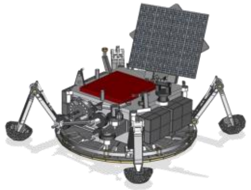

Development of High Specific Energy Li/CF_x Primary Battery Cells for Deep Space Missions

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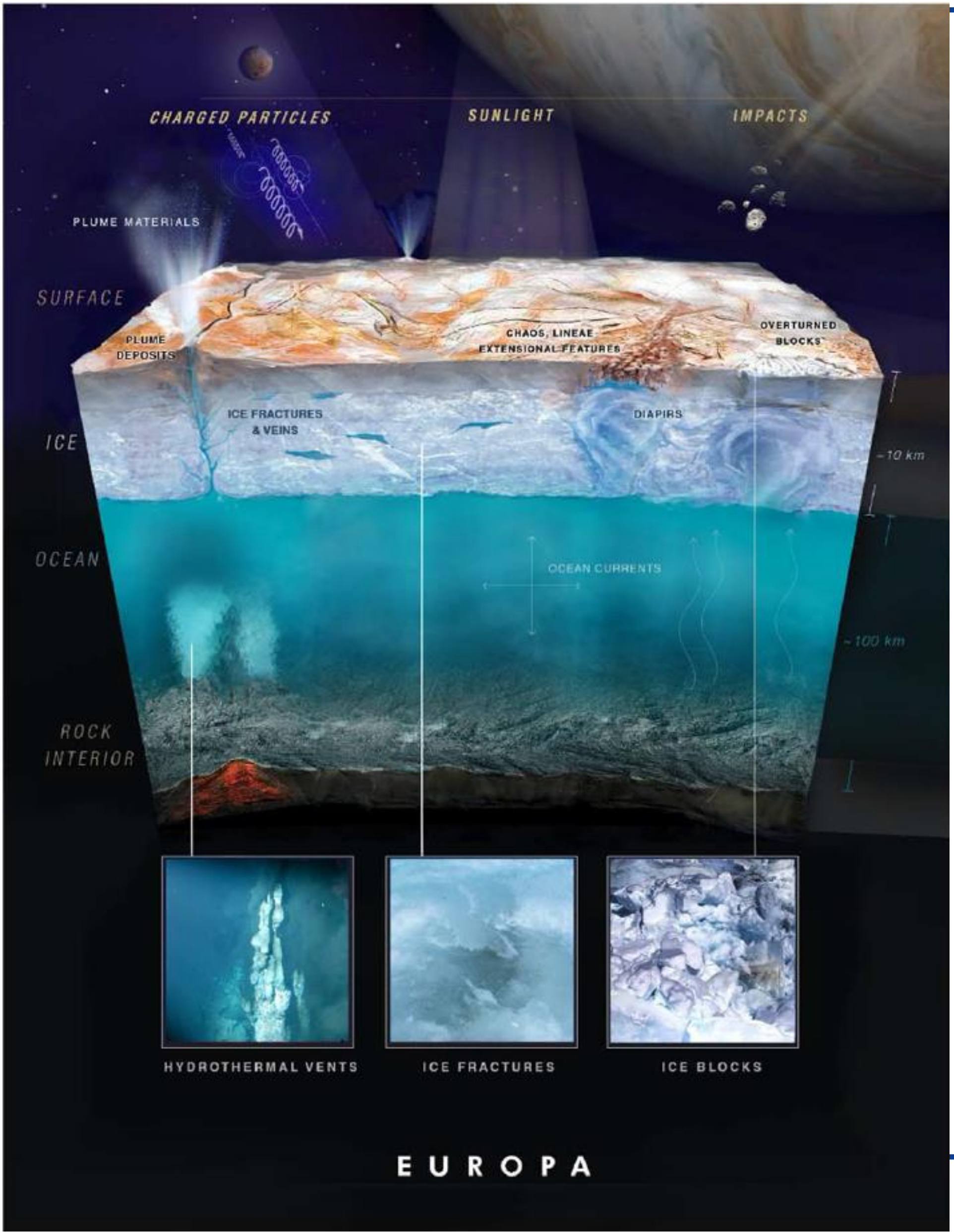
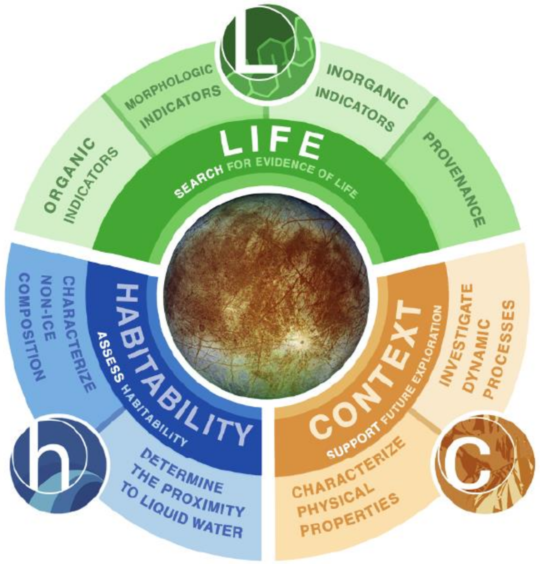
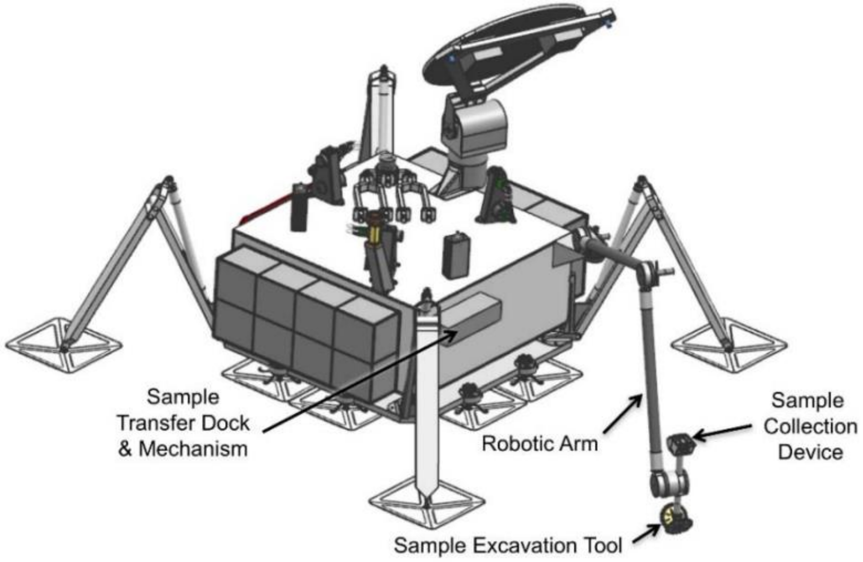
Space Power Workshop (Virtual)
April 28, 2022

Europa Lander Mission Concept

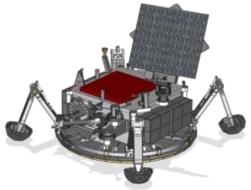


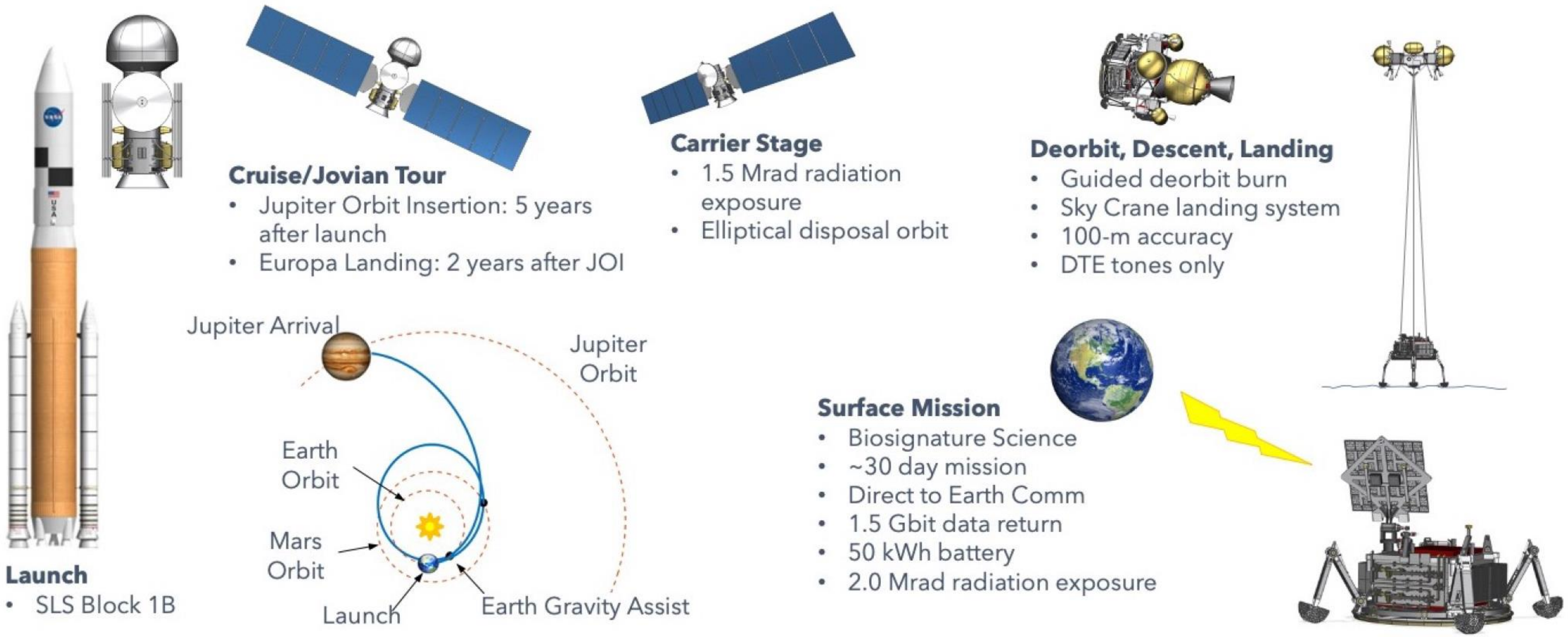




- A mission concept to land on Europa
- Europa is an ocean world within our solar system, believed to harbor significant liquid water under an icy shell
- Mission objectives:
  - Assess habitability
  - Search for evidence of life
  - Characterize the surface to support future exploration

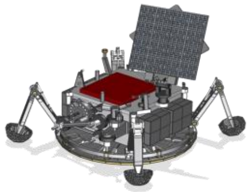
Europa Lander Mission Timeline

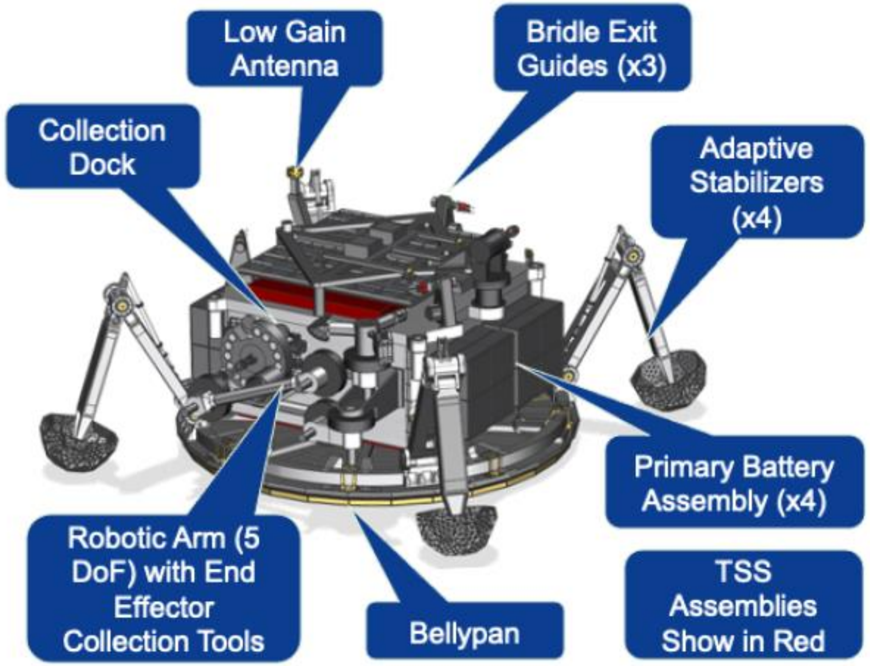




- **5+ year cruise time** after launch to reach Jupiter Orbital Insertion (JOI)
- Europa landing **two years after JOI**
- **20-30 day mission**

Defining Europa Lander Battery Needs

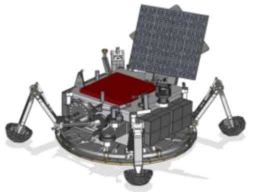




Parameter	Values	Comments
Operational temperature	0 to +70°C	Significant waste heat from avionics and cells
Non-operational temperature	-40 to +70°C	During cruise stored at 0ºC
Peak power	~500 W	Sampling
Average power	~20 W	Sleep
Radiation tolerance	2-3 Mrad	JOI and Landing
Storage Duration	7-11 years	Pre-launch, cruise and JOI

- **Primary battery only mission**
- Initial 50 kWh energy target with 100 kg battery mass for 20-30 day mission to achieve primary science objectives
- Initial target of 500 Wh/kg battery (4X battery modules, each ~12.5 kWh)
- Estimate >650 Wh/kg for primary cells, with 25% overhead for battery packaging/structure
- Must also consider de-ratings for losses and design principles, further increasing specific energy requirement
- Identify opportunities to increase specific energy, to provide margin and extend timeline on the surface

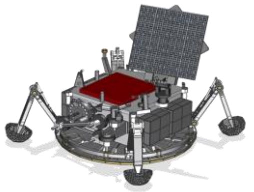
Consideration of Battery Deratings



Loss Factor	Value	Comments
Depassivation Requirement	-3%	JPL Design Principle
80% Depth of Discharge Requirement	-20%	JPL Design Principle
Loss of string	~600 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

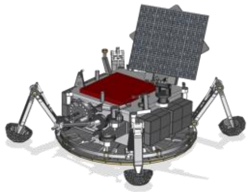
- Taken off the top of the initial 50 kWh energy target
- What can we do to increase cell specific energy?
- What can we do to address deratings?

Increasing Cell Specific Energy



Cell Chemistry	Vendor	Part Number	Format	Flight Heritage	Specific Energy, Wh/kg (20ºC, 50 mA)
Li/SO_2	Saft	LO 26 SXC	D cell	Yes	420
$Li/SOCl_2$	Saft	LSH 20	D cell	Yes	421
Li/MnO_2	Ultralife	CR15270	D cell	No	250
Li/FeS_2	Energizer	L91	AA cell	No	350
Li/CF_x-MnO_2	EaglePicher	LCF-133 (COTS and modified)	D cell	No	514
Li/CF_x	EaglePicher	LCF-129	D cell	No	690

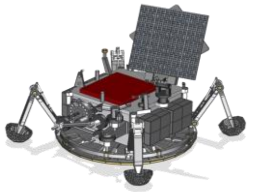
- Could not come close to targets using cells with flight heritage
- Identify opportunities to increase cell specific energy using higher energy chemistries
- Must consider battery chemistry with no flight heritage
- Rates will be relatively low given battery size and power requirements (50 to 750 mA / cell)



Europa Lander Battery Development

- JPL engaged in development with EaglePicher starting in 2018, for series of three cell “builds” with successively increasing performance
- Focus on increasing specific energy through cell process improvements
- Utilize aluminum can design and increase active material loadings
- Final delivery of Build 3 cells to JPL in January 22
- Designed and implementing extensive test campaign to evaluate suitability for Europa Lander mission concept

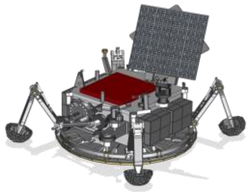
Build 3 Li/CF_x Cell Test Campaign



- 200 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

Cell Performance Test Matrix



Cell Type: Pristine, non-irradiated cells at beginning-of-life (BOL)

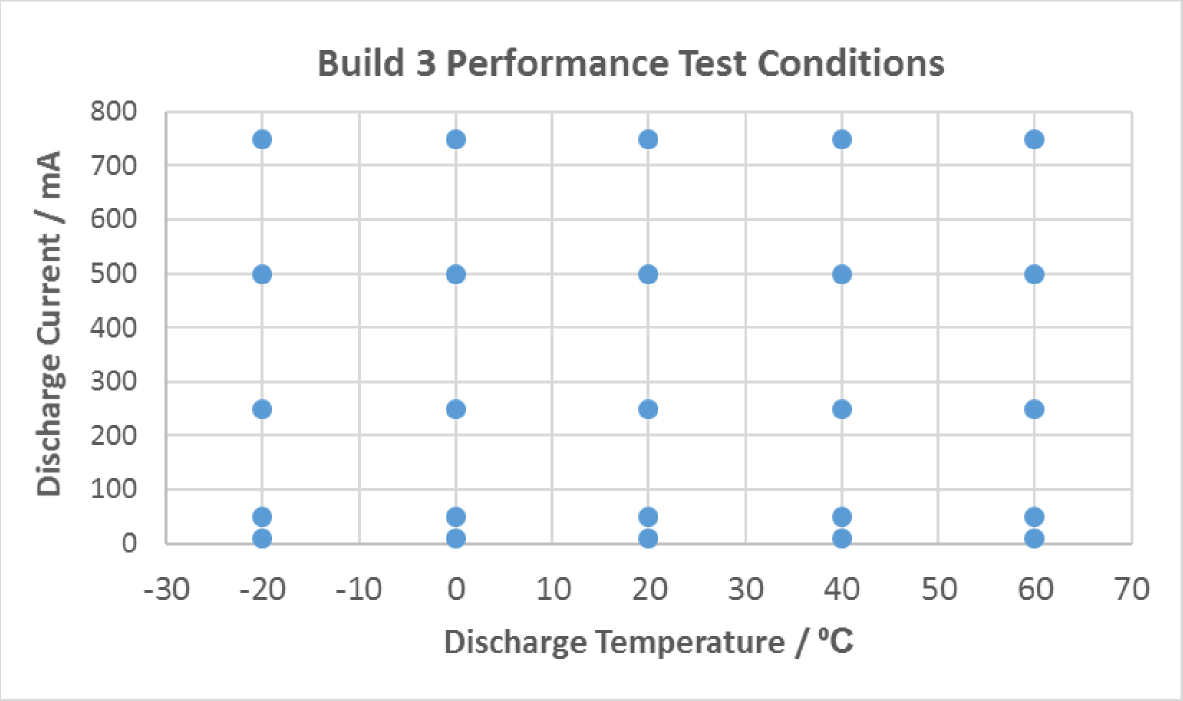
Test Description: Pulse discharge testing at mission relevant temperatures

Test Conditions

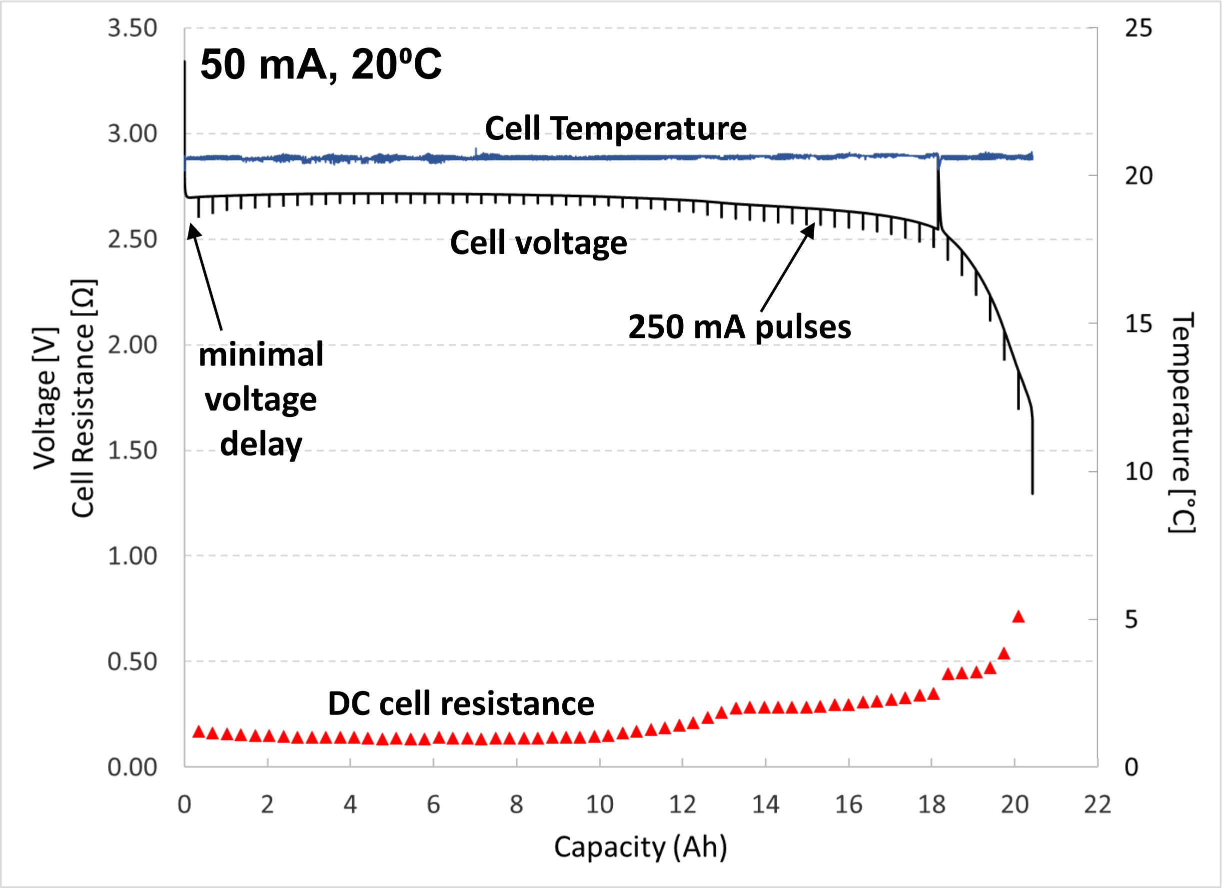
- 3 cells per condition (72 cells total)
- -20ºC, 0ºC, 20ºC, 40ºC, 60ºC
- 10, 50, 250, 500, 750 mA

Rationale for test

- Benchmark cell design improvements over range of mission relevant conditions (Builds 1-3)
- Support future power modeling
- 250 mA is standard baseline current
- 500, 750 mA represent maximum currents, depending on battery sizing

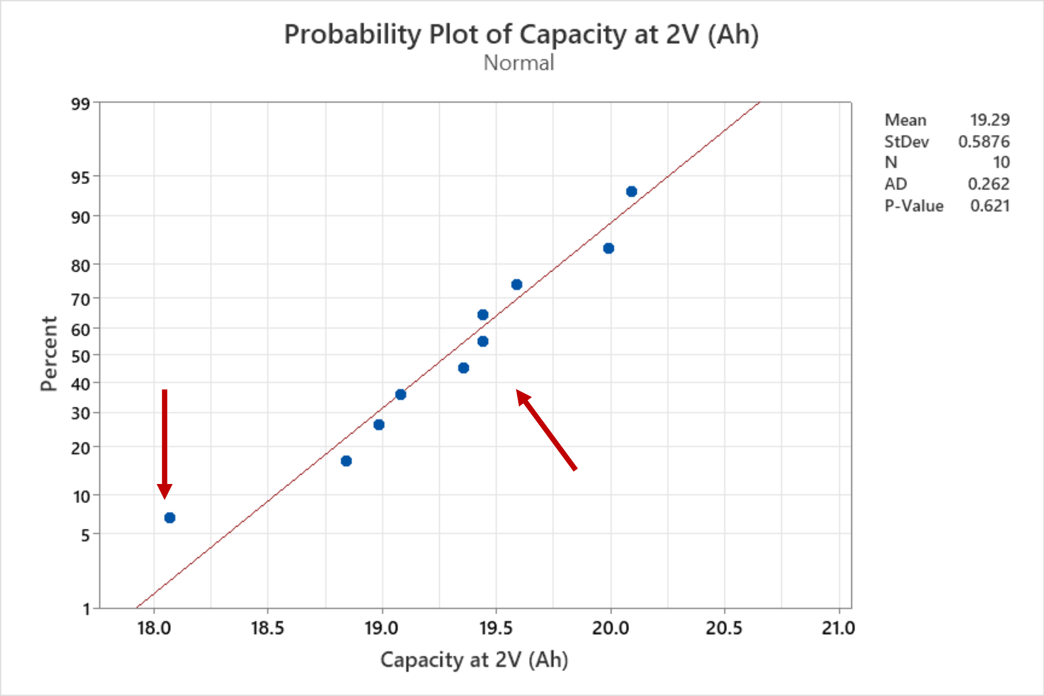


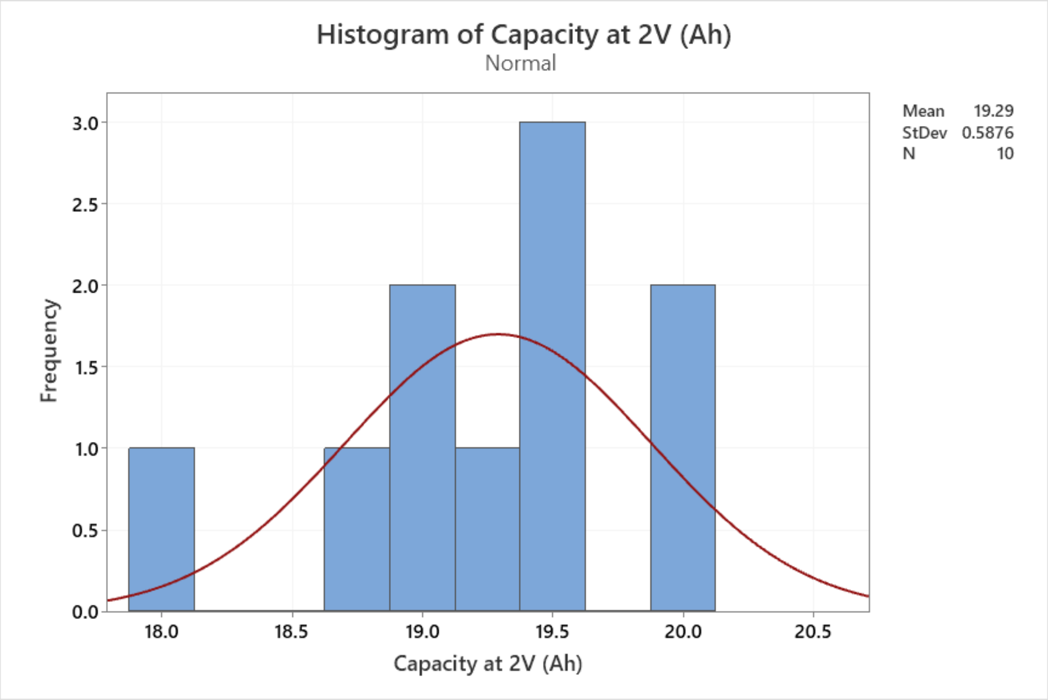
Representative Build 3 Performance Data for Li/CF_x D-Cell



- Example performance test data at 50 mA and 20ºC discharge condition
- Superimpose periodic 250 mA pulse current on top of 50 mA baseload current, to extract cell resistance
- Nominal on-load voltage reach with little delay even at low current; de-passivation may not be required
- Testing over full range of test matrix conditions in progress for Build 3 cells

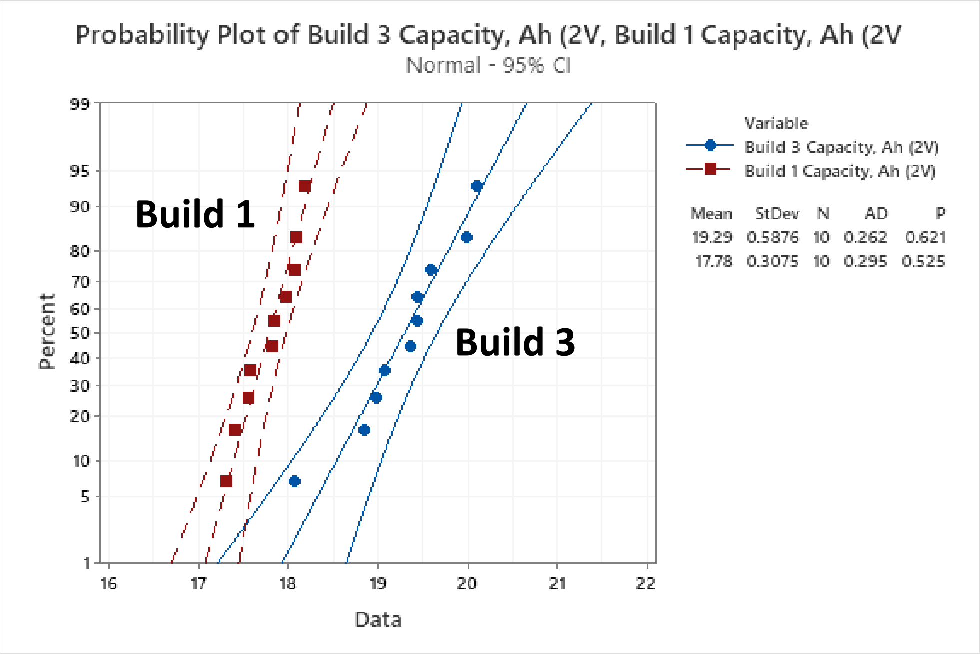
Build 3 Capacity Dispersion Data
Li/CF_x D-Cells

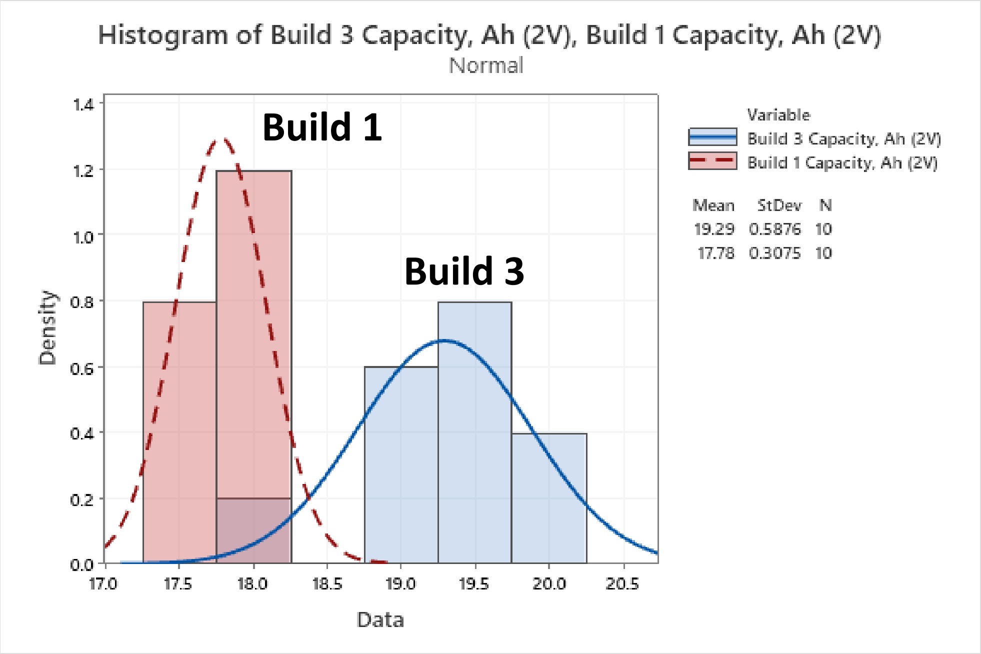




- Test 10 cells at 250 mA and 20ºC to evaluate capacity dispersion
- Monitor manufacturing process
- Use to re-consider 80% DOD battery requirement, by better understanding cell-to-cell variances

Li/CF$_x$ D-Cell Capacity Dispersion
Build 1 vs. Build 3

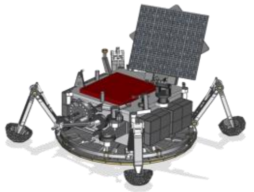




ID	Mean Capacity (Ah)	Standard Dev.
Build 1	17.78	0.3075
Build 3	19.29	0.5876

- 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

Progress of Europa Lander Battery Development

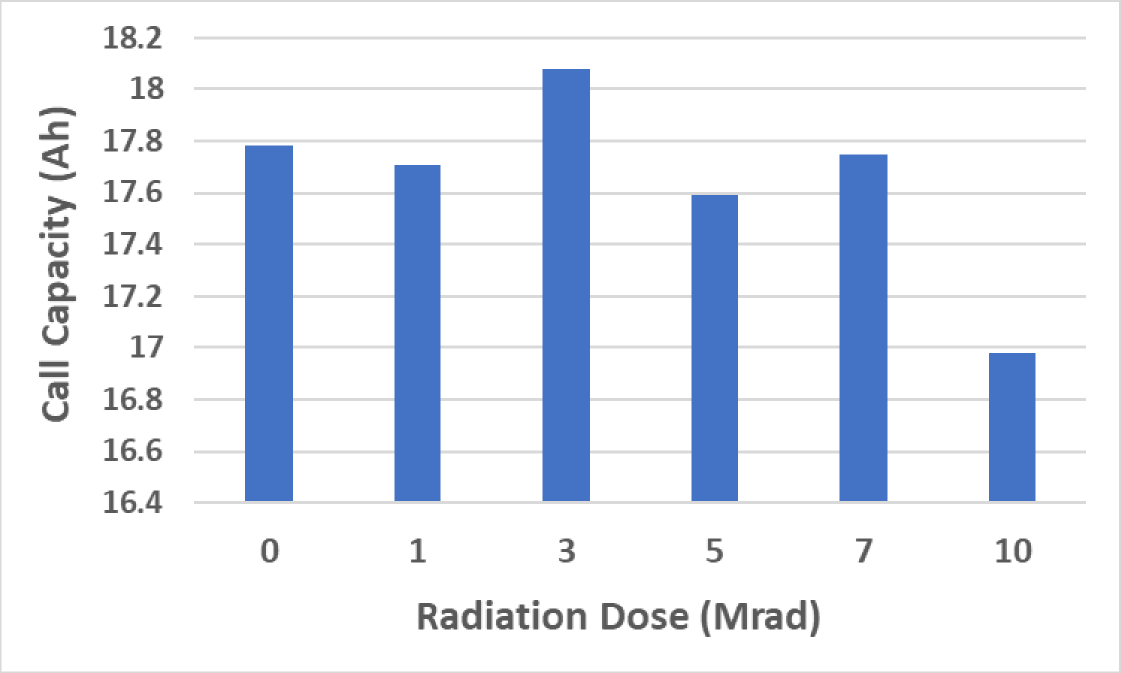


	Capacity (Ah)	Energy (Wh)	Cell Specific Energy at 20^{0}C and 250 mA to 2V cut-off (Wh kg^{-1})
Baseline cell design	16.98	43.3	614
Build 1	17.78	45.1	654
Build 2	17.80	42.8	657
Build 3	19.29	49.5	695
Baseline to Build 3 Increase	**+2.31**	**+6.2**	**+81**

Battery Design 1: 1248 cells → 7.7 kWh additional energy (Baseline)
Battery Design 2: 1548 cells → 9.6 kWh additional energy (Mission Life Extension)

Battery Design	# of Cells	Cell Mass (kg)	Battery Mass	BOL Energy
1	1248	89	119	61,855
2	1548	109	145	75,755

Updated Radiation Losses on Li/CF_x Build 1 D-Cells



- Updating radiation deratings
- Previous assumption was radiation levels of up to 10 Mrad total ionizing dose (TID)
- Assumed pre-radiation of cells prior to launch, for planetary protection purposes (no longer required)
- Initial testing of small sample sizes (2 cells per dose condition) indicates little impact on initially delivered capacity for dose levels of 1-7 Mrad

Irradiation of Build 3 Li/CF_x D-Cells to 5 Mrad TID

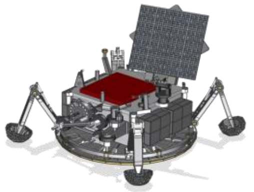
Non-irradiated/Pristine Control Cells

Cells Irradiated to 5 Mrad TID

- Received at JPL Build 3 cells irradiated to 5 Mrad TID at Sandia National Lab (2X expected 2.5 Mrad mission dose)
- Visual inspection indicates no issues (no damage, electrolyte leakage or cell expansion)
- Will commence performance testing, to verify any losses at <10 Mrad dose

Storage Testing of Build 1 Li/CF_x D-Cells

Initial BOL Capacity: 17.78 Ah

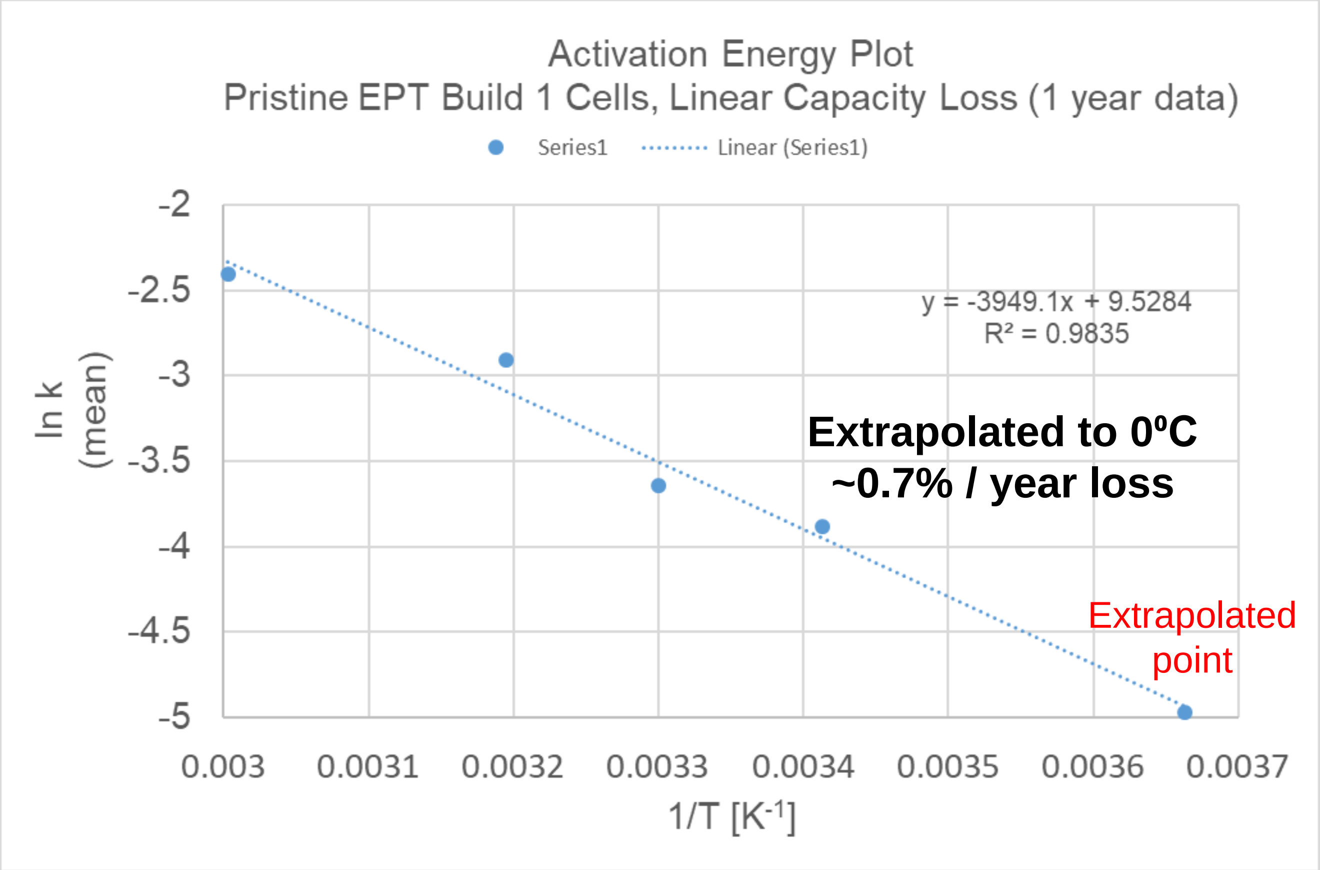


Storage Temperature (ºC)	12 month measured capacity (Ah)	12 month capacity Loss (-Ah)	12 month % Loss	Annual % Loss at Temperature
20	17.43	0.37	2.1	2.1
30	17.33	0.47	2.62	2.62
40	16.84	0.96	5.39	5.39
60	16.27	1.53	8.60	8.60

Storage Temperature (ºC)	18 month measured capacity (Ah)	18 month capacity Loss (-Ah)	18 month % Loss	Annual % Loss at Temperature
20	17.26	0.54	3.1	2.1
30	16.93	0.87	4.9	3.3
40	16.93	0.87	4.9	3.3
60	15.65	2.15	12	8

- Cell discharged at 250 mA at 20ºC, following storage for 12 and 18 months at JPL
- Typically averaged over 3 cells per storage condition
- Initial storage results reported at 2021 Space Power Workshop

Arrhenius Analysis of Build 1 Cells



$$c(t) = c(0) - kt$$

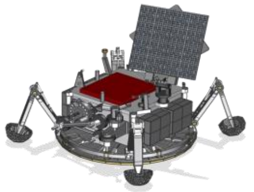
c(0): initial capacity (Ah)
c(t): capacity at time t (Ah)
k: rate constant (Ah/year)
t: time (years)

$$\ln k = \ln k_0 - \frac{E_a}{RT}$$

E_a: activation energy (J/mol)
R: gas constant (J/mol-K)
T= absolute temperature (K)

E_a: 31.5 kJ / mol

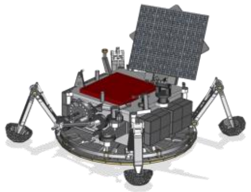
- Each ln k vs. 1/T data point an average of 3 rate constants
- Batteries will be held at 0ºC during cruise and prior to landing
- Activation energy in range of typical self-discharge processes for other battery chemistries
- Using the 2X rate increase for every 10ºC increase in temperature rule-of-thumb, estimate about 0.5% annual loss at 0ºC



Updated Cell Derating Considerations

Loss Factor	Value	Comments	Update
Depassivation Requirement	-3%	JPL Design Principle	Nominal on-load voltage reached without de-passivation step
80% Depth of Discharge Requirement	-20%	JPL Design Principle	Actual cell-to-cell variance is close to 10% from dispersion testing
Loss of string	~600 Wh (-1%)	JPL Design Principle	
Storage Losses	-16%	Estimate based on 2% annual loss at 20ºC	Storage at 0ºC could bring to ~0.5% annually and ~4% total
Other losses	-5%	Estimate based on 10 Mrad radiation dose	Likely <1% based on limited lower dose testing results

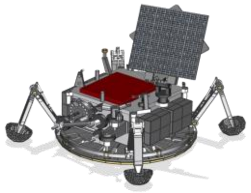
- Opportunities to reduce estimated deratings from ~45% to ~16% based on test campaign results
- Planned Build 3 testing will support further updates



Summary and Plans Forward

- **Europa Lander battery development has led to improvements in EaglePicher Li/CF_x cell capacity and specific energy**
  - Additional 2.3 Ah cell capacity
  - Additional 6.2 Wh of cell energy
- **Able to support Europa Lander concept baseline science mission**
  - Identified opportunities for extending mission timeline and providing additional margin
  - Implemented cell improvements and improved understanding of cell deratings
- **All Build 3 cells received at JPL since January 2022**
- **Commencing with Build 3 test campaign**
  - Further benchmark cells improvements and understand cell deratings
  - Performance testing over range of rates and temperatures
  - Radiation testing
  - Thermal testing

Acknowledgements



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