Li/CF_x Cell Development and Testing for Deep Space Missions

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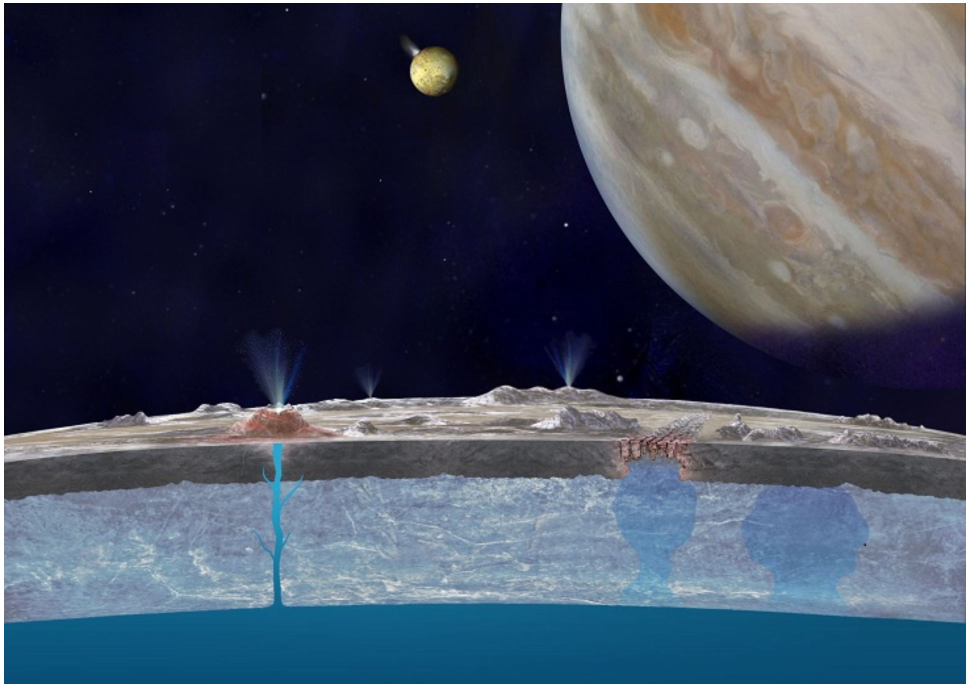
Jet Propulsion Laboratory
California Institute of Technology

Proposed Europa Lander
(Re-cap from Sept. 2019 IAPG Meeting)

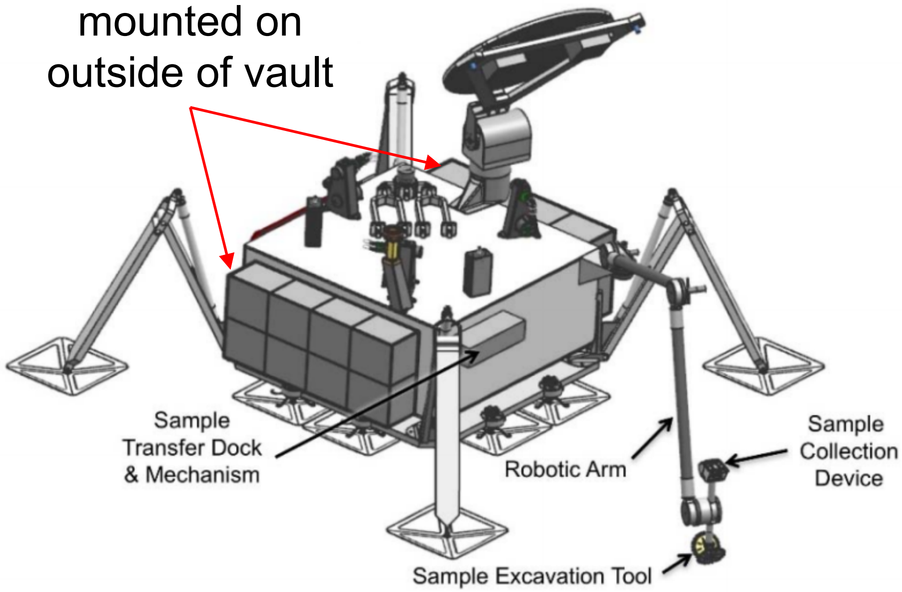


- Space science community interested in landing on an “Ocean World”
- These are the icy moons that orbit gas giants such as Jupiter and Saturn
- Significant liquid water is likely present under icy shell
- Cryo-volcanism has been observed
- May harbor “extant” life

Emerging Power Requirements for a Notional Europa Lander

- 20+ day surface mission
- Search for bio-signatures
- Assess habitability
- Characterize the surface
- Main power loads
  - Sample acquisition
  - Science instruments
  - Communication to orbiter
- 5 to 500 W power range
- Current baseline concept features primary batteries only
- ~100 kg mass allocation for batteries

Batteries mounted on outside of vault



Notional Lander Concept

Pre-Decisional Information -- For Planning and Discussion Purposes Only

Battery Selection Considerations

- **Spacecraft thermal management maintains optimal battery temperature**
  - Despite Europa surface temperatures of ~-180ºC
  - Battery self-heating
  - Waste heat from avionics
  - Batteries anticipated to operate between 0º and +60ºC

- **High specific energy delivered at low rates**
  - Mission energy requirements in the 50-60 kWh range
  - Targeting ~400 Wh/kg at the battery level
  - Targeting >700 Wh/kg at the cell level
  - Battery sizing in progress based on Li/CF_x D-size cell and evolving requirements
  - Estimate ~10 to 250 mA per cell at end-of-mission based on current pack sizing
  - Must accommodate various "deratings" (next slide)

- **Minimize capacity loss during >5 year cruise at 0ºC**

- **Radiation tolerant**

Consider Various Derating Factors

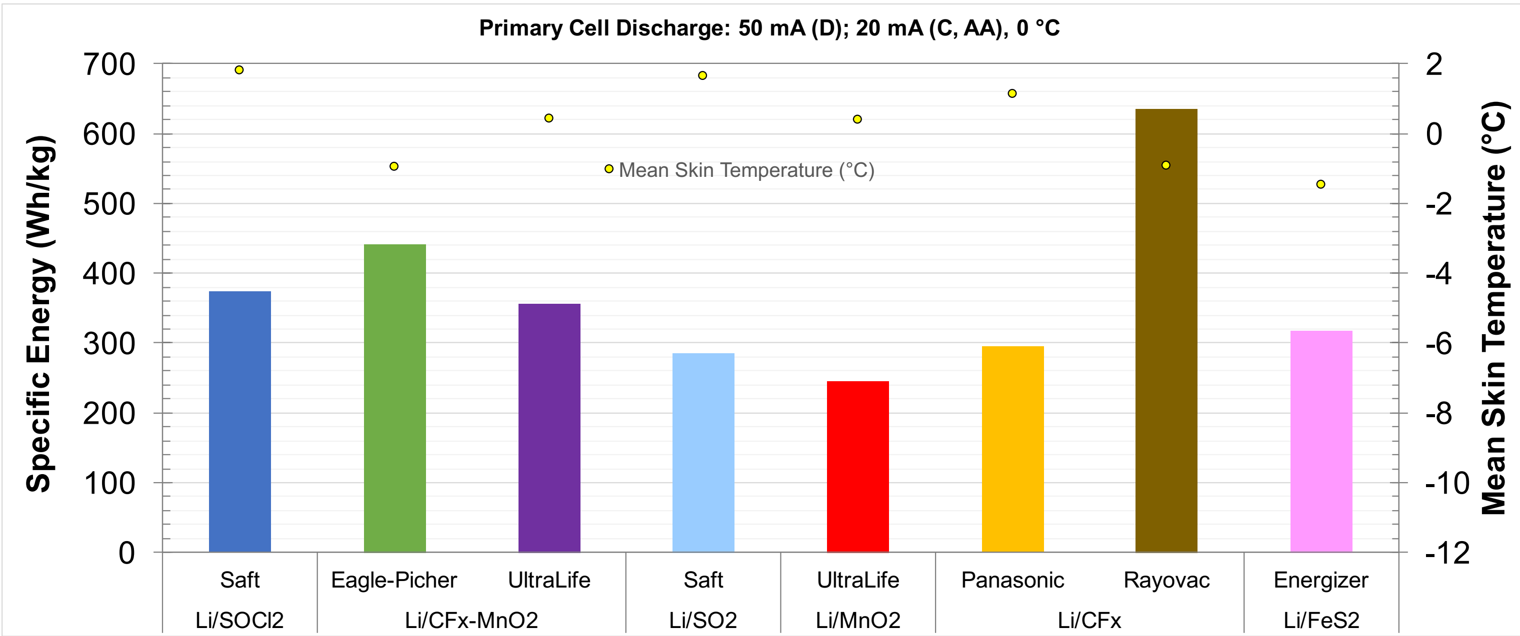
- **Use statistical methodology based on test data to estimate energy available upon landing**

- **Time from cell manufacture/filling to end of mission could be 10 years total**

- **Need to consider various derating factors to support statistical modeling of available energy**
  - Cell-to-cell variation during manufacturing
  - Losses due to radiation dose for sterilizing cells (planetary protection protocol)
  - 10 years of storage losses/self-discharge (0 to 40ºC)
  - Cell depassivation protocol prior to landing
  - Losses due to environmental radiation

- **Current test campaign aimed at understanding these losses to support derating of cells**

Initial Screening of Cell Options



- Discharge Testing at ~C/300 and 0 ºC
- Li/CF_x most promising option to meet mission requirements
- Enabled by moderate temperature and low rate conditions

Further Development of Primary Battery Option

- **Selected Li/CF_x cell chemistry**
  - Based on initial screening of commercially available cells
  - Only option that could meet mission energy, mass requirements
  - Selected D-size format due to wider availability
- **Issued RFP followed by RFQ to 2 vendors**
  - Eagle-Picher and Rayovac
  - Based on initial performance evaluation
  - Both offered relatively mature aluminum packaging option
- **Pre-Project and Phase A (Mission Concept) Development Plan**
  - Perform 3 total cell “build” iterations
  - Perform extensive testing to understand contribution of various losses
  - Incorporate lessons learned into subsequent builds
  - Leads to cell down-select followed by cell and battery design/qualification in Phase B (Preliminary Design) and beyond

Vendor Datasheet Cell Descriptions

	Eagle-Picher	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	471*	716**
Case	Steel***	Aluminum

*Evaluated at 25ºC, 2 A to 2V cut-off

**Evaluated at 22ºC, 50 mA to 2V cut-off

***Original COTS version; developed Al version tested here

Build 1 Test Campaign

- **Issued contracts to EaglePicher and Rayovac**
- **Received 185 cells from each vendor**
  - Built considering specifications from RFQ
  - Target is >700 Wh/kg at cell level (50 mA discharge at 20ºC)
- **Evaluate dispersion in performance values**
- **Constant current discharge performance**
  - Discharge over range of current (50-250 mA)
  - Temperature range = 0 to +70ºC
- **Storage testing**
  - Real time and accelerated
  - Micro-calorimetry
- **Isothermal calorimetry**
- **Radiation testing**

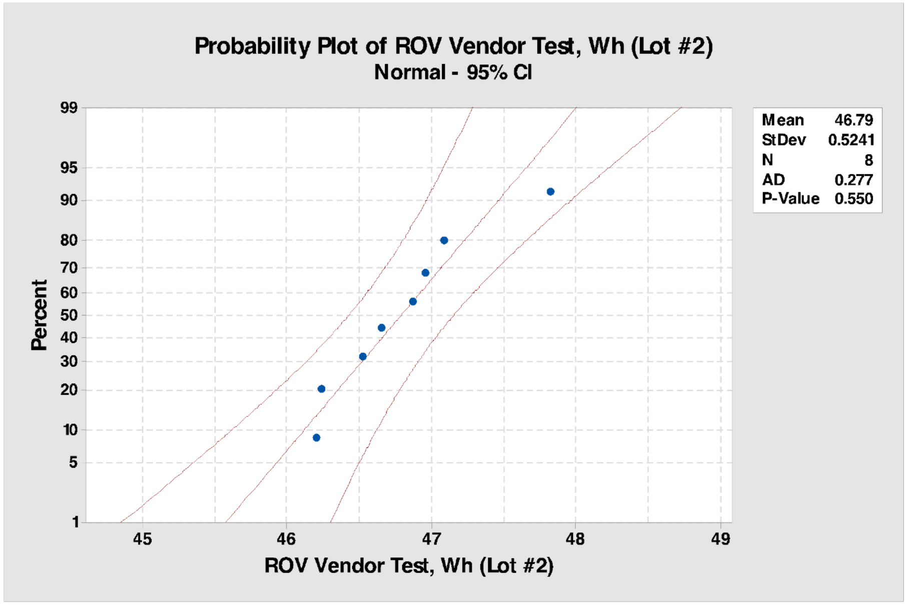
Build 1 Performance Test Matrix

Cells for Each Condition		Discharge Conditions		
Vendor	Temperature (ºC)	**50**	**90**	**250**
Eagle-Picher	**0**	3	3	3
	20	3	3	10
	40	3	3	3
	70	3	3	3
Rayovac	**0**	3	3	3
	20	3	3	10
	40	3	3	3
	70	3	3	3

- Test conditions selected based on mission profile
- Results used to compare vendors and populate power models
- 20ºC / 250 mA condition used as baseline to evaluate dispersion in manufacturing lots (cells in red)

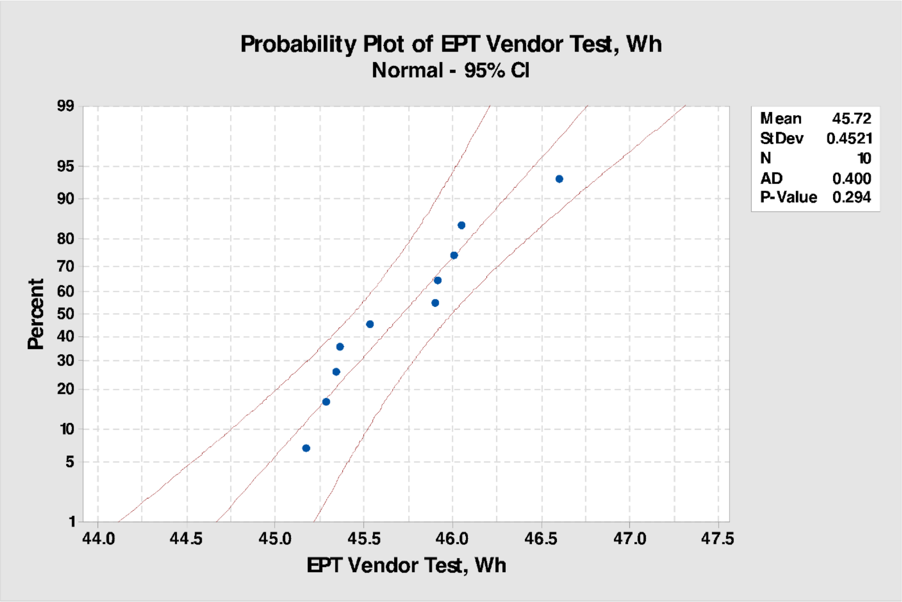
Dispersion in Specific Energy Values

Rayovac Vendor Test



Mean: 46.79 Wh
Std. Dev.: 0.5241

EaglePicher Vendor Test



Mean: 45.72 Wh
Std. Dev.: 0.4521

- Cells from same manufacturing lot discharged at vendor and JPL
- 250 mA and 20ºC discharge conditions
- Use data to help support future statistical based models for energy delivery

Example of Test Results: EaglePicher Results

Cell	OCV (V)	Impedance (Ω)	Mass(g)	Corrected Mass (g)*	Capacity (Ah)	Energy (Wh)	Specific Energy (Wh/kg)	Corrected Specific Energy (Wh/kg)
EPBR-31	3.207	0.0765	72.867	69.346	17.84	45.031806	618	649
EPBR-36	3.322	0.0773	73.077	69.556	17.98	45.380817	621	652
EPBR-40	3.316	0.0745	73.197	69.676	18.09	45.748125	625	657
EPBR-45	3.322	0.0761	73.11	69.589	18.07	45.83997	627	659
EPBR-50	3.325	0.0738	72.753	69.232	17.82	45.252366	622	654
EPBR-55	3.305	0.0746	73.325	69.804	18.19	46.19475	630	662
EPBR-60	3.265	0.0798	73.396	69.875	17.4	43.523828	593	623
EPBR-65	3.271	0.0776	72.228	68.707	17.57	44.78136	620	652
EPBR-71	3.288	0.076	71.7	68.179	17.31	44.1672	616	648
EPBR-75	3.303	0.074	72.031	68.51	17.56	44.803282	622	654
Mean	3.29	0.076	72.77	69.25	**17.78**	**45.07**	619	651
σ	0.034877	0.0018	0.5556	0.5556	**0.2918**	**0.7622**	10.16	10.69
3σ	0.105	0.0054	1.667	1.667	**0.8753**	**2.287**	30.5	32.1

*subtract 3.521 g to account for tabs, insulators and wrapper

JPL Testing

Mean: 45.07 Wh

3σ: 2.287

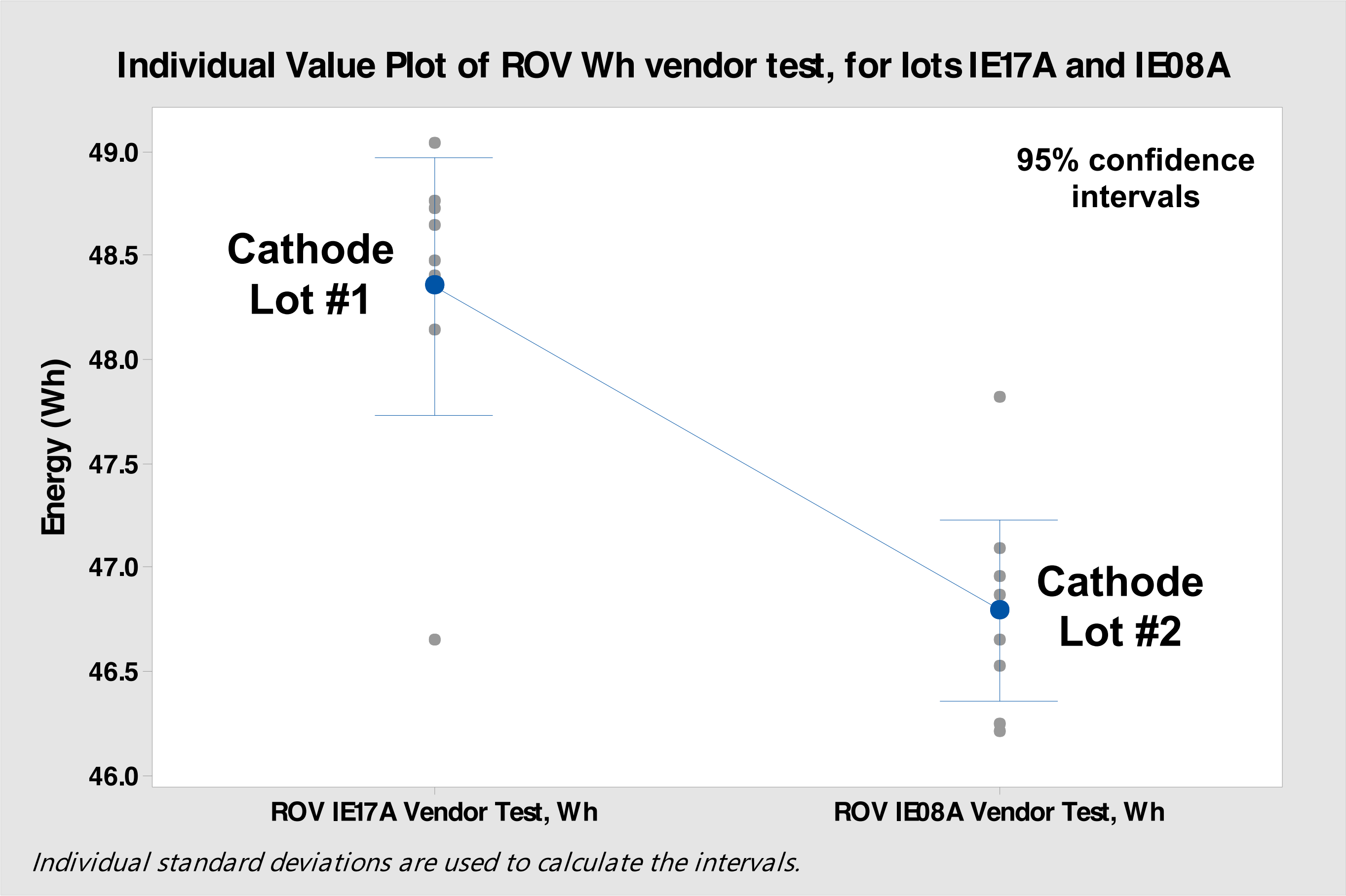
Cell	OCV (V)	Impedance, 1 kHz (Ω)	Mass (g)	Corrected Mass (g)	Capacity (Ah)	Energy (Wh)	Specific Energy (Wh/kg)	Corrected Specific Energy (Wh/kg)
4663F-52	3.21	0.096	72.775	69.254	18.32	46.60	640	673
4663F-56	3.269	0.097	72.376	68.8548	18.12	46.05	636	669
4663F-63	3.292	0.093	71.687	68.1656	17.69	45.36	633	665
4663K-13	3.286	0.094	71.637	68.1163	18.01	45.92	641	674
4663L-21	3.266	0.101	72.114	68.5932	18.04	46.00	638	671
4663L-37	3.308	0.095	71.929	68.408	17.93	45.90	638	671
4663L-43	3.297	0.094	71.915	68.3937	17.79	45.53	633	666
4663M-35	3.286	0.101	71.693	68.1719	17.76	45.17	630	663
4663M-43	3.216	0.101	71.599	68.0783	17.79	45.34	633	666
4663M-50	3.274	0.098	71.251	67.7301	17.67	45.28	636	669
Mean	3.27	0.097	71.90	68.38	**17.91**	**45.72**	636	669
σ	0.0329	0.0031	0.4356	0.4356	**0.2100**	**0.4522**	3.52	3.65
3σ	0.099	0.0094	1.31	1.31	**0.6299**	**1.356**	10.6	11.0

Vendor Testing

Mean: 45.72 Wh

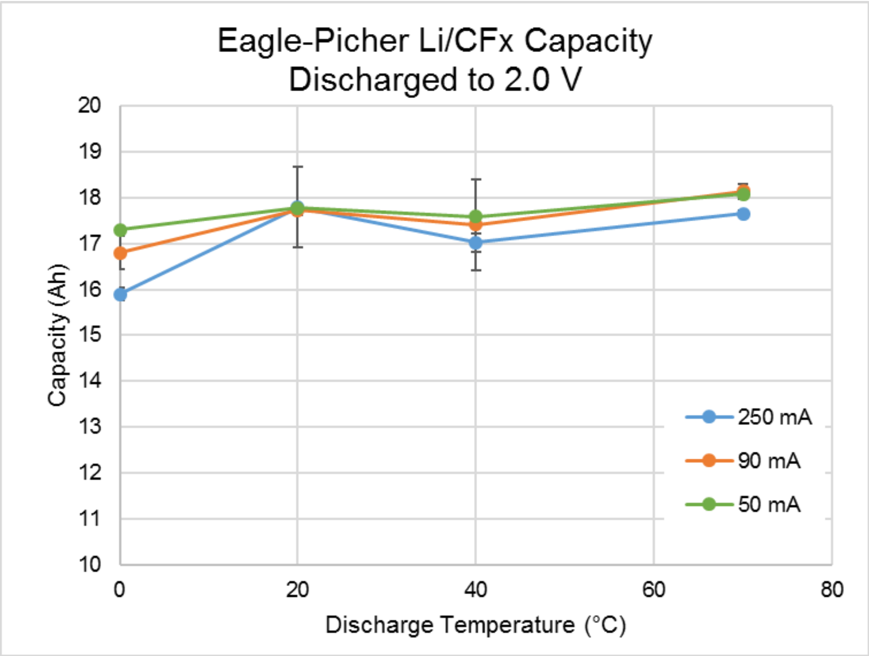
3σ: 1.356

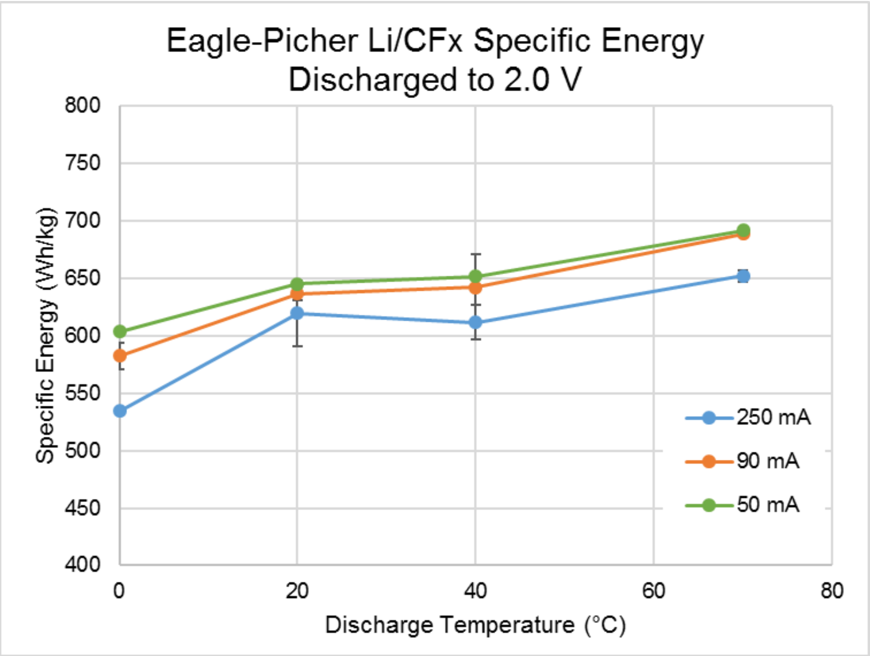
Example of Variation in Delivered Energy Due to Different Cathode Lots



- Observed statistically significant difference in energy with Rayovac cells
- Rayovac had noted this prior to delivery
- Attributed to typical variations in CF_x cathode material lots

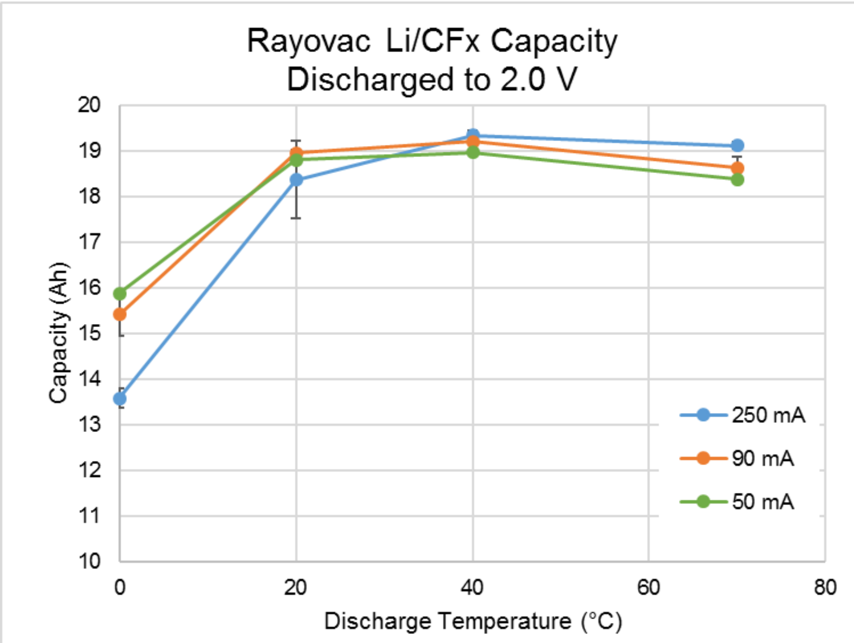
EaglePicher Performance

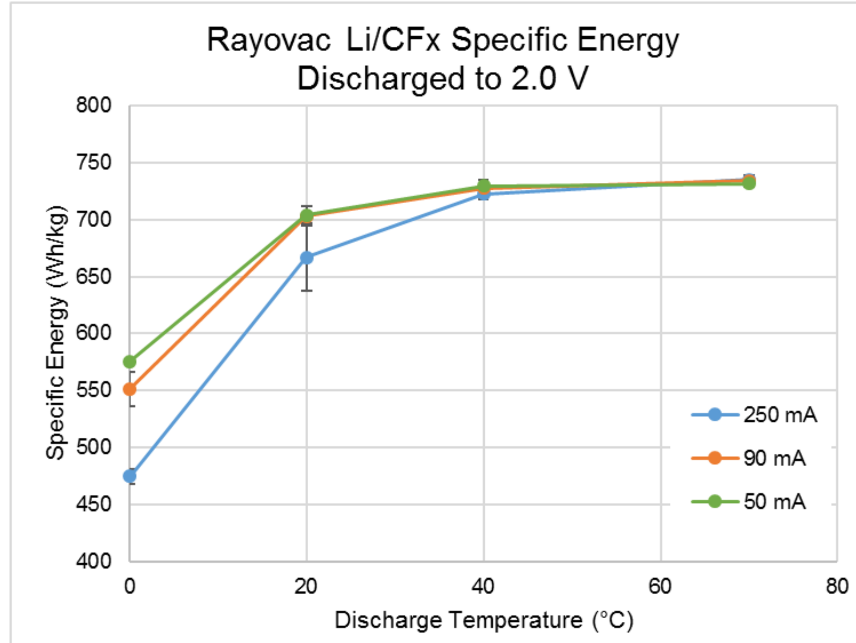




- **Capacity:** Between ~16-18 Ah
- **Specific Energy:** Between ~525 and 700 Wh/kg
- Falls short of 700 Wh/kg target (although correction for larger tabs increases specific energy ~5%)
- Room for improvement with higher cathode loadings

Rayovac Performance





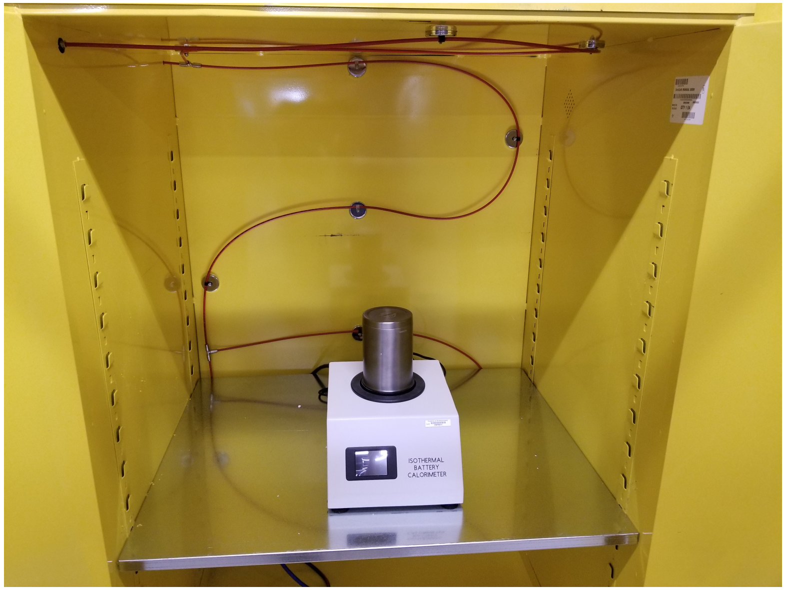
- **Capacity:** Between ~13.5 and 19.5 Ah
- **Specific Energy:** Between ~475 and 725 Wh/kg
- Meets >700 Wh/kg target

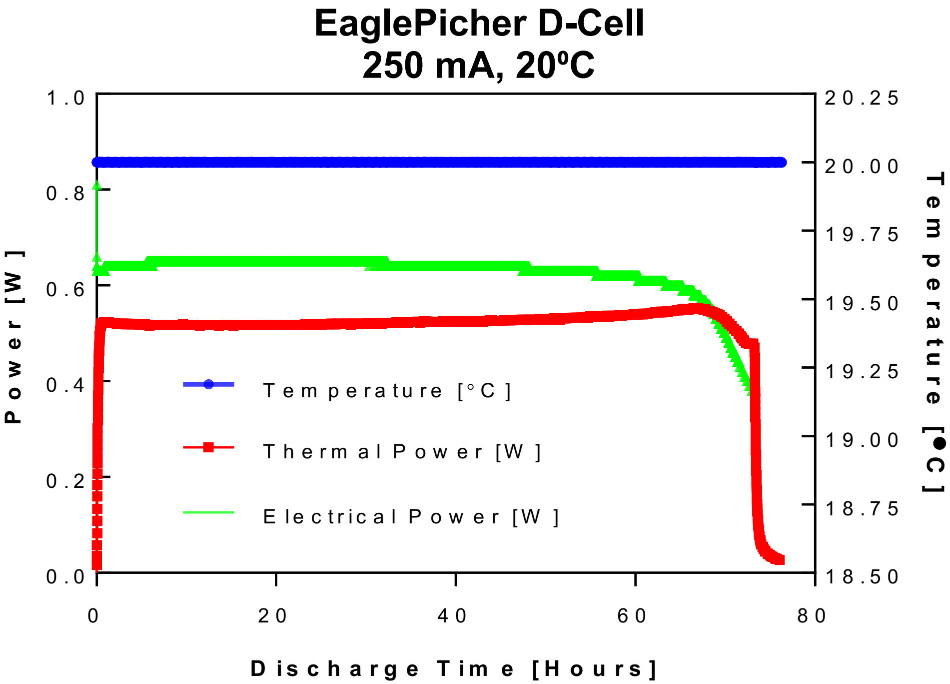
Build 1 Storage Test Matrix

Cells on Storage		Months on Storage			
Vendor	Temperature (ºC)	**0**	**6**	**12**	**18**
Eagle-Picher	**20**	6	6	6	6
	30	-	6	6	6
	40	-	6	6	6
	60	-	6	6	6
Rayovac	**20**	6	6	6	6
	30	-	6	6	6
	40	-	6	6	6
	60	-	6	6	6

- Evaluate impedance, capacity (20ºC, 250 mA) delivered during storage
- Real time and accelerated storage for 18 months
- Half of all cells will be irradiated to 10 Mrad, half pristine
- Correlate with micro-calorimetry results (cells in red)
- First 6 months cells coming off testing in late February 2019

Isothermal Calorimetry





- First tests initiated this month
- Critical for pack design (performance and safety)
- Confirms ~55:45 split between thermal and electrical energy

Radiation Testing

- Planned at Sandia National Labs Gamma Radiation Facility
- Cells are currently being irradiated at three different dose rates
- Discharge cells at JPL, to determine if there is an effect of dose rate on performance
- Dial in radiation conditions for Build 1 testing and planetary protection sterilization protocols

Sandia Facility

Dose Rate Testing Matrix

Table 1. D-Cell ID and Corresponding Dose Rates

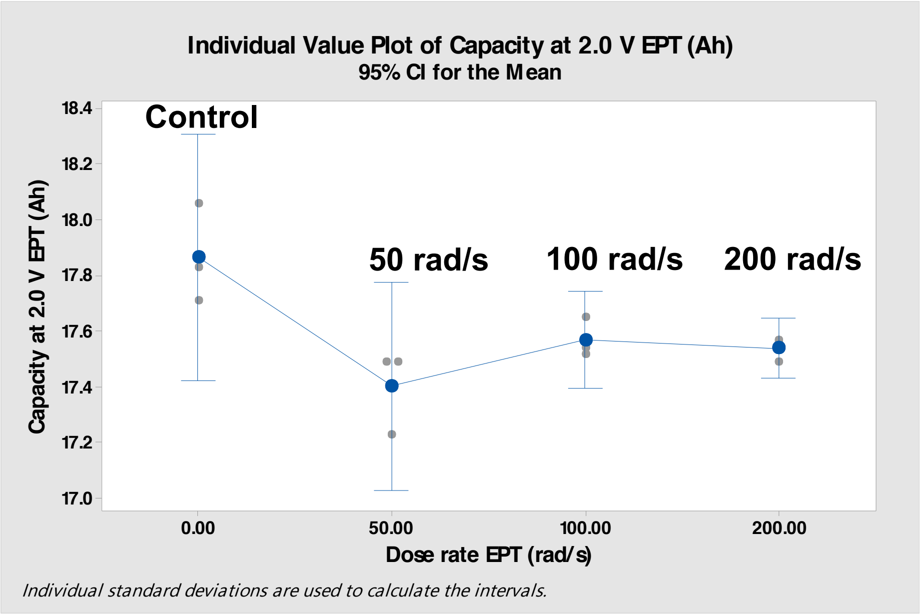
Eagle-Picher D-Cells		
#	Cell ID	Dose rate, rad/s
1	EPBR-32	Control
2	EPBR-37	Control
3	EPBR-38	Control
4	EPBR-43	200
5	EPBR-47	200
6	EPBR-48	200
7	EPBR-51	50
8	EPBR-57	50
9	EPBR-61	50
10	EPBR-63	100
11	EPBR-64	100
12	EPBR-69	100

Rayovac D-Cells		
#	Cell ID	Dose rate, rad/s
1	RBR-68	Control
2	RBR-69	Control
3	RBR-70	Control
4	RBR-93	200
5	RBR-135	200
6	RBR-145	200
7	RBR-146	50
8	RBR-149	50
9	RBR-157	50
10	RBR-160	100
11	RBR-167	100
12	RBR-174	100

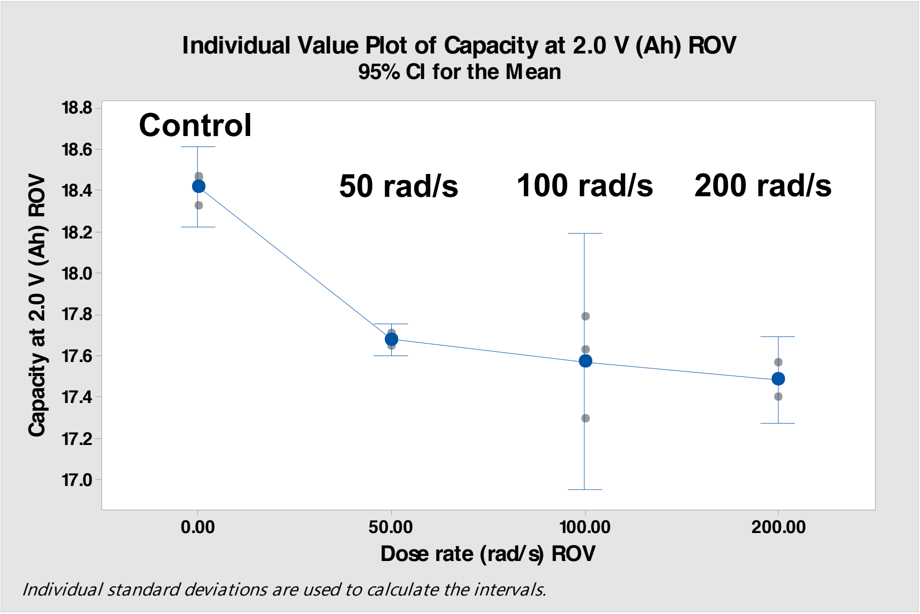
All cells irradiated to 10 Mrad TID

Dose Rate Testing
10 Mrad Total Ionizing Dose, Gamma Radiation

EaglePicher



Rayovac

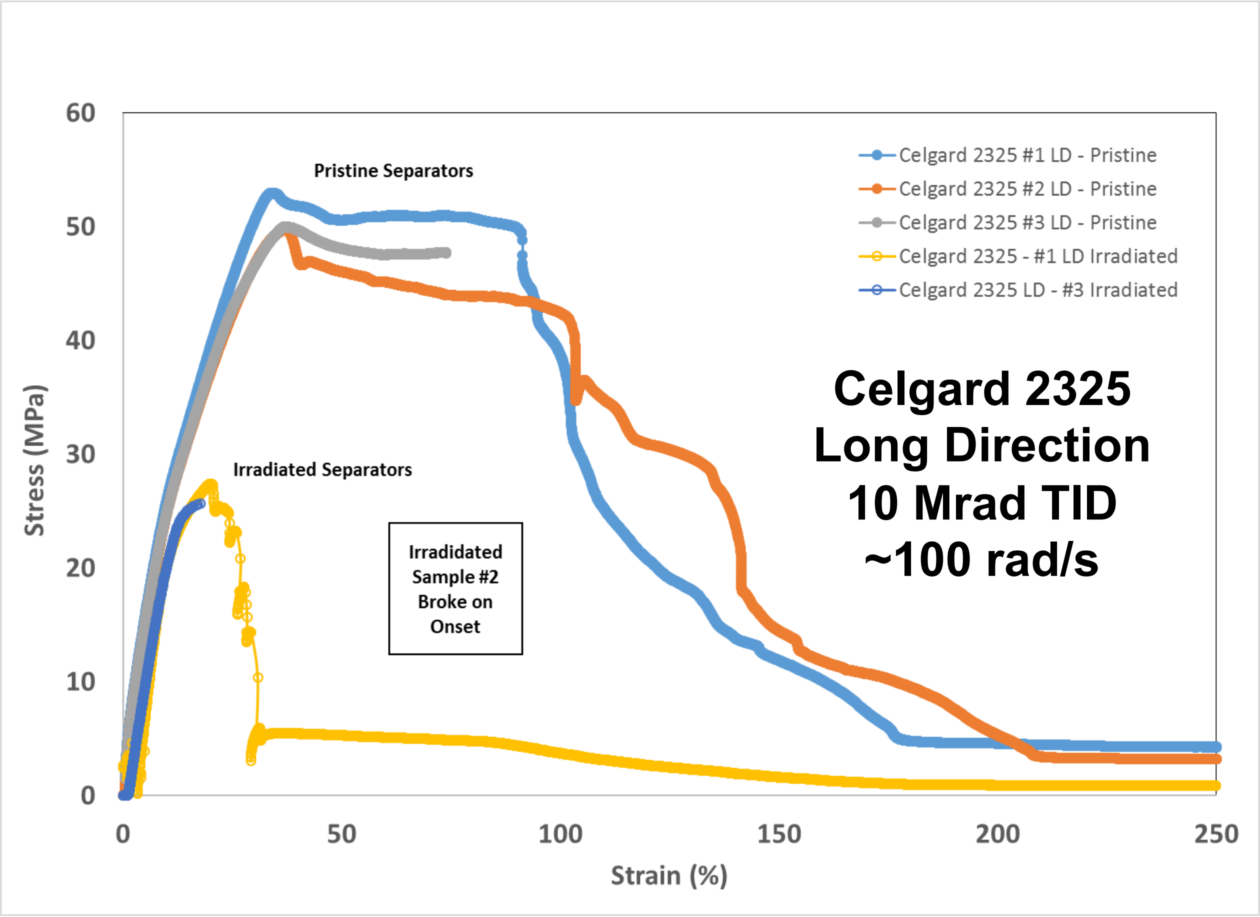


- Rayovac have initially higher capacity values
- EaglePicher capacity less sensitive to radiation
- End result is similar mean values across range of dose rates
- Little statistical different in dose rates
- Selected 100 rad/s (shorter time in beam vs. 50 rad/s, slightly lower impact vs. 200 rad/s)

Electrolyte Leakage Observed in Irradiated Rayovac Cells

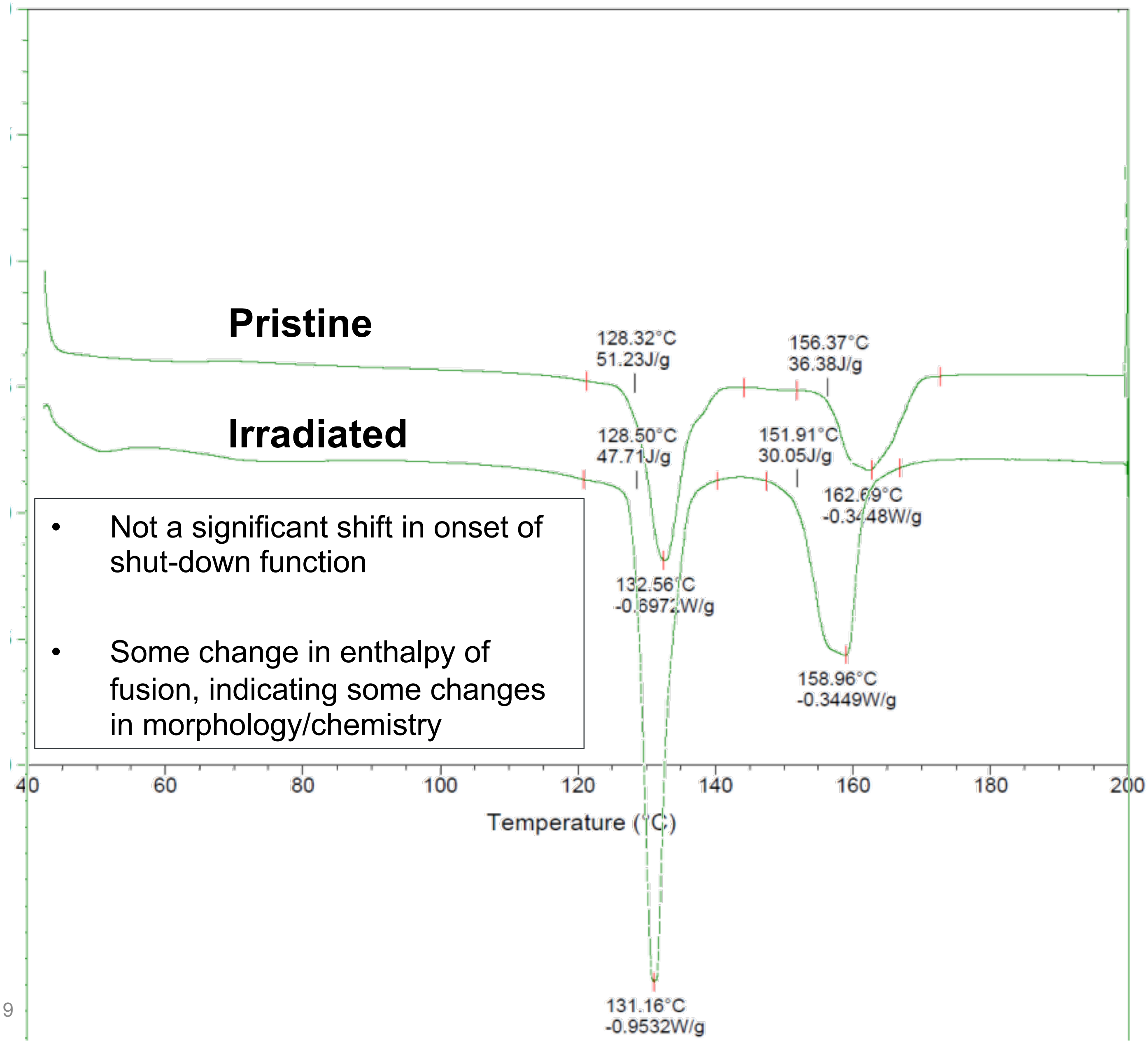

- Visual inspection indicates some leakage of electrolytes
- Earlier measurements indicated some cell expansion of irradiated Rayovac cells
- Sending charged, expanded cells to Rayovac for DPA

Dynamic Mechanical Analysis Testing of Separators



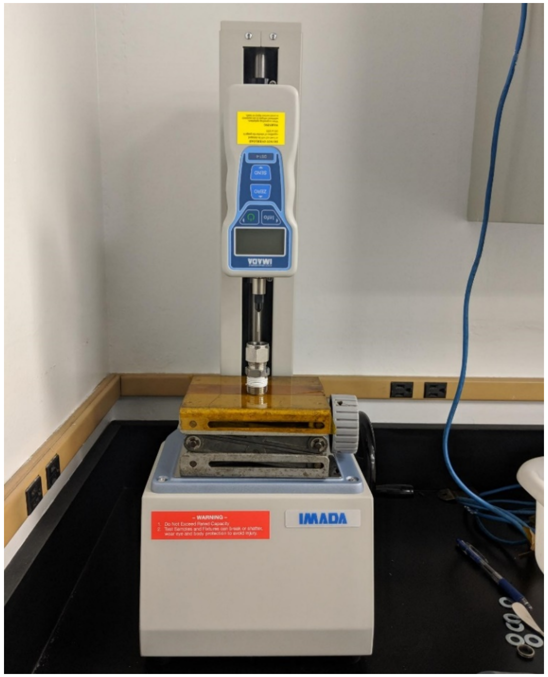
- Concerns over integrity of separators after radiation dosing
- Clear impact on mechanical strength
- May not be a concern once in jellyroll

Differential Scanning Calorimetry of Celgard 2325



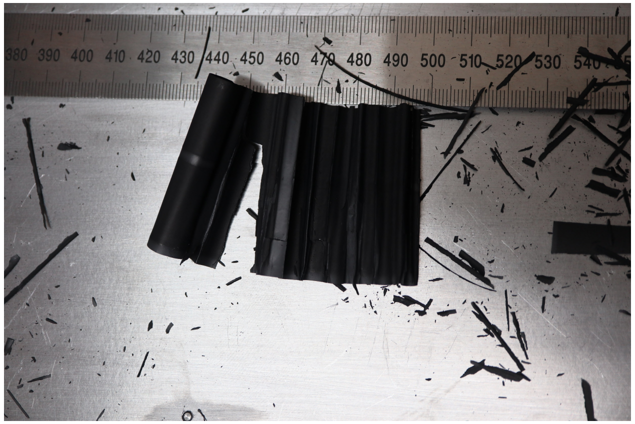
- Not a significant shift in onset of shut-down function
- Some change in enthalpy of fusion, indicating some changes in morphology/chemistry

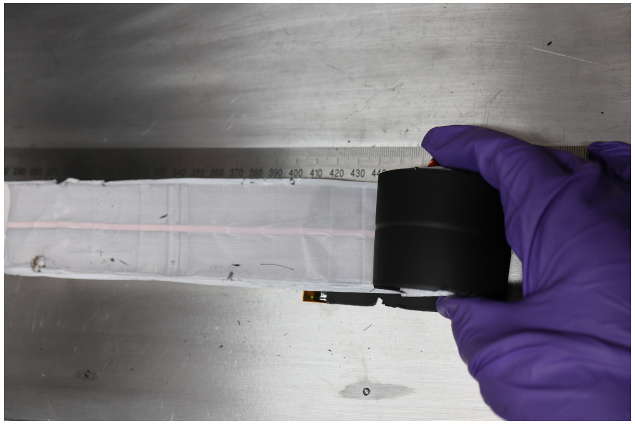
Other Safety Related Testing



Initiating puncture testing on pristine vs. irradiated separator samples

Extraction of PTC safety device from fully charged irradiated cells, for evaluation at vendor





Ongoing destructive physical analysis of irradiated cells at JPL and vendor

Planned Safety Testing with Sandia Battery Abuse Test Lab

- **Thermal ramp testing:** Cells will be heated at 5 °C/min to thermal runaway or 250 °C.
- **External short circuit testing:** A resistive load (shunt) of 1 mOhm will be applied to the cell for 60 minutes.
- **Overdischarge tests:** The cell will be discharged from full charge to -150% total state of charge (by coulomb counting) or until thermal runaway is observed.
- **Nail penetration tests:** Cells will be fully penetrated with a sharp, conductive nail and observed for at least 60 minutes, or until a thermal runaway event is fully observed.
- **Mechanical crush tests:** A cylindrical impactor will be used to mechanically crush the cell until thermal runaway occurs or until at least 50% total deformation in the direction the crush is applied.
- **Overcharge/forced charge tests:** A charging current will be applied to the cell until 250% total state of charge or until thermal runaway is observed.

Plans Forward

- **Complete Evaluation of Build 1 Cells**
  - Performance testing (pristine and irradiatied)
  - 18 month storage (pristine and irradiated)

- **Support Build 2**
  - Planned safety/abuse testing of irradiated cells at Sandia National Labs
  - Leads to Build 3, final down-select for battery design

- **Monitor Risks and Concerns**
  - Use of single CF_x source for both cell vendors (discussing qualification of alternative materials sources with vendors in D-size format)
  - Continuing evolution of battery company ownership

Acknowledgements

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California Institute of Technology

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