Jet Propulsion Laboratory
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Update on Li/CFx Primary Cell Testing for Space Applications

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Proposed Europa Lander Mission Concept

(Source: 2020 Europa/Ocean Worlds Lander Mission Concept Update, May 14, 2020)

- Notional lander lands on Europa for a 22-day surface mission.
- Sample acquisition, analysis and data transmission back to Earth will be powered by Li/CFx primary batteries.
- Battery modules are on the exterior of the Lander.

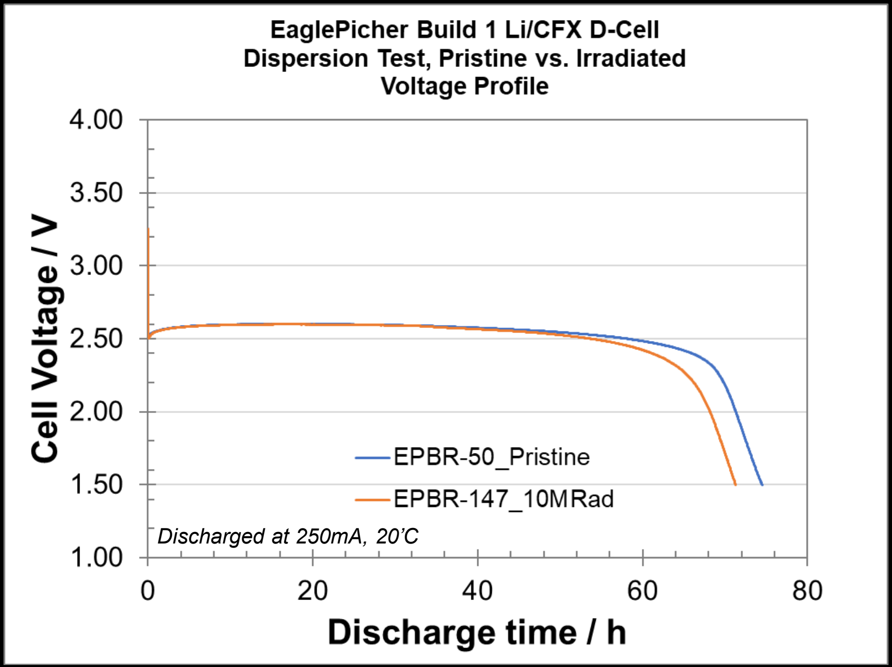
Build 1 Test Campaign

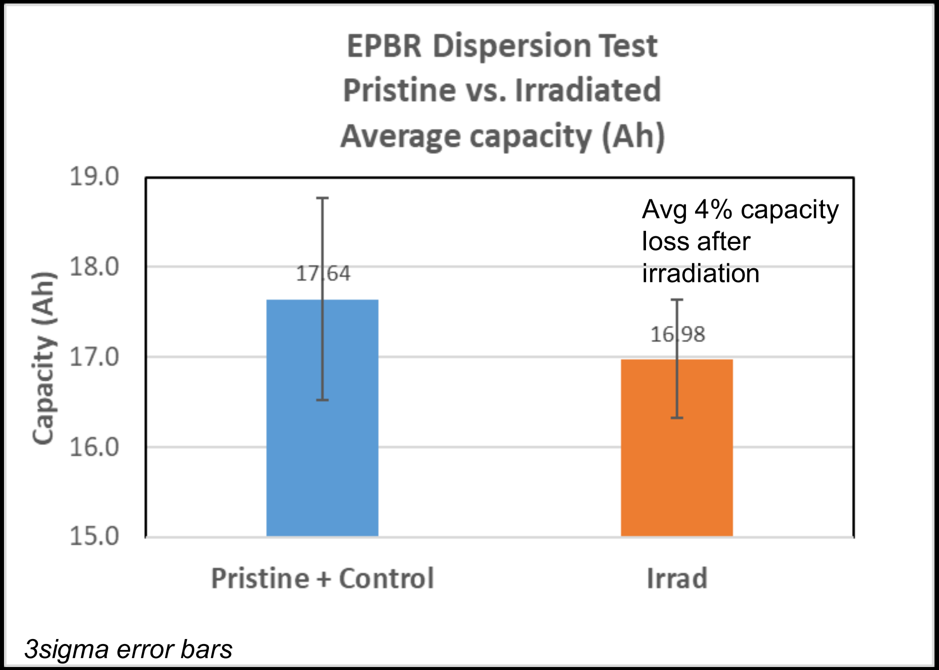
- **Issued contracts to two vendors in early 2018.**
  - Eagle Picher Technologies and Rayovac Corporation.
  - Target spec is >700 Wh/kg at cell level (50 mA discharge at 20ºC)

- **Tests:**
  1) Capacity dispersion in manufacturing lots
  2) Constant current discharge performance
     1) Discharge over range of current and temperatures (50 to 250 mA, 0 to +70ºC)
  3) Storage testing
     1) Real time and accelerated storage, micro-calorimetry
     2) Understand battery self-discharge for up to 10 years storage
  4) Isothermal calorimetry
     1) Compare electrical to thermal power ratio
     2) Critical for battery thermal design

- **Radiation testing**
  - Understand radiation effects on battery performance (electrical, safety)
- **Provide comprehensive data to support power de-rating model**

Eagle Picher Dispersion Test

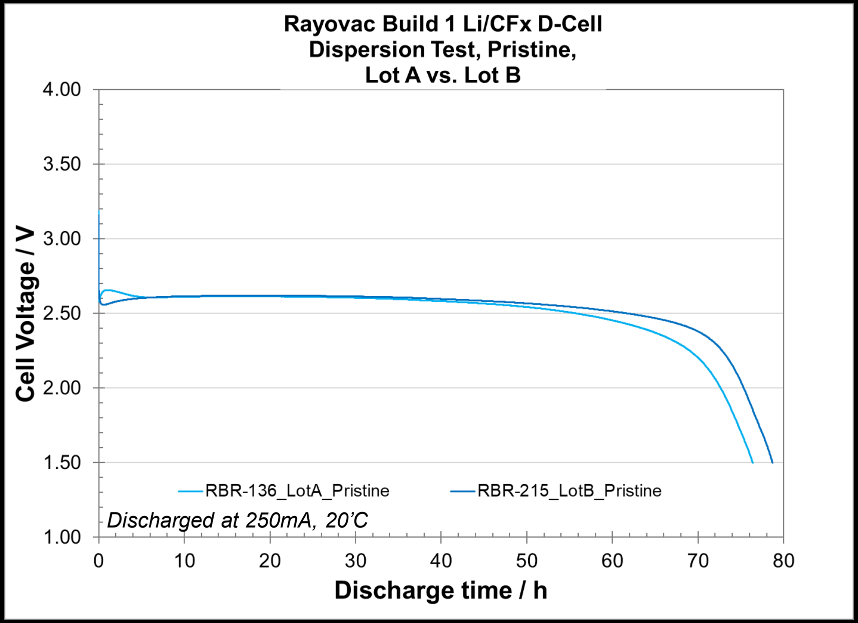


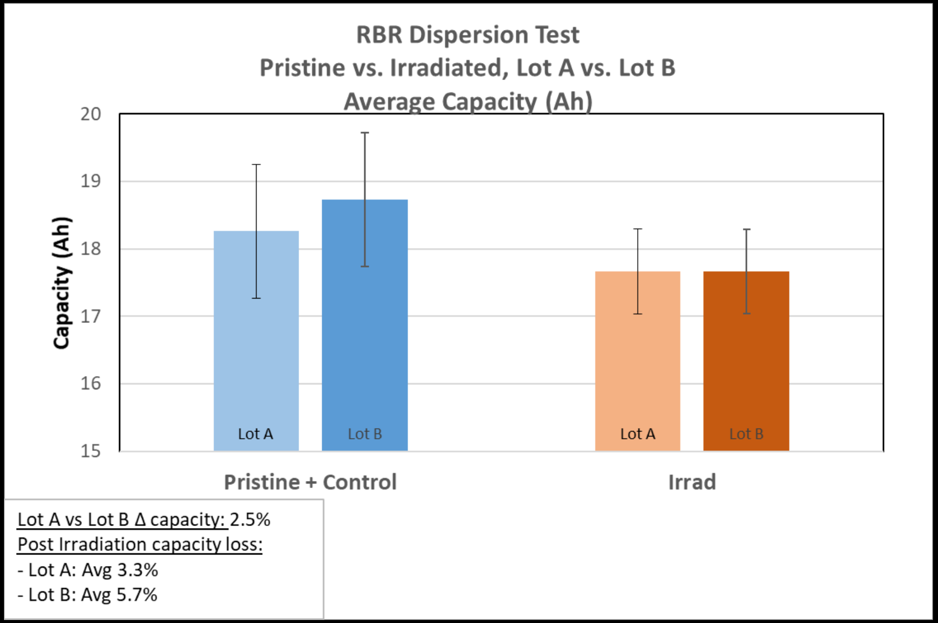


- Discharge cells at 250mA, 20ºC
  - 10 pristine cells selected across manufacturing lot
  - 10 Irradiated cells + 3 control cells

- Eagle Picher Li/CFx (EPBR) D-cell:
  - *Pristine cell-to-cell variation: ~±5.0% capacity (3σ)*
  - *Post-irradiation capacity loss = ~4.0%*
  - *Irradiated cell-to-cell variation = ~±4.0% capacity (3σ)*

Rayovac Dispersion Test





**3sigma error bars*

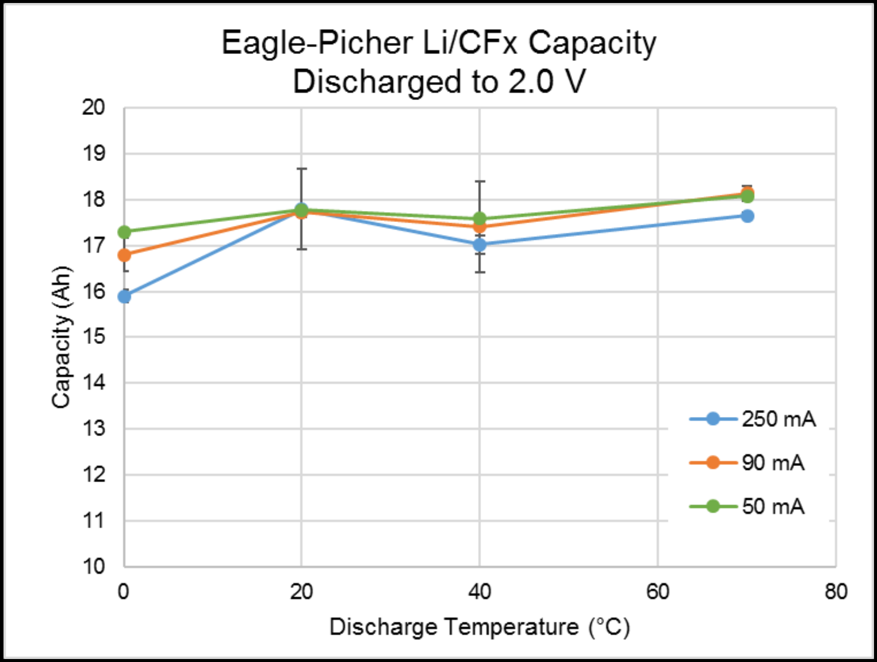
- Rayovac Li/CFx (RBR) D-Cell
  - Two manufacturing lots with distinct bifurcation
    - Part of manufacturing variability
      - *2.5% capacity difference between two lots.*
      - *Overall cell-to-cell variation (3σ): ±5% of capacity*
  - Post Irradiation cells lose an average of 4.5% capacity loss, with ±3.4% variation
    - *Capacity loss: ~3.0% (LotA) and ~6.0% (LotB)*

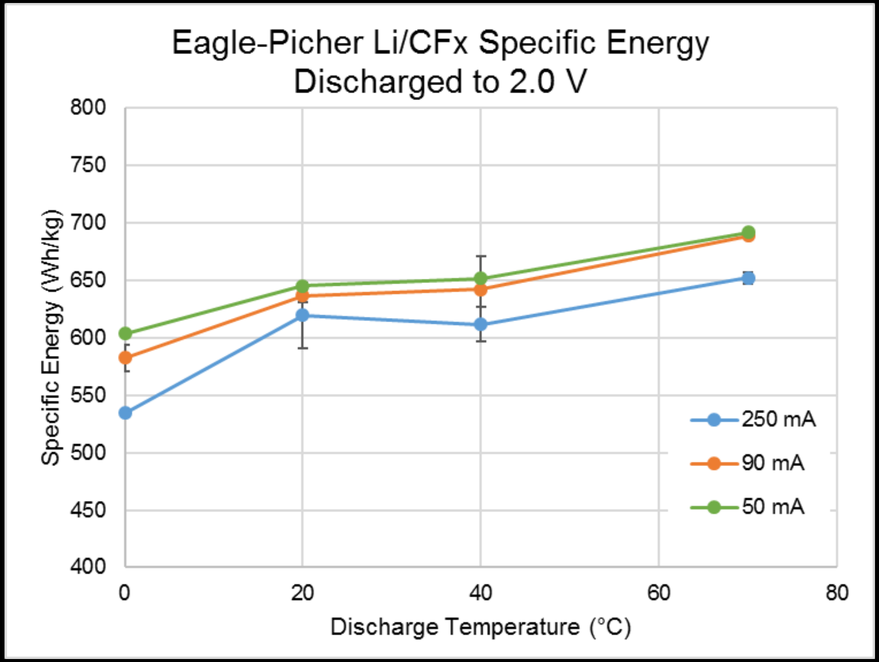
Build 1 Performance Test Matrix

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 populate power models
- 20ºC / 250 mA condition used as baseline to evaluate dispersion in manufacturing lots (cells in red)
- Test on pristine cells only

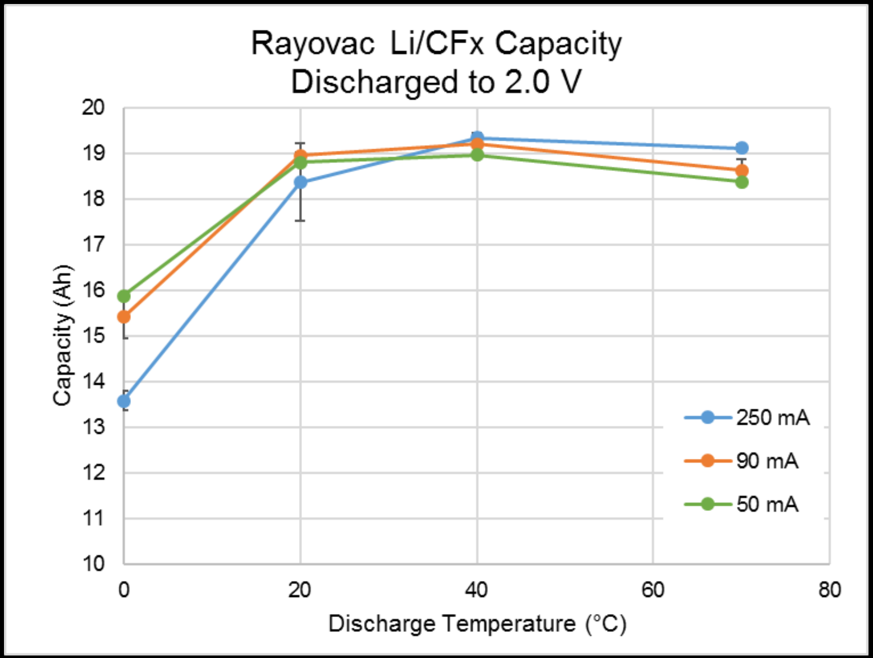
Eagle Picher Performance Test

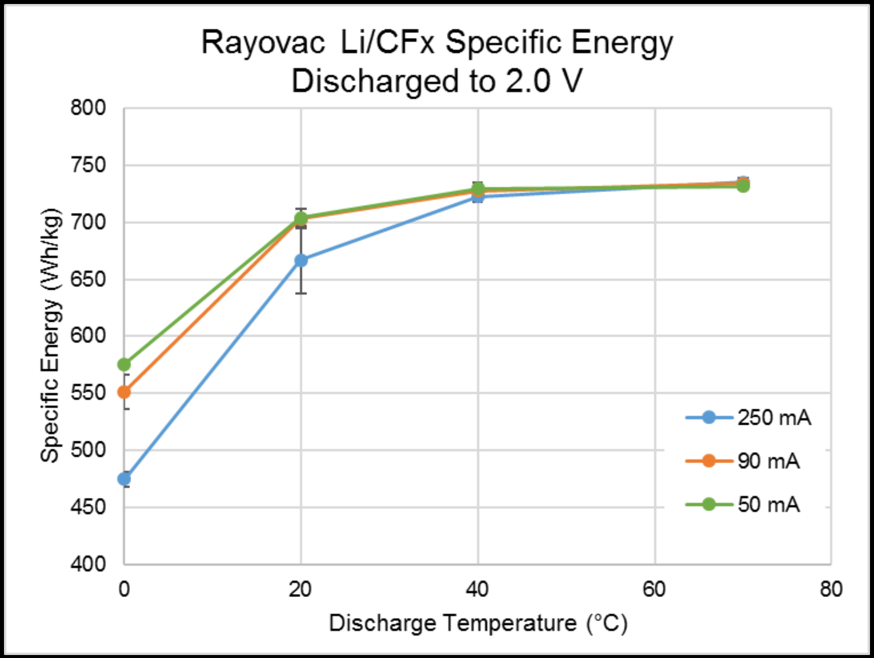




- **Capacity:** Between ~16-18 Ah
- **Specific Energy:** Between ~525 and 700 Wh/kg
  - *Falls short of 700 Wh/kg target (although correction for larger tabs increases specific energy ~5%)*
  - *Targeted improvements with cathode optimization in Build 2*

Rayovac Performance Test





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

Storage Test Matrix

Cells on Storage		Storage Duration			
Vendor	Temperature (ºC)	**0 days/mth**	**183 days 6 mth**	**365 days 12 mth**	**548 days 18 mth**
Eagle Picher	***20**	10	6	6	6
	30	-	6	6	6
	40	-	6	6	6
	60	-	6	6	6
Rayovac	***20**	10	6	6	6
	30	-	6	6	6
	40	-	6	6	6
	60	-	6	6	6

**20'C storage temp → 18'C actual temp*

- Different storage temperatures for real time and accelerated shelf-life studies.
- Half of all cells will be irradiated to 10 Mrad, half pristine
- Due to COVID-19 schedule impacts, some cells were stored for 13.5 and 22 months.

Storage Test Method

1) **Visual Inspection** and **dimensional measurement** before vs. after storage

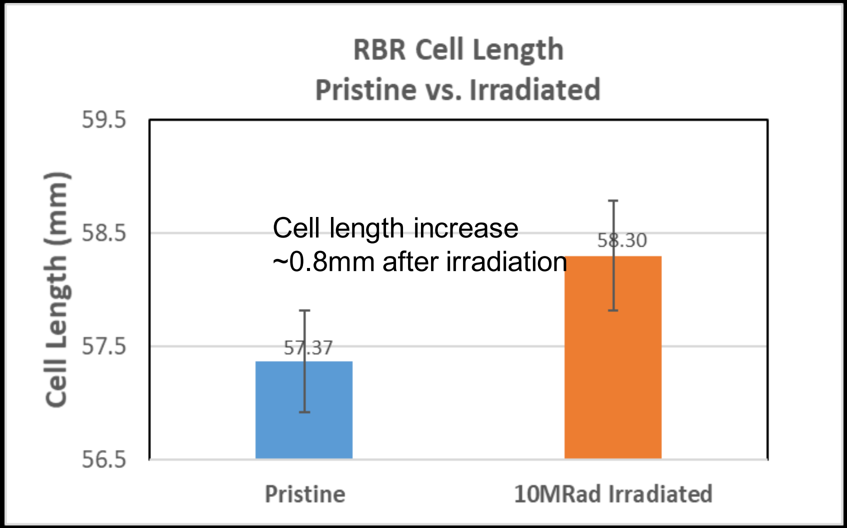
2) **Non-destructive measurements before vs. after storage:**
   - OCV and 1kHz alternating current internal resistance (ACIR)
   - 100kHz to 10mHz full sweep electrochemical impedance spectroscopy (EIS)
   - Microcalorimetry on 18mo storage samples *(data analysis in progress)*

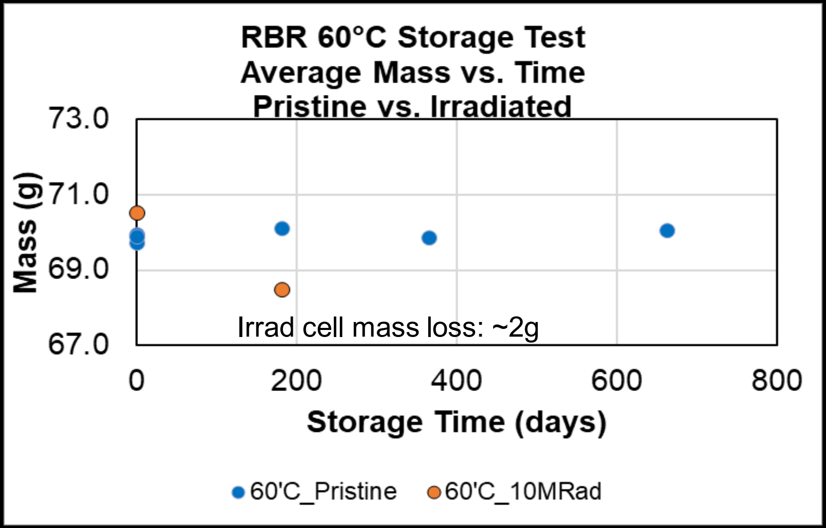
3) **Discharge Performance:**
   - Constant current discharge (250mA, 20°C)
   - Initial voltage drop
     - *Minimum voltage recorded within the first hour of discharge*
   - Mid-point/operating voltage
     - *Voltage at 50% DOD*
   - Capacity achieved at 2.0V

Storage test: Visual Inspection and Dimensional Measurements

- **Pristine** cells from both vendors remain visually unchanged with <1% change in dimensional measurements after storage.

- **Irradiated** cells:
  - RBR cells increased in cell length after radiation.
  - After 6 months at 60°C storage, EPBR cells showed signs of bulging in the axial direction while RBR cells leaked electrolyte.
    - 2 of 3 RBR cells had a measurable mass loss of ~2g



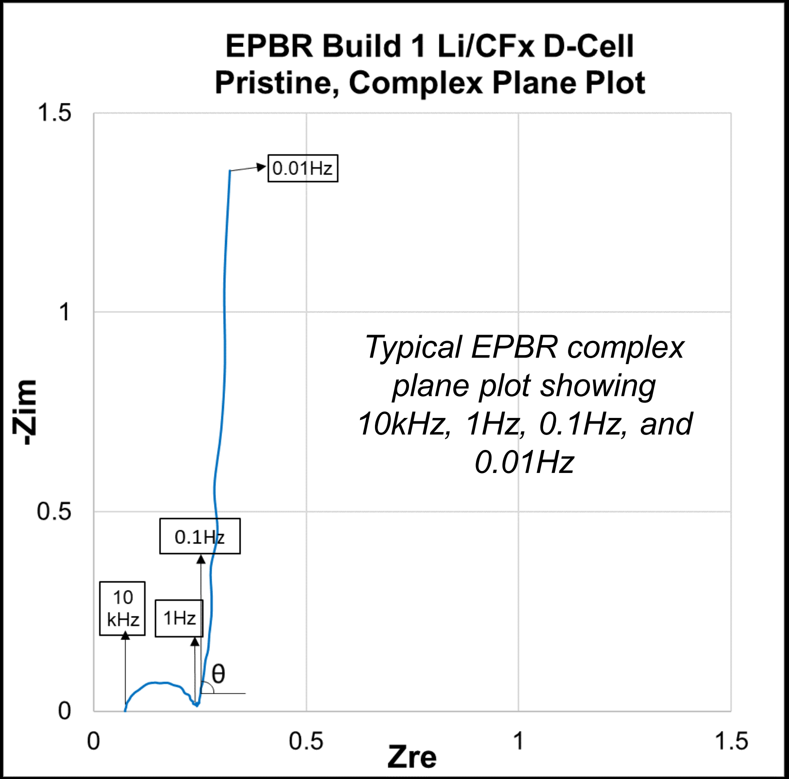


Storage Test: EIS

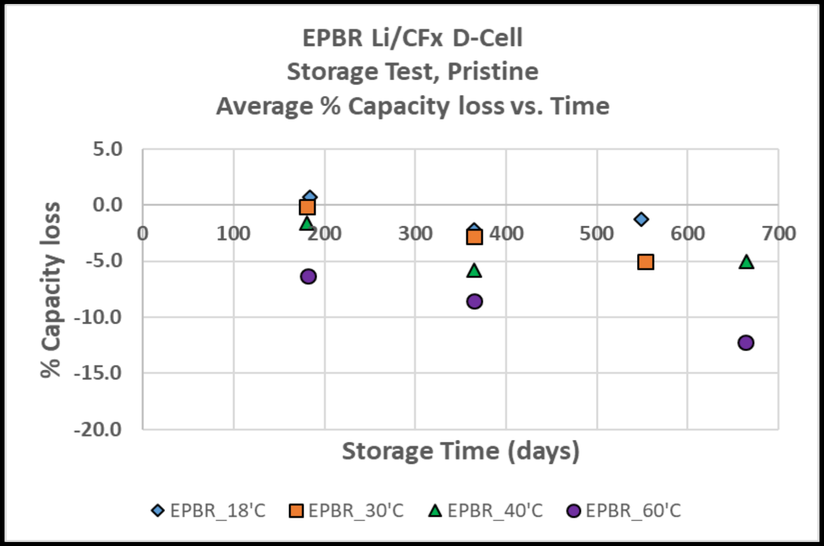
- EIS as a non-destructive battery screening method

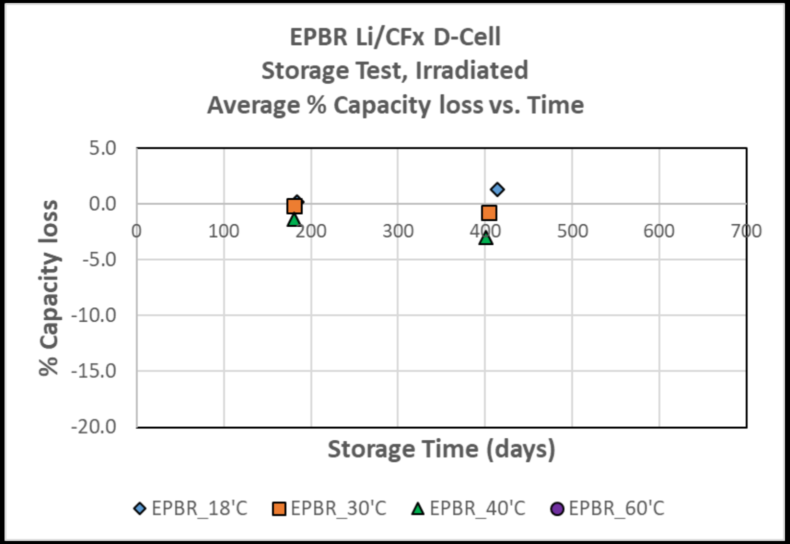
- Settings:
  - 100kHz – 1.25Hz, 1mV amplitude
  - 1.00Hz – 10mHz, 5mV amplitude
  - 10 pts/decade

- From complex plane plot, evaluate:
  - Series resistance:
    - *Zre at 10kHz*
  - Semicircle resistance:
    - *Zre @ (1Hz – 10kHz)*
  - Low frequency slope:
    - $\tan^{-1} \dfrac{(\,Zim\ @\ 0.01Hz - 0.1Hz)}{(\,Zre\ @\ 0.01Hz - 0.1Hz)} = \theta$



Eagle Picher Storage test: Pristine Vs. Irradiated Average Capacity Loss vs. Storage Time (days)





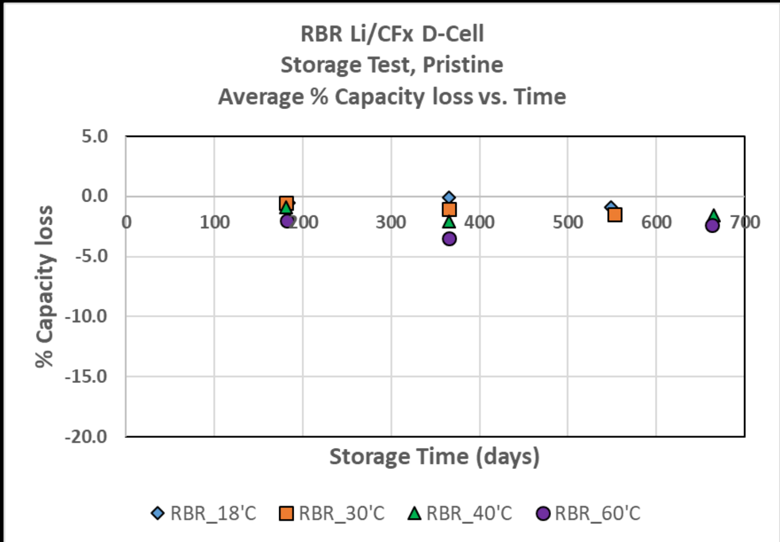
Storage Condition	Pristine % Capacity Loss			
	6mo	12mo	18mo	22mo
18°C	+0.7	-2.2	-1.3	NA
30°C	-0.1	-2.8	-5.0	NA
40°C	-1.6	-5.8	NA	-5.1
60°C	-6.3	-8.6	NA	*-12.2

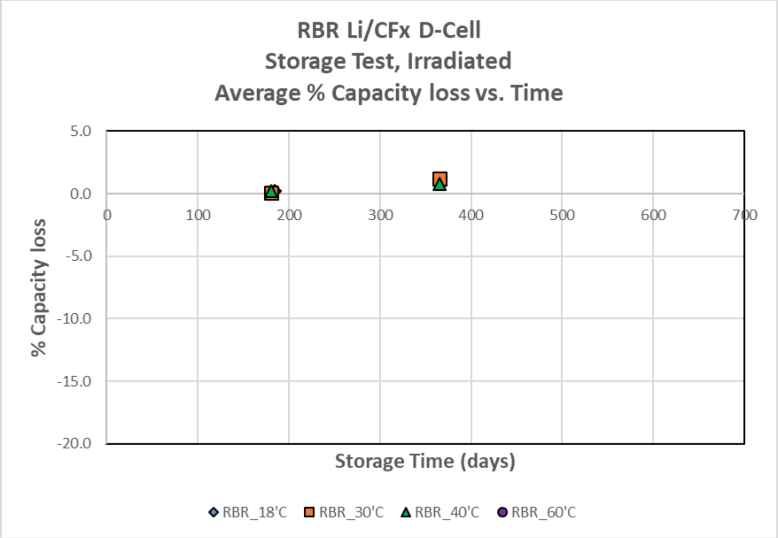
*2 cells only

Storage Condition	Irradiated % Capacity Loss		
	6mo	13.5mo	18mo
18°C	+0.2	+1.3	TBD
30°C	-0.2	-0.8	TBD
40°C	-1.4	-3.0	TBD

- At 18°C storage, **Pristine** EPBR shows ~2% capacity loss every year.
- After initial capacity loss of ~4% due to radiation exposure, **Irradiated** EPBR storage cells lose ~1% capacity every year.

Rayovac Storage test: Pristine vs. Irradiated
Average Capacity Loss vs. Storage Time (days)





Storage Condition	Pristine % Capacity change			
	6mo	12mo	18mo	22mo
18°C	-0.5	-0.1	-0.9	NA
30°C	-0.5	-1.0	-1.5	NA
40°C	-0.9	-2.1	NA	-1.6
60°C	-2.0	-3.5	NA	-2.4

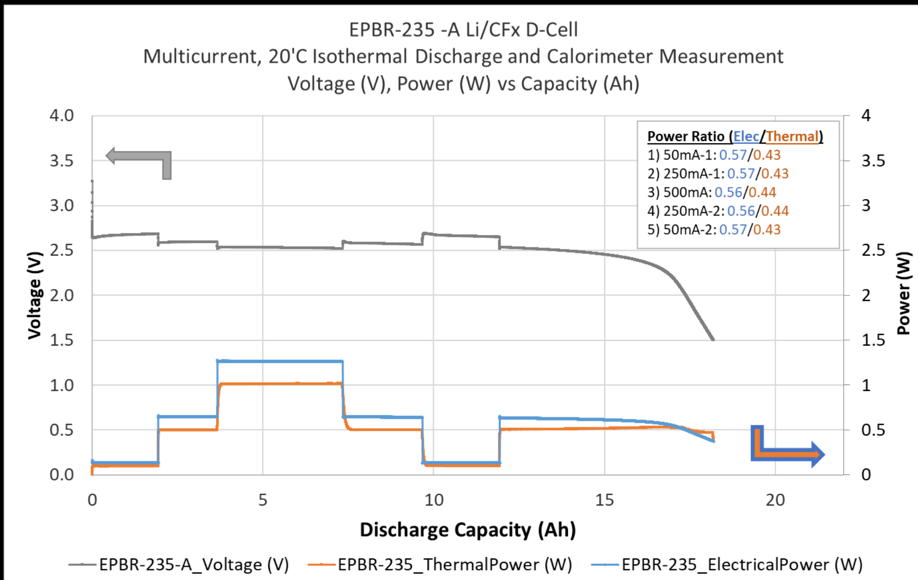
Storage Condition	Irradiated % Capacity change		
	6mo	13.5mo	18mo
18°C	0.2	0.8	TBD
30°C	0.1	1.2	TBD
40°C	0.2	0.8	TBD

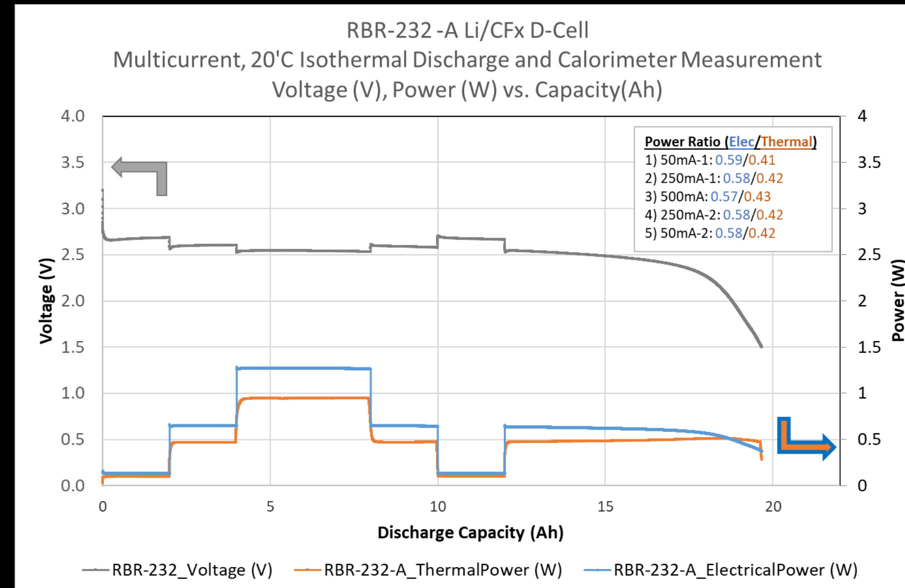
- **Pristine** RBR cells show low self-discharge rate.
- Similar to EPBR, after initial capacity loss of ~3-6%, **irradiated** cells do not lose significantly more capacity vs. storage time.
  - *Slight apparent capacity increase in **irradiated** cell is within cell-to-cell variation.*

Isothermal Calorimetry

Test Objective	Radiation Dose	Temp, °C	Current (mA)	# of Cells	Cell Conditions
Measure heat evolved during discharge	0	20	50	1	BOL/pristine
			250	1	
			500	1	
			Multicurrent	3	
	10MRad		50	1	BOL/irradiated
			250	1	
			500	1	
			Multicurrent	3	

Heat Evolution studies





Eagle Picher Li/CFx D-Cell				
Discharge Current (mA)	Pristine		Irradiated	
	Electrical Power (%)	Thermal Power (%)	Electrical Power (%)	Thermal Power (%)
50	57	43	64	37
250	56	44	59	42
500	57	43	58	42

Rayovac Li/CFx D-Cell				
Discharge Current (mA)	Pristine		Irradiated	
	Electrical Power (%)	Thermal Power (%)	Electrical Power (%)	Thermal Power (%)
50	58	42	61	39
250	59	41	58	42
500	58	42	57	43

- **At various currents, electrical to thermal power ratio of pristine cell is ~60:40**
- **Radiation exposure does not significantly affect the electrical to thermal power ratio of Li/CFx D-cell**

Build 1 Overall Test Summary

Cell Type / Test	EPBR		RBR	
	Pristine	Irradiated	Pristine	Irradiated
Post-radiation capacity loss	-4.0%		-4.5%	
Cell-to-cell capacity variation (3σ)	±5%	±4%	±5%	±3%
Performance Test (50mA, 20°C)	650 Wh/kg	NA	700 Wh/kg	NA
Annual Self-Discharge	~2%	~1%	<1%	<1%
Heat Evolution (Electrical : Thermal)	60:40	60:40	60:40	60:40

- **Optimization of EPBR cells to achieve 700Wh/kg specific energy in Build 2.**
- **RBR cells has low self discharge, but is more radiation-sensitive than EPBR:**
  - 0.8mm increase in cell length after radiation exposure
  - Cell leaking at 60'C storage after 6 months.
- **Investigate electrolyte additives and radiation effects.**

Acknowledgements

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