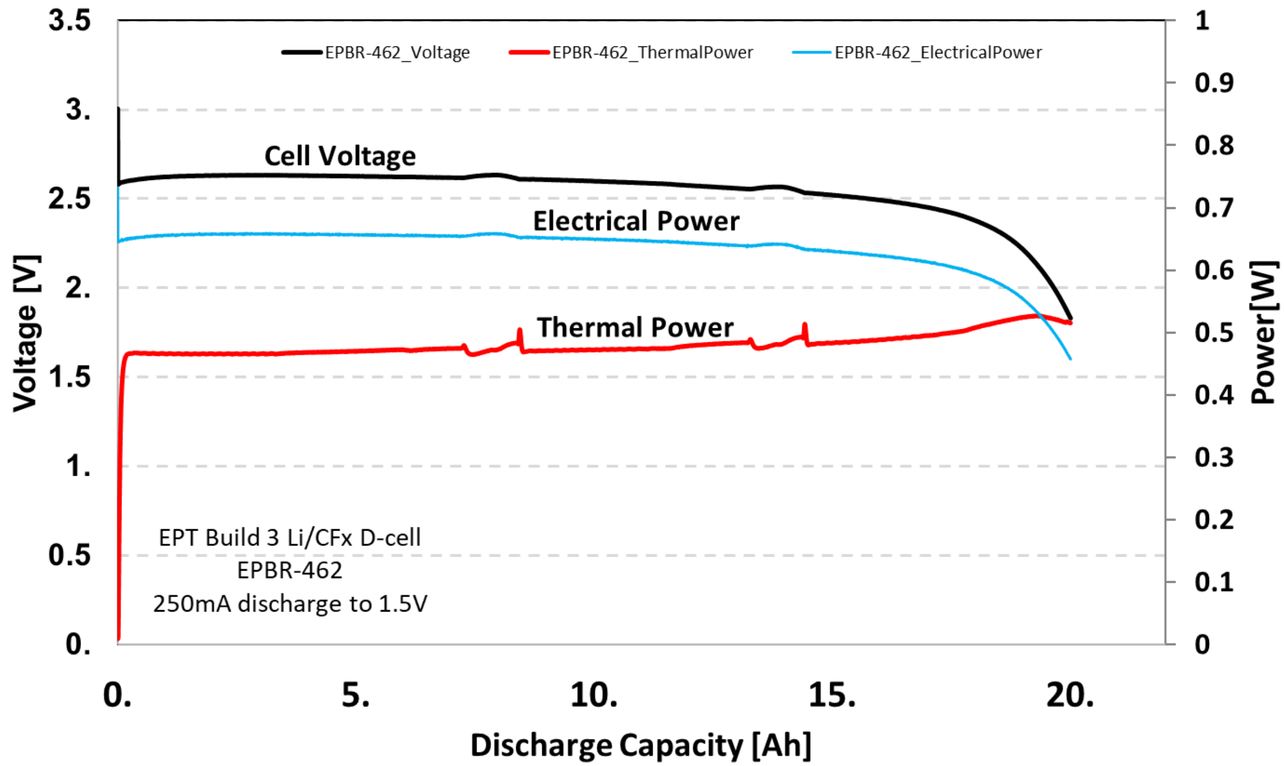


Electrolyte	Current	Capacity	Specific Energy
Baseline	10	18.8	716
Perchlorate salt	10	20.2	771
$LiNO_3$ additive	10	19.2	732
Baseline	50	19.8	741
Baseline	250	19.4	698
Baseline	500	19.4	680
Baseline	750	18.7	653

Baseline: 0.75 M $LiBF_4$ salt in PC:DME (3:7)
$LiNO_3$: 0.75 M $LiBF_4$ salt in PC:DME (3:7) with <1% $LiNO_3$
Perchlorate: 0.75 M $LiClO_4$ salt in PC:DME (3:7)

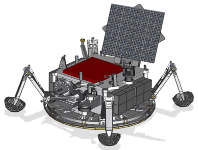
Cell specific energy now in the 650 – 770 Wh/kg range from 10 – 750 mA at 20°C

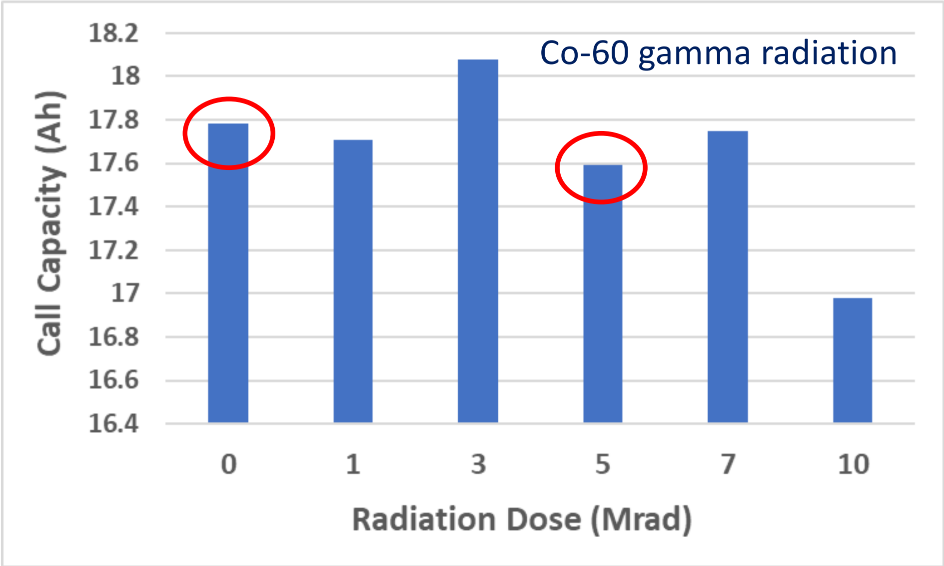
Build 3 Isothermal Calorimetry to Evaluate Thermal Power Output



Across all rates there is a ~55 to 45% ratio of electrical to thermal power output

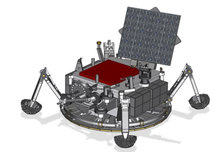
Radiation Losses on Build 1 Li/CF_x D-Cells





- Initial radiation testing indicates little impact on capacity for <10 Mrad TID
- Prior Build 1 testing indicated approximately 5% loss in capacity at 10 Mrad TID
- Updating more extensive 5 Mrad results from Build 3
- Expect little impact on cell performance (but concerns with use of perchlorate salt)
- Safety testing performed on irradiated cells by Sandia National Laboratory indicated no impact on cell behavior

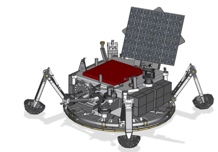
Updated Cell Derating Estimates Based on Extensive JPL Test Campaign

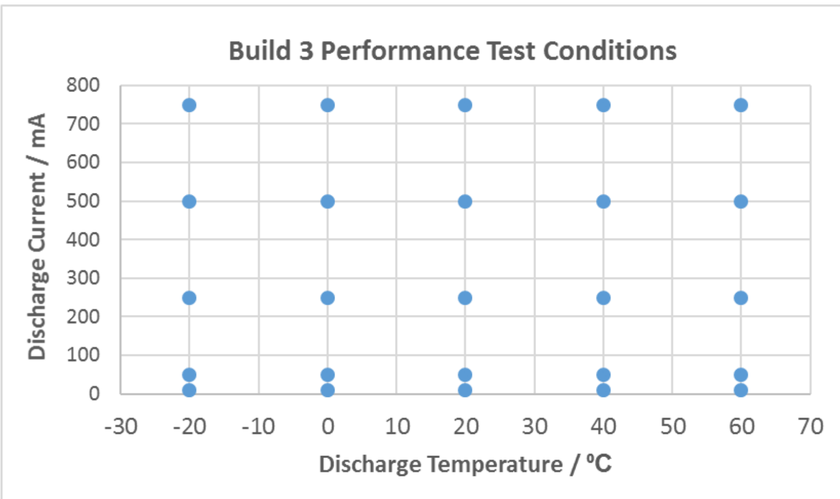


Loss Factor	Comments	Update	Original Estimate	New Value
Depassivation Requirement	JPL Design Principle	Nominal on-load voltage reached without de-passivation step; will seek waiver	-3%	-0%
80% Depth of Discharge Requirement	JPL Design Principle	Actual cell-to-cell variance is close to 10% from dispersion testing	-20%	-10%
Loss of string	JPL Design Principle		~500 Wh (-1%)	-1%
Storage Losses	Estimate based on 2% annual loss at 20ºC	Actual testing indicates storage at 0ºC could bring to ~0.5% annually and ~4% total	-16%	-4%
Other losses	Estimate based on 10 Mrad radiation dose	Likely <1% based on actual testing results and updated 5 Mrad target	-5%	-1%
Total			**-45%**	**-16%**

Opportunity for improved deratings estimates and more realistic mission design

Creating a Power Model
JPL Multi-Mission Power Analysis Tool (MMPAT)





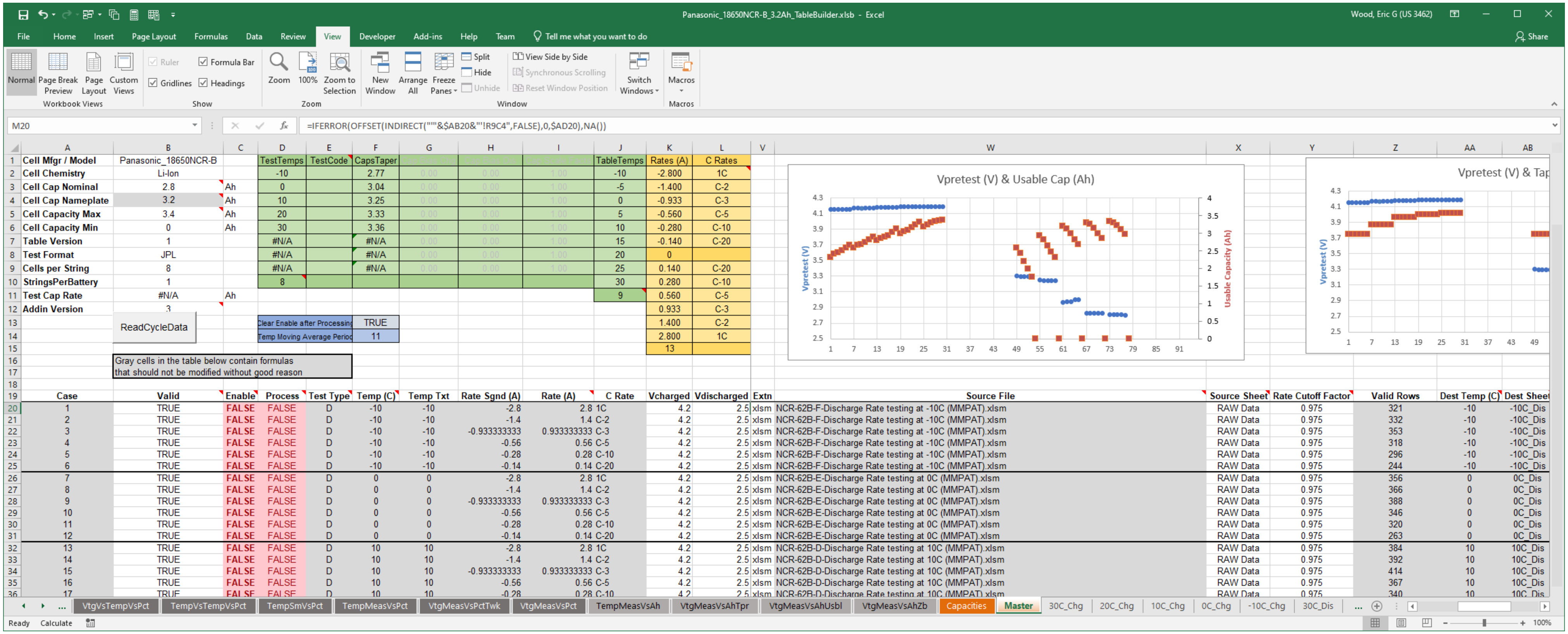
3 cells per condition (72 cells total)

Voltages at various rates, temperatures → **Table of voltages vs. SOC at various rates, temperatures**

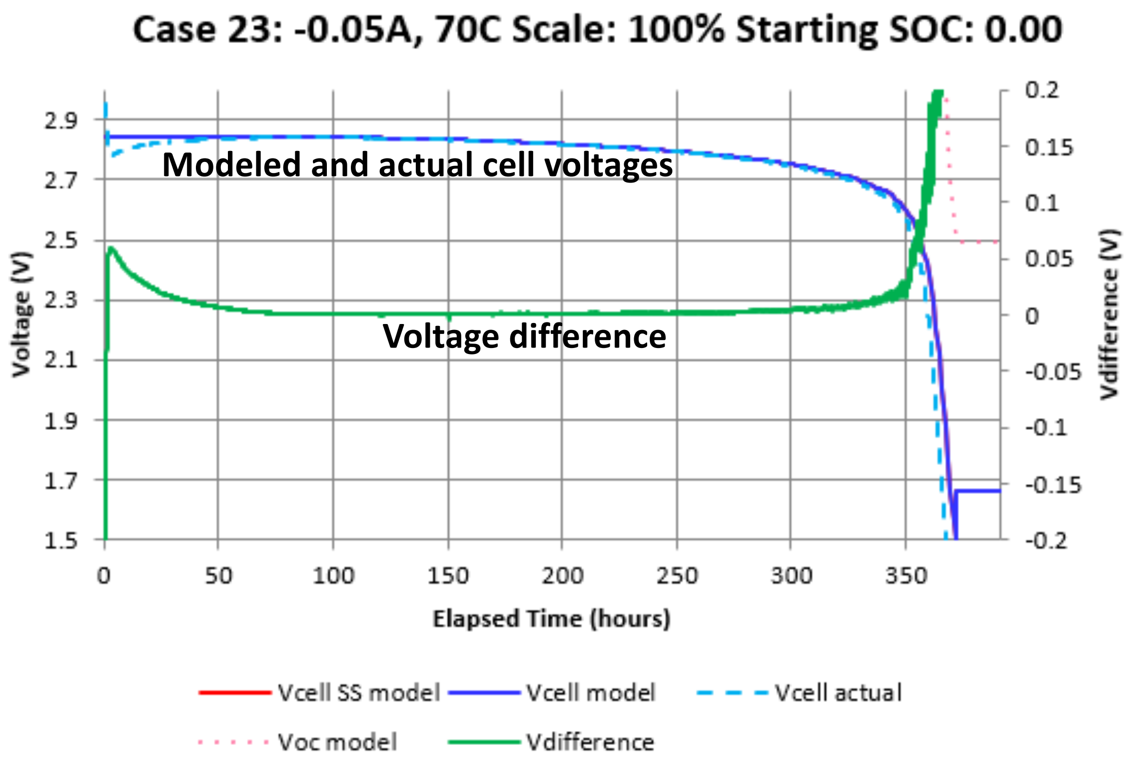
MMPAT Model Development Process

1. Incorporate all test cases into a single Excel Workbook
2. Create tables of voltage vs. SOC as a percentage of usable capacity at each test temperature and rate
3. Convert tables of voltage vs. measured test temperatures at a series of usable SOC% values at each rate
4. From the above create a set of tables of temperature-corrected voltages vs. SOC at each nominal test temperature and rate
5. Write a consolidated voltage table for MMPAT to read
6. Run each of the original test cases in MMPAT
7. Plot the results of the MMPAT runs on the same axes with the original test data and compare the results

Assembling Cell Test Data into a Single Excel Workbook

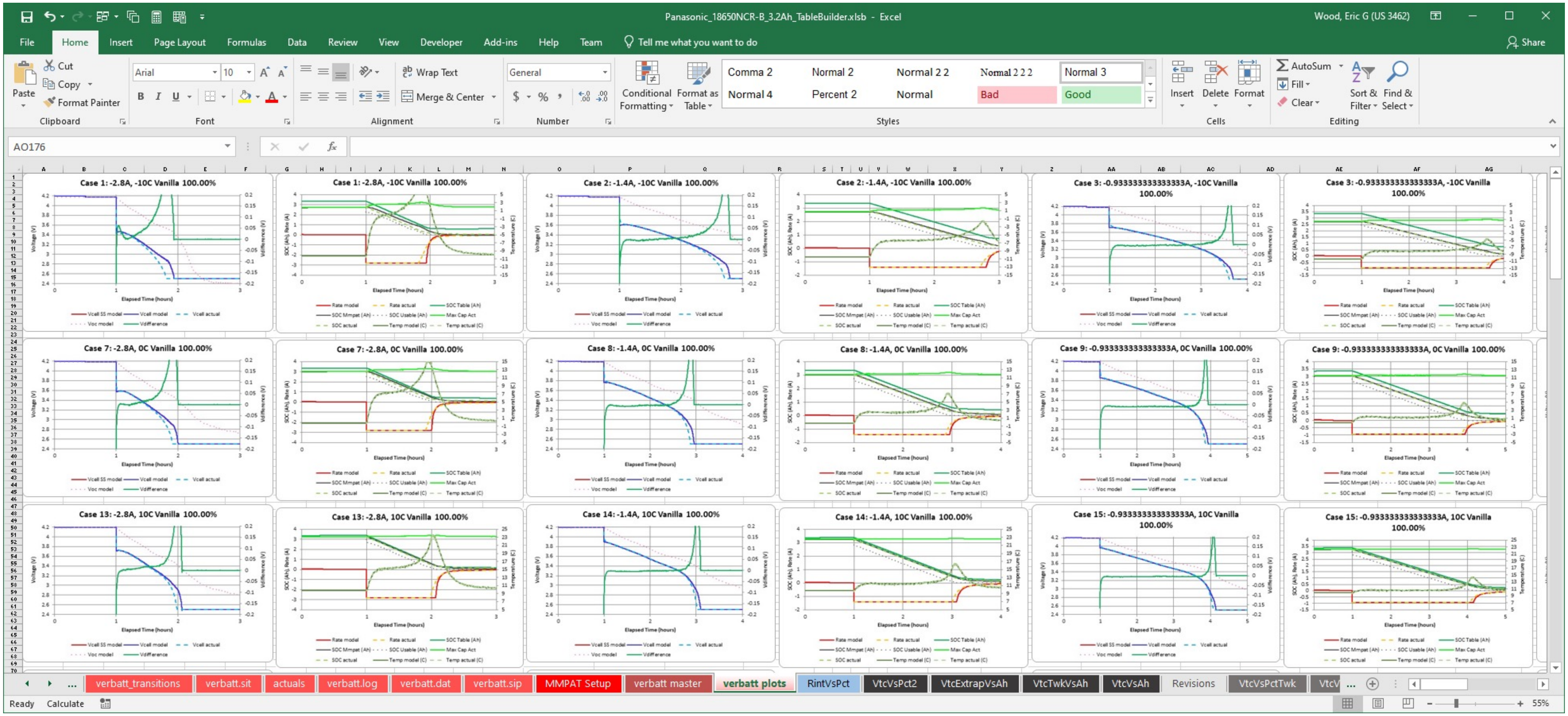


Comparison of Actual to Modeled Cell Voltage Based on One Validation Test Case

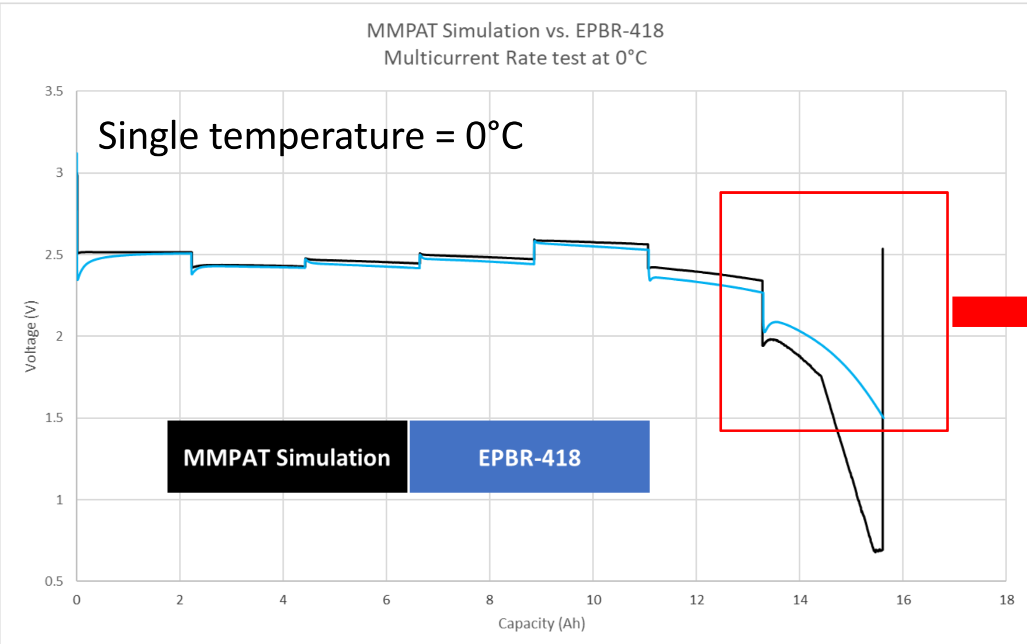


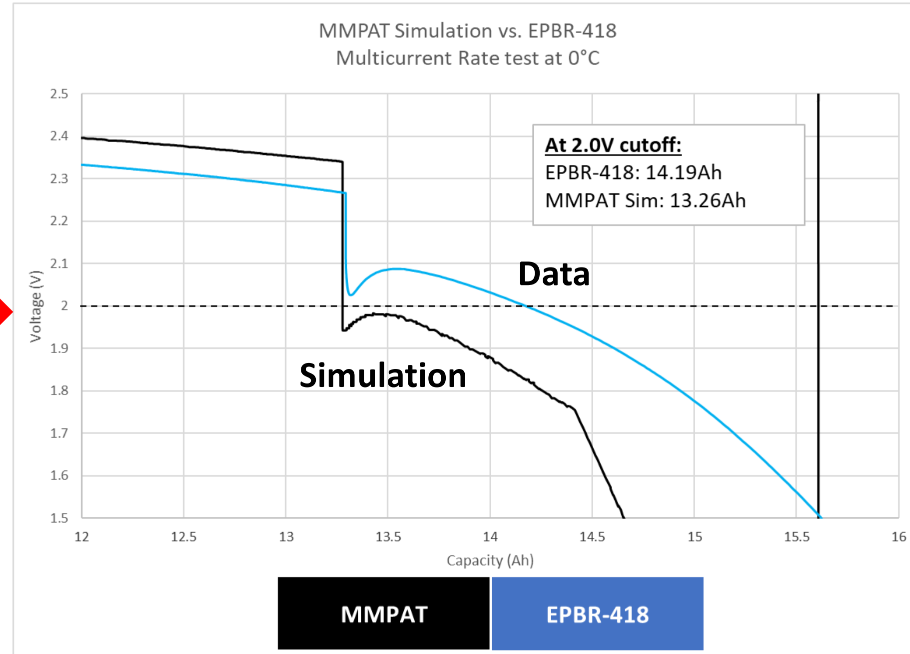
Good tracking of actual vs. modeled voltage, with larger deviation at the end of discharge

Validation of Cell Voltage Table Using the MMPAT Simulation Running All Original Test Cases



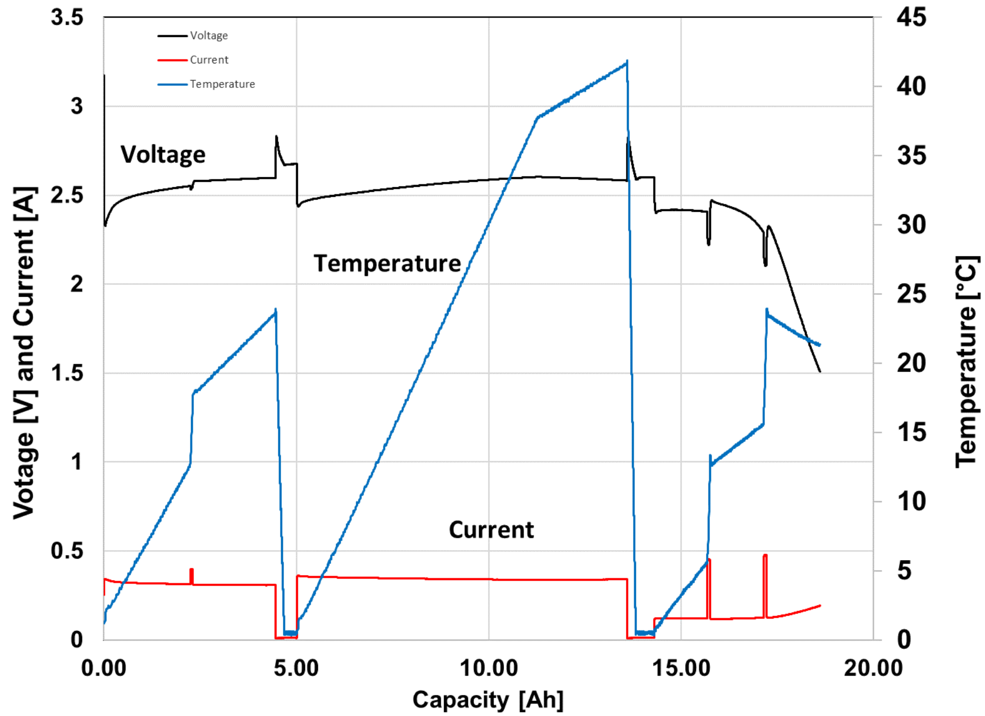
Initial Low Complexity MMPAT Test





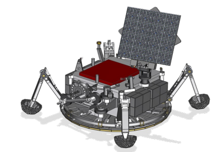
- Good voltage tracking with greater deviation at the end of discharge
- Underestimated capacity by ~7%
- Spread from dispersion testing ~5%

More Realistic Mission Sim Modeling and Testing



Evaluating more complex multi-rate, multi-temperature profiles (in progress)

Progress of Europa Lander Battery Cell Development 2018 - 2022

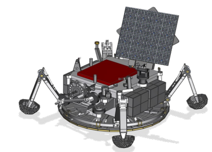


	Capacity (Ah)	Energy (Wh)	Cell Specific Energy at 20^{0}C and 250 mA to 2V cut-off (Wh kg^{-1})
Initial COTS cell design	16.98	43.3	614
Europa Lander Build 1	17.78	45.1	654
Europa Lander Build 2	17.80	42.8	657
Europa Lander Build 3	19.29	49.5	695
Baseline to Build 3 Increase	**+2.31**	**+6.2**	**+81**

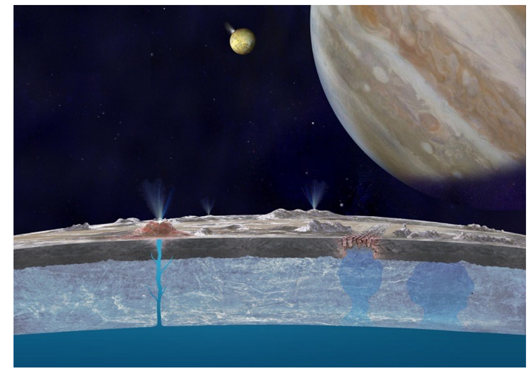
Battery Design 1: 1248 cells → ~8 kWh additional energy vs. COTS (Baseline design)
Battery Design 2: 1584 cells → ~10 kWh additional energy vs. COTS (Mission Life Extension)

Battery Design	# of Cells	Cell Mass (kg)	Battery Mass	BOL Energy
1	1248	89	119	61,855
2	1584	112	150	76,626

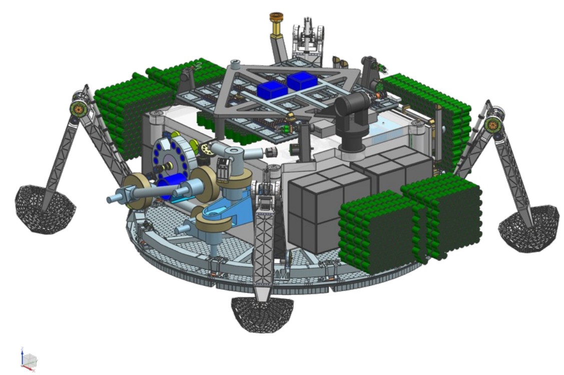
Conclusions and Path Forward



- Europa Lander investments in Li/CF_x technology have resulted in significant cell level performance enhancements (~650 to 770 Wh/kg)

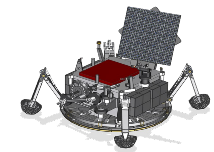


- Extensive test campaign has supported improved deratings estimates
- Europa Lander mission concept future uncertain, but many other space applications on the horizon
- Using power models to simulate operations for other mission concepts



- Next: New electrode materials and electrolytes to increase capacity
- Current collaboration with the City College of New York (Dr. Rob Messinger and his group), focused on detailed studies of CF_x

Acknowledgements



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