Development and Testing of High Specific Energy Primary Lithium Battery Cells for Space Applications

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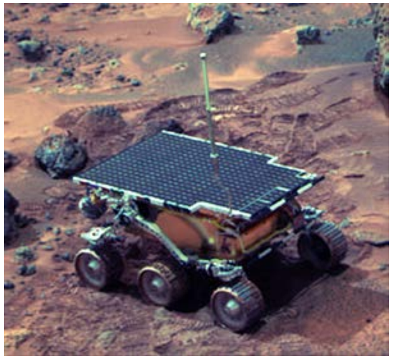
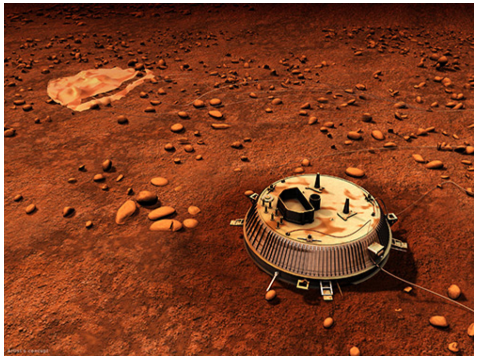
Pioneering Exploration Missions Require Primary Batteries with Increasing Capability

First US satellite (Explorer 1)

First Jupiter probe (Galileo Probe)



First Mars rover (Sojourner)

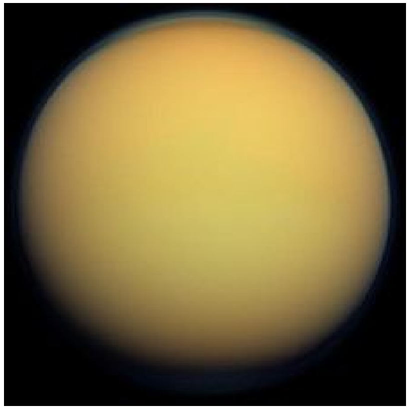


First Titan probe and farthest landed mission (Cassini/Huygens Probe)

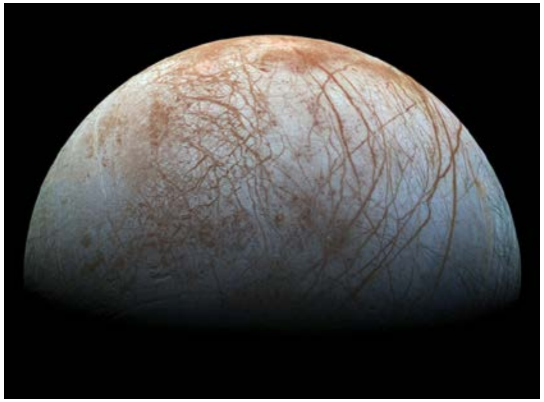
Future missions focused on Lunar Exploration, Ocean Worlds

Moon

Enceladus



Titan



Europa

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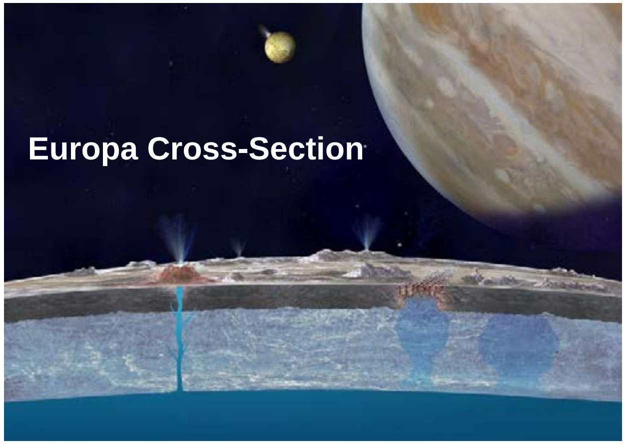
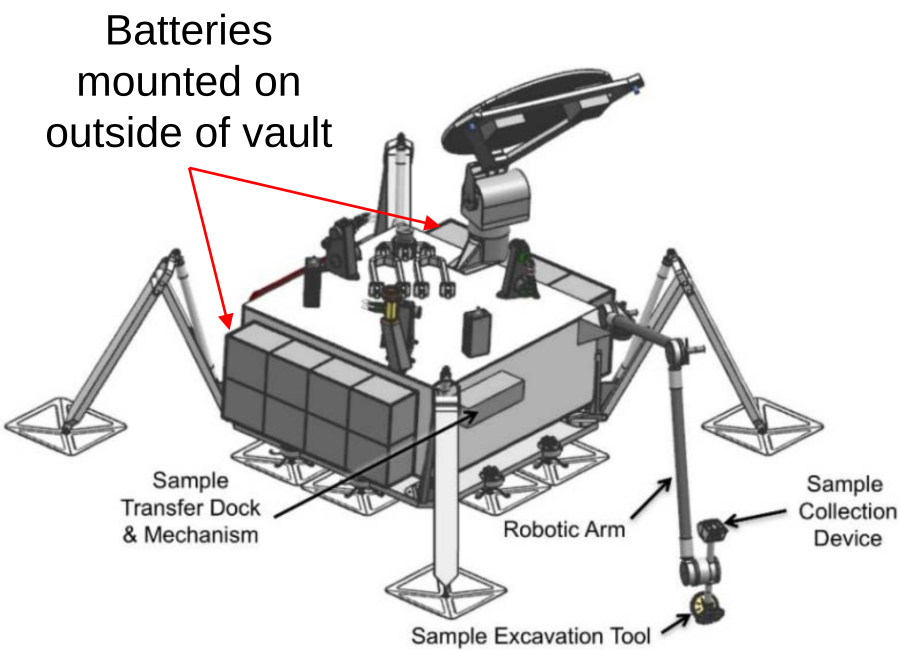
Emerging Power Requirements for a Notional Europa Lander

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





Notional Lander Concept

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 ~500 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)
  - Up to 10 years of storage losses/self-discharge (0 to 40ºC)
  - Cell depassivation protocol prior to landing
  - Losses due to environmental radiation

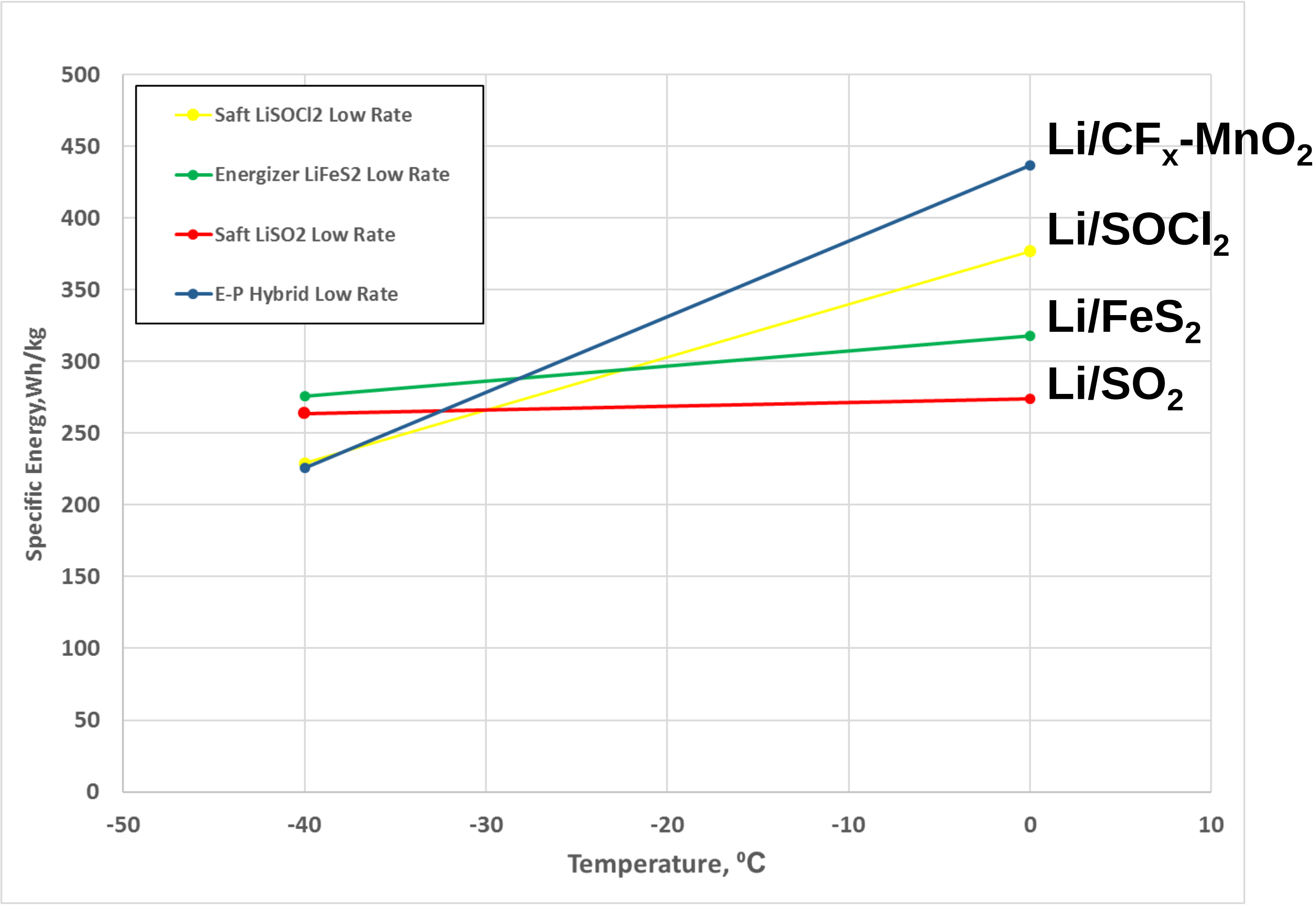
- **Current test campaign aimed at understanding these losses to support derating of cells**

Initial Goal: Evaluate Current Primary Cell Options

Cell Chemistry	Vendor	Part Number	Format
Li/SO_2	Saft	LO 26 SXC	D cell
$Li/SOCl_2$	Saft	LSH 20	D cell
Li/FeS_2	Energizer	L91	AA cell
Li/MnO_2	Ultralife	CR15270	D cell
$Li/CF_x\text{-}MnO_2$	Eagle-Picher	LCF-133 (COTS and modified)	D cell
Li/CF_x	Ray-O-Vac	DP-BR-20Al	D cell

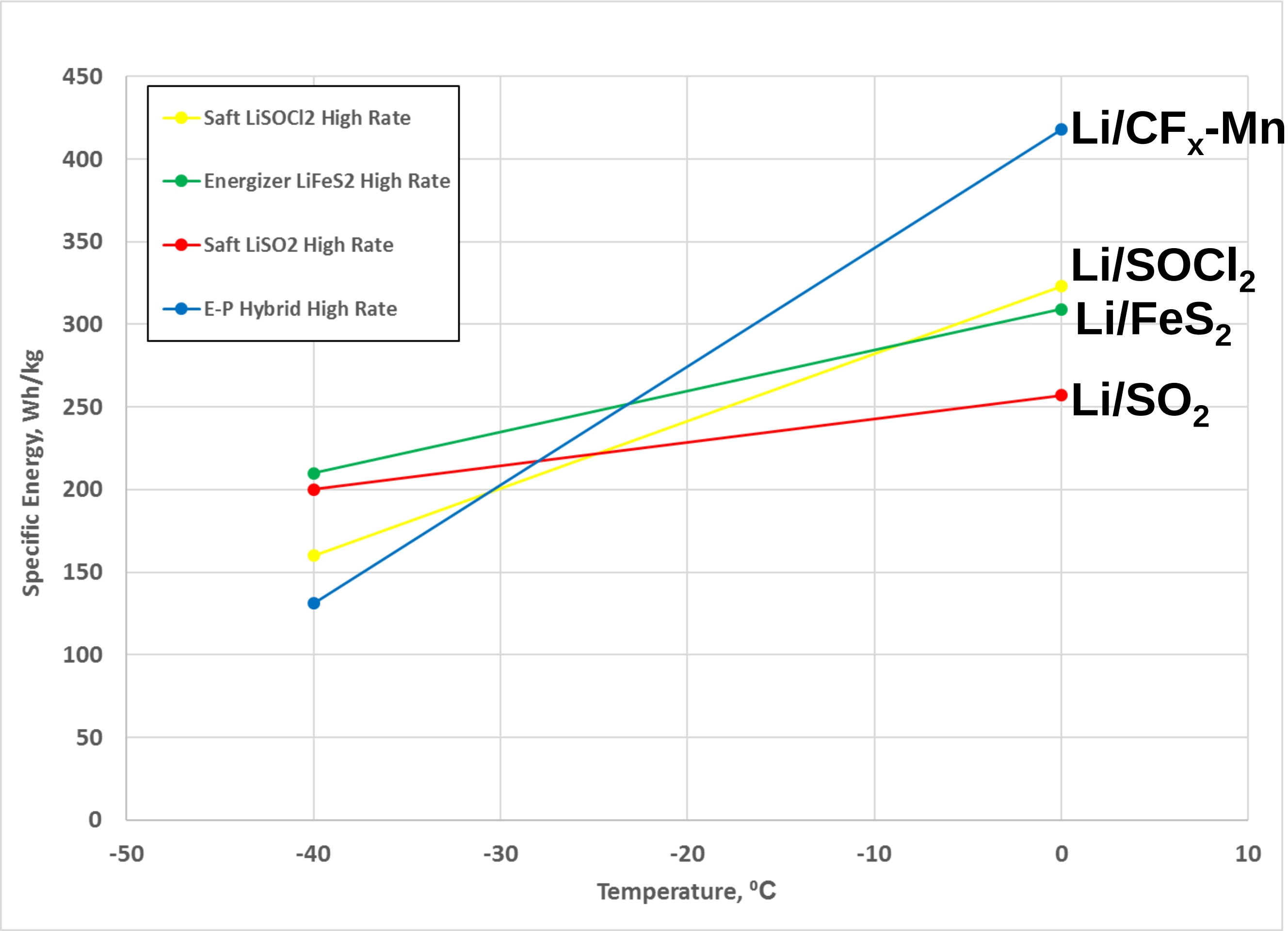
Initially targeted high specific energy at moderate rates (50-600 mA for a D cell) and temperatures of -40 to +30ºC

Moderate Rate Discharge ~C/300 between -40ºC and 0ºC



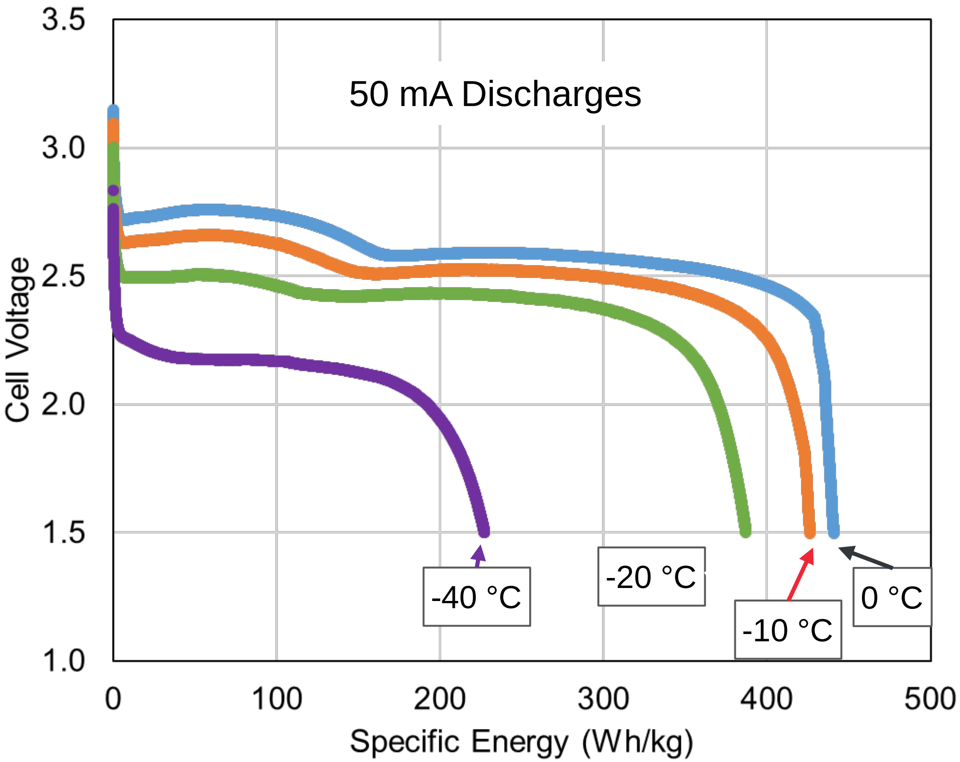
- At lowest temperatures, Li/FeS$_2$ delivers the highest specific energy
- At ~-30ºC there is a cross-over, and Li/CF$_x$-MnO$_2$ is highest

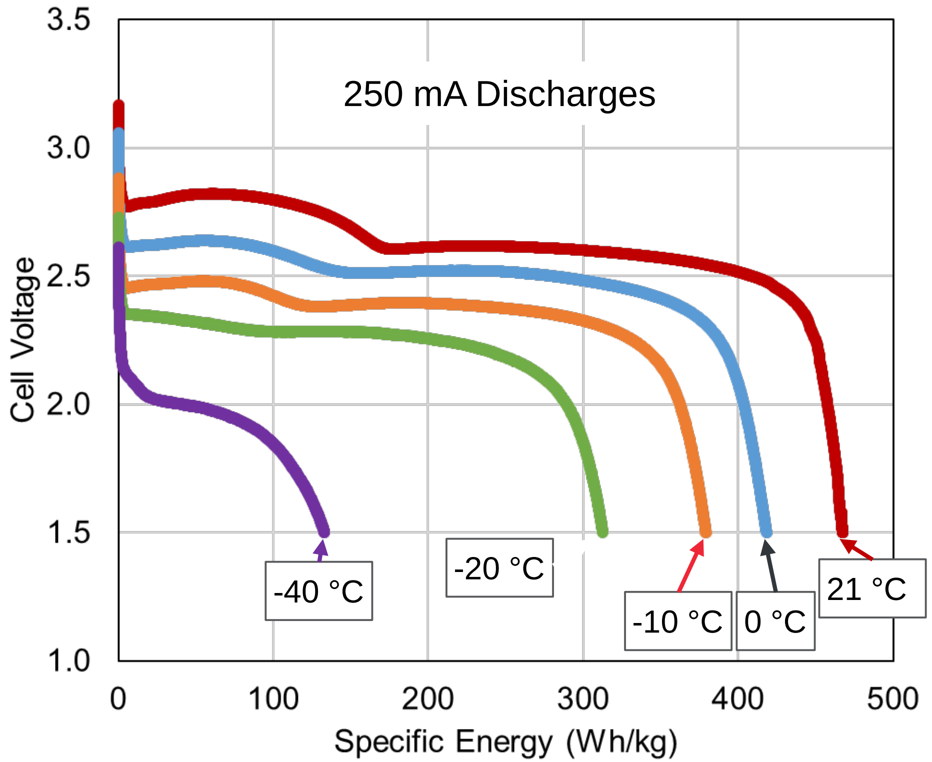
Moderate Rate Discharge
~C/60 between -40ºC and 0ºC



- Similar situation at higher rates
- Li/CF_x-MnO_2 significantly higher performance at 0ºC

Early Focus on Li/CF_x-MnO_2 Cell Chemistry

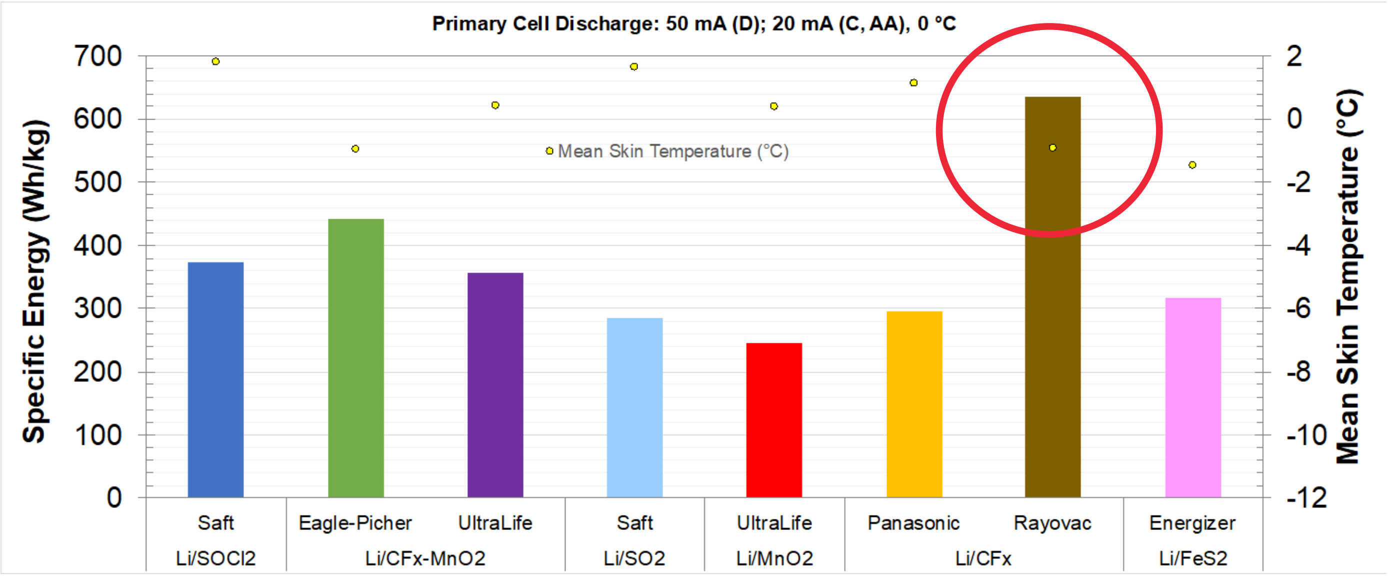




Delivered capacity reduced at low temperatures and moderate rates

Eagle-Picher LCF-133

System Trade Studies Indicated Higher Specific Energy Required



- Target ~500 Wh/kg at the battery level, for operation at 0ºC to +60ºC
- Requires cells in the 700 Wh/kg range
- Initial 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

Requires Consideration of Numerous Cell “Deratings” to Project End-of-Mission Performance

Example de-ratings exercise (starting with a 12s86p pack design):

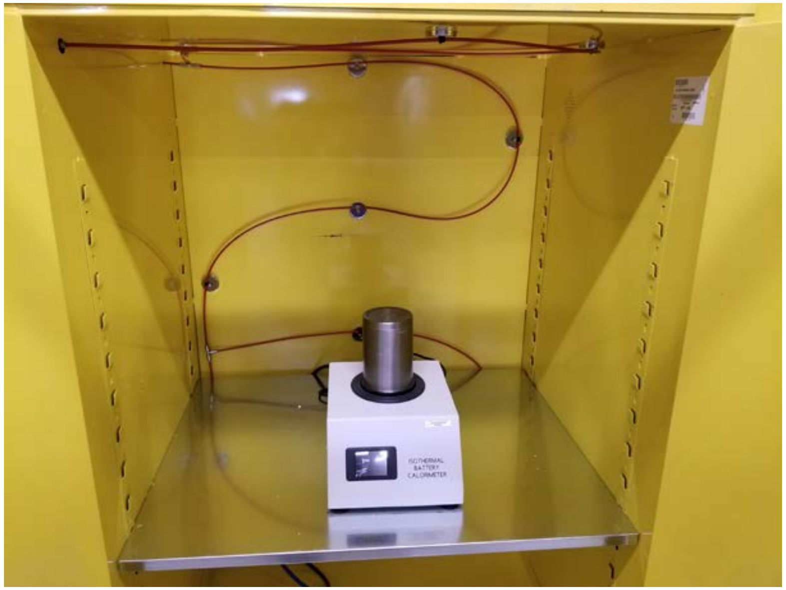
Item	Energy (Wh)	Rationale
12s86p Battery BOL Energy based on Li/CF_x	51,600	JPL testing at 21ºC (2V cut-off, 50 mA, 1032 cells at 50 Wh/cell)
Storage Losses (-1% at RT x 10 years = -10%)	46,440	Lower losses at º0 C storage temperature, but degradation rate may be enhanced by PP radiation TID (testing in progress)
Depassivation Losses (-3%)	45,047	JPL Design Principles (requirement may be lower with solid cathode)
Radiation Losses (Planetary Protection) (-5%)	42,794	Worst case BOL estimate (current testing indicates 0% loss)
Radiation Losses (Environmental) (-5%)	40,655	Worst case BOL estimate (current testing indicates 0% loss)
Loss of one string (-600 Wh)	40,055	600 Wh per string, JPL Design Principles
Cell-to-cell variation within qualified lot (-5%)	38,052	Worst case, probabilistic approach (replaces 80% DOD Design Principles)
Final cell level energy available	38,052	

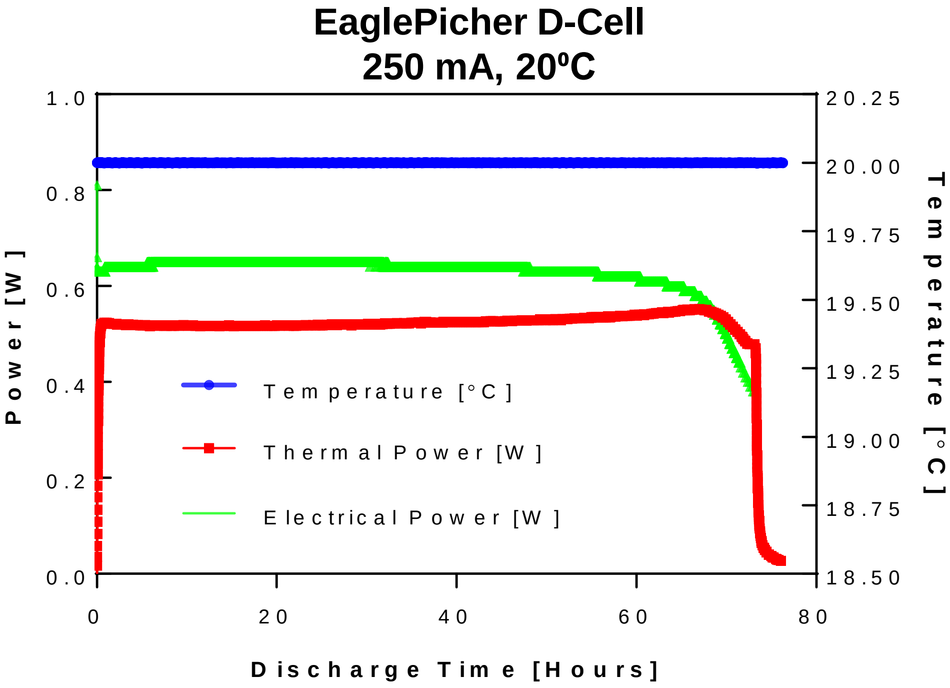
Understanding Li/CF_x Calendar Life Critical to Battery Design

Cells on Storage		Months on Storage			
Cell	Temperature (ºC)	**0**	**6**	**12**	**18**
Li/CF_x	**20**	6	6	6	6
	30	-	6	6	6
	40	-	6	6	6
	60	-	6	6	6

- May be 5-6 year cruise
- Perhaps 10 year total mission lifecycle
- Implement storage testing
  - 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

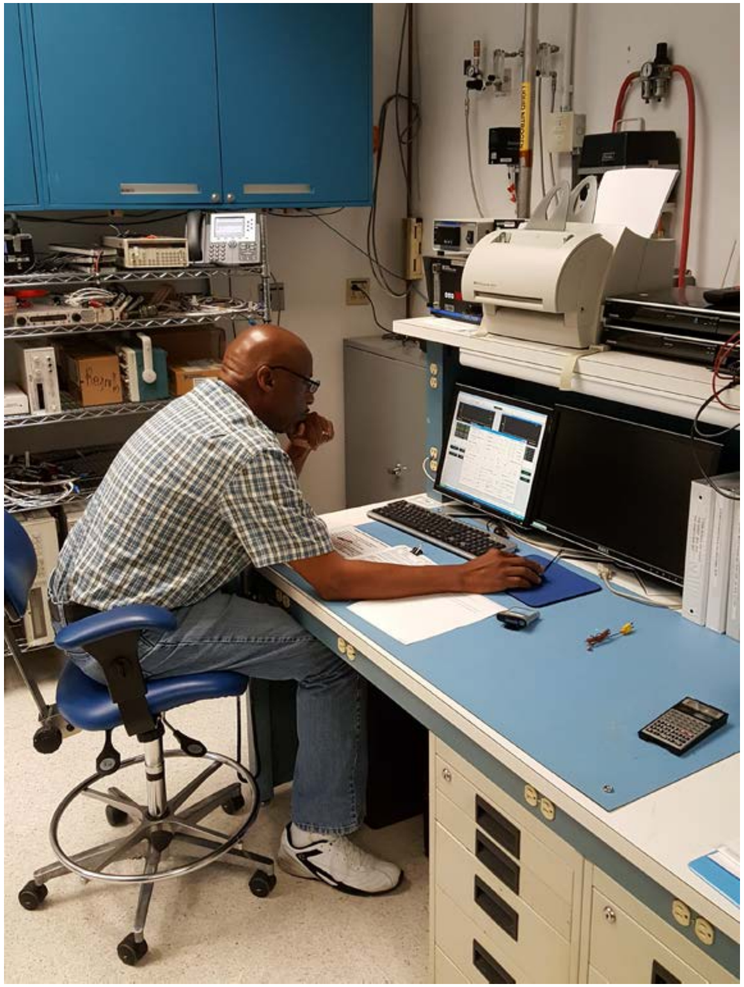
Using Heat Generated from Li/CF_x During Discharge Isothermal Calorimetry



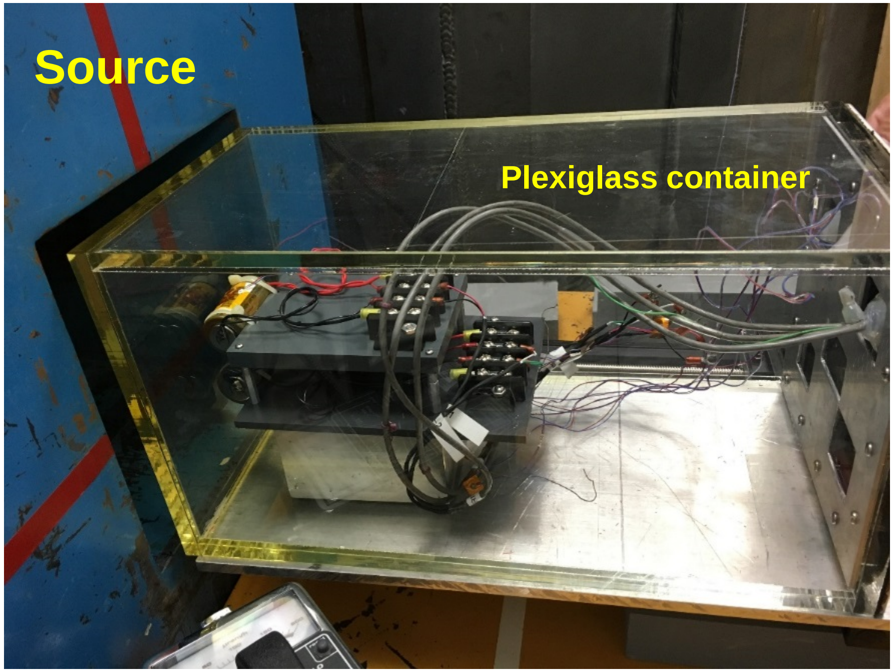


- Initiated testing on pristine and irradiated cells
- Critical for pack design (performance and safety)
- Confirms ~55:45 split between thermal and electrical energy

Cell and Component Level Testing Using Gamma Radiation Source at JPL

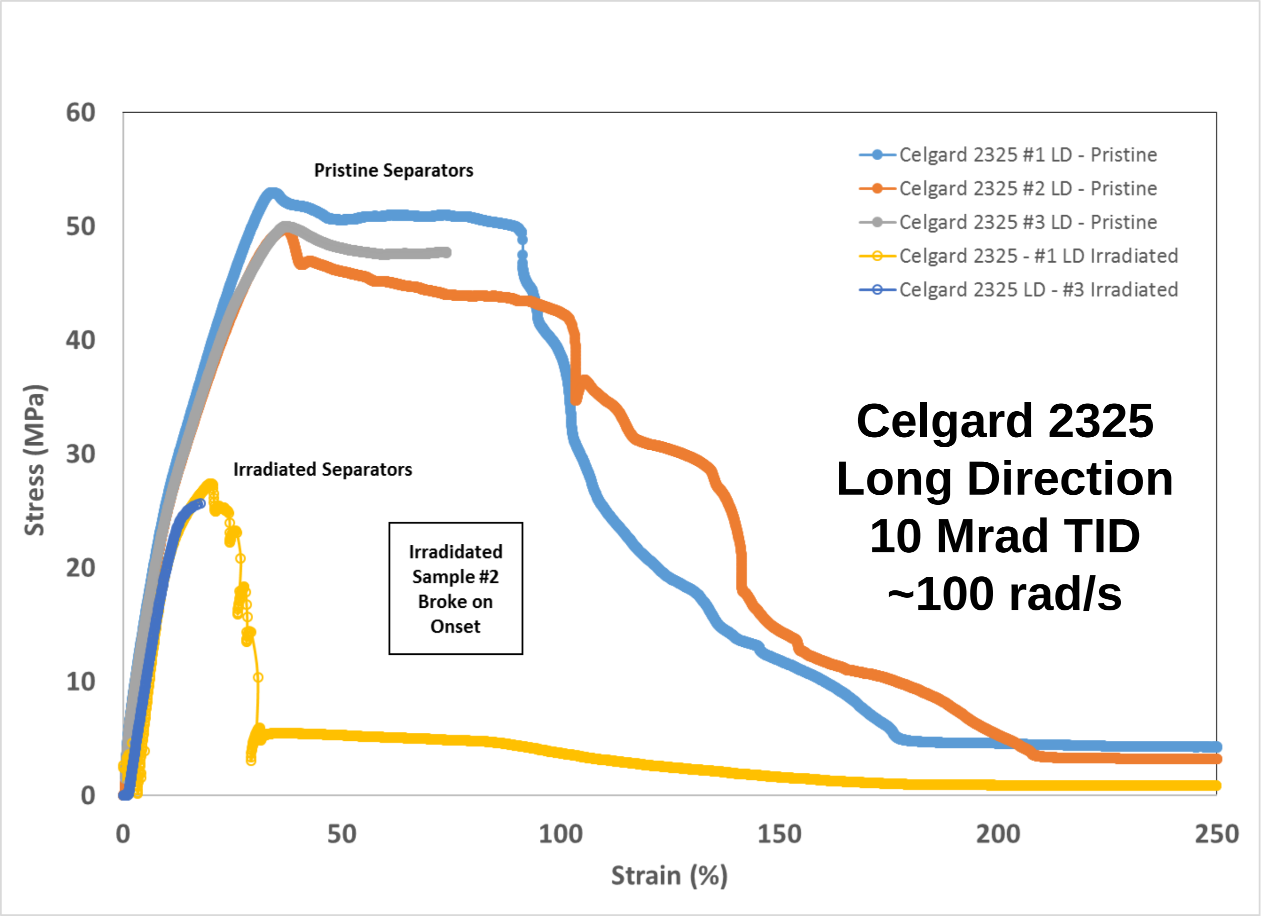


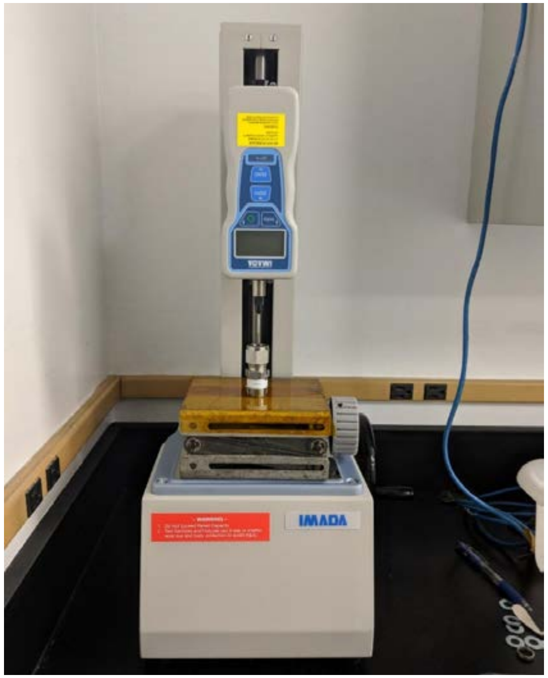
Bernie Rax (Radiation Test Engineer)



Cell and sample holder

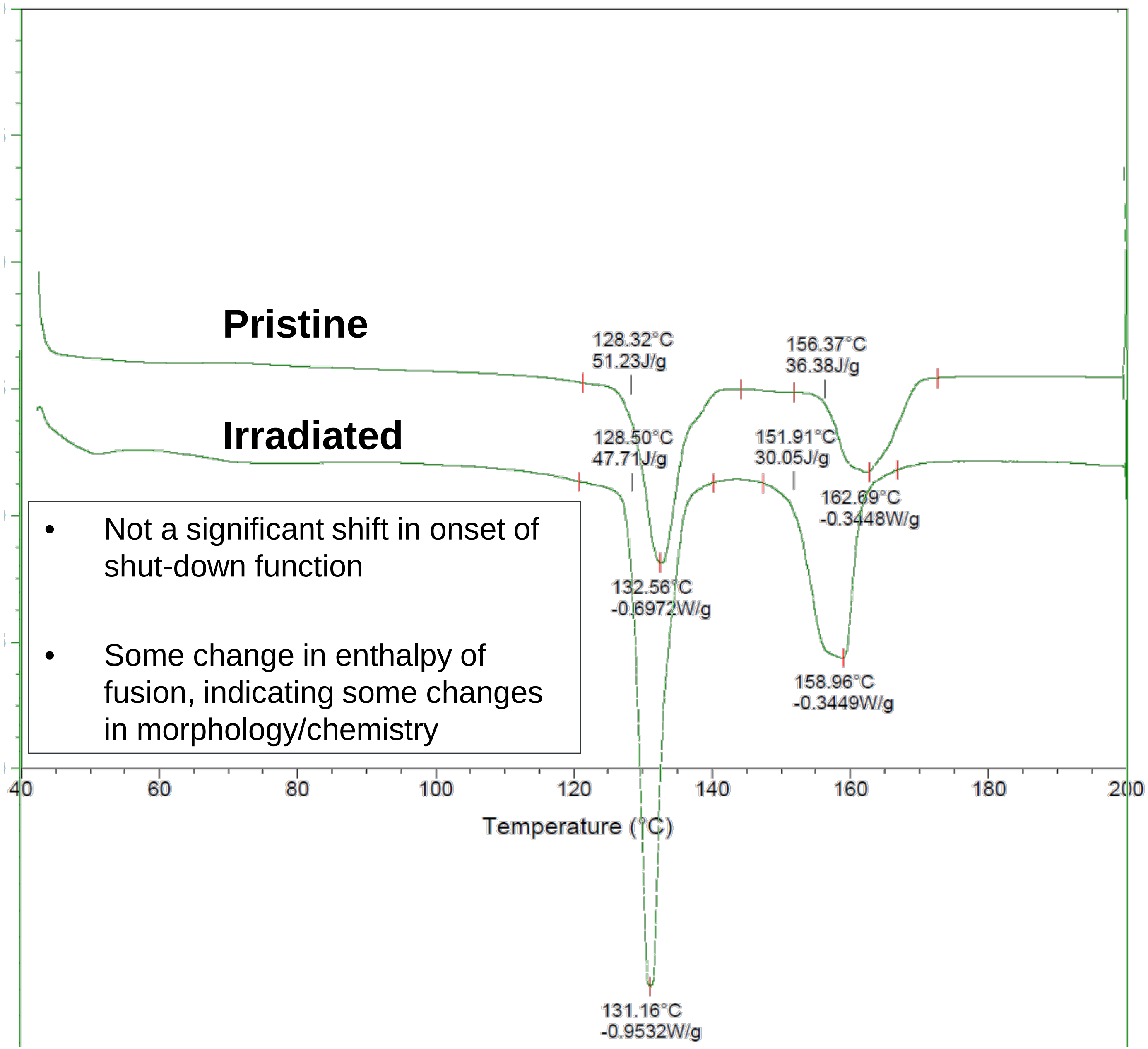
Dynamic Mechanical Analysis Testing of Separators





- Reduce risks related to reliability of components, as well as cell performance
- Clear impact of radiation on mechanical strength of separators
- May not be a concern once in jellyroll
- Supplemented with puncture testing

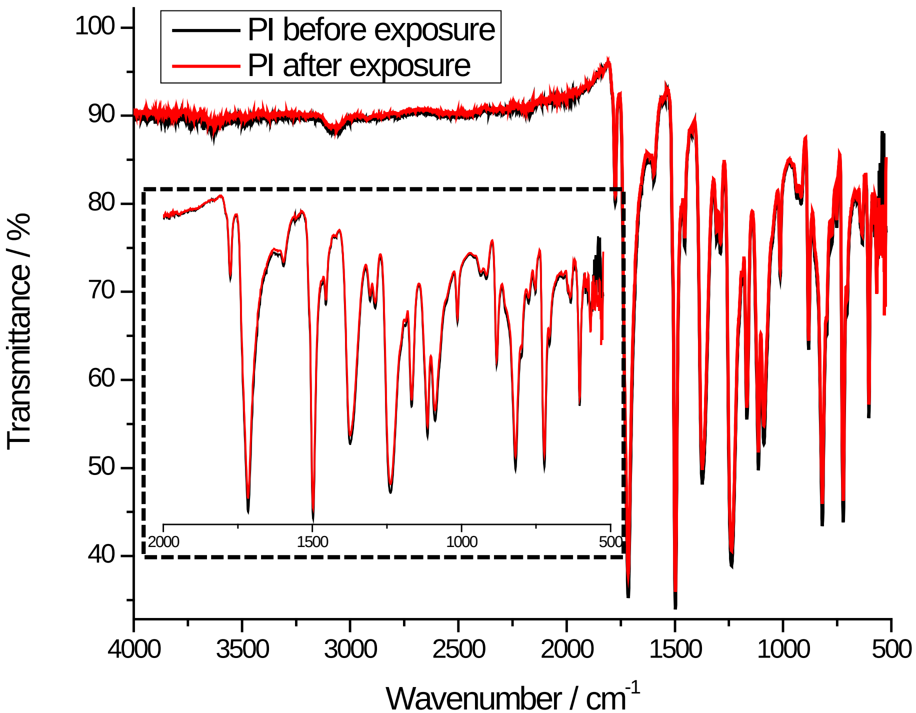
Differential Scanning Calorimetry of Celgard 2325



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

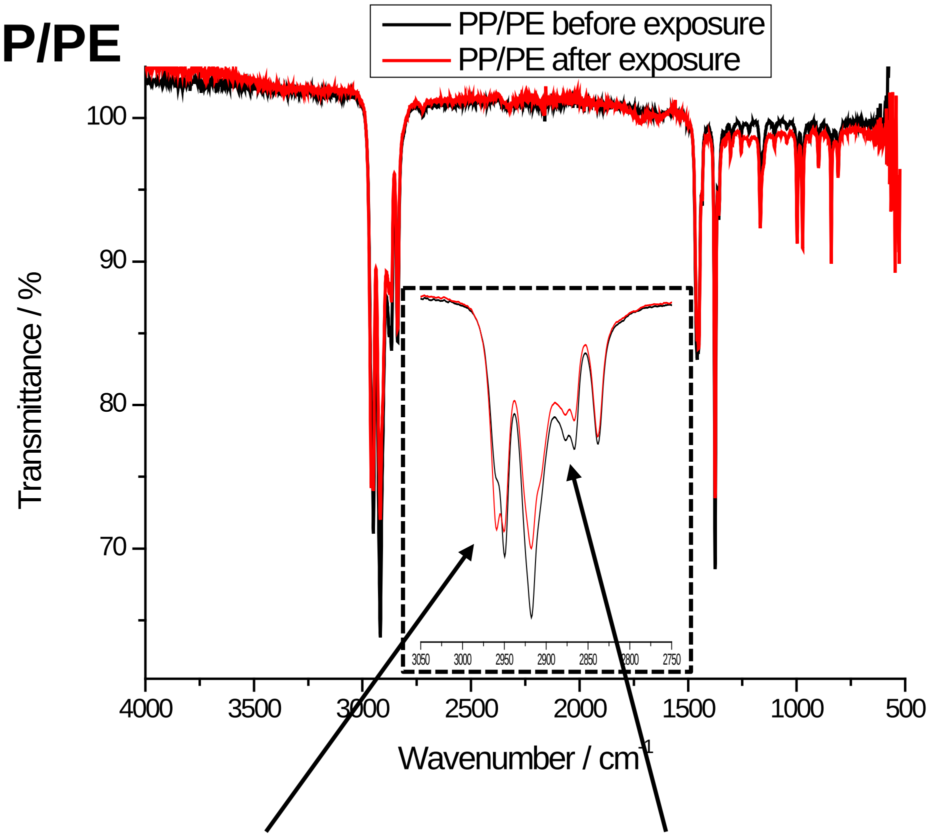
IR Spectroscopy of 10 Mrad TID Irradiated Separators

Polyimide



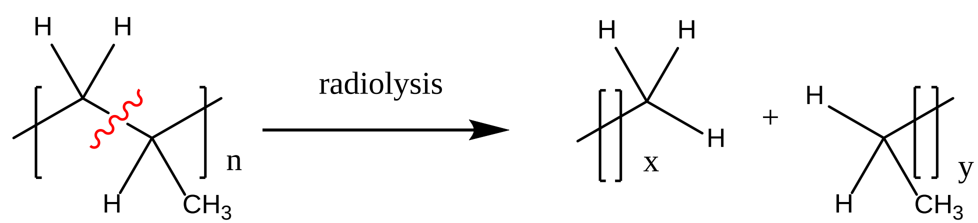
no obvious change

PP/PE



$I_{(CH3)}$ increases, $I_{(CH)}$ decreases

consistent with NASA CR-1787, 1971



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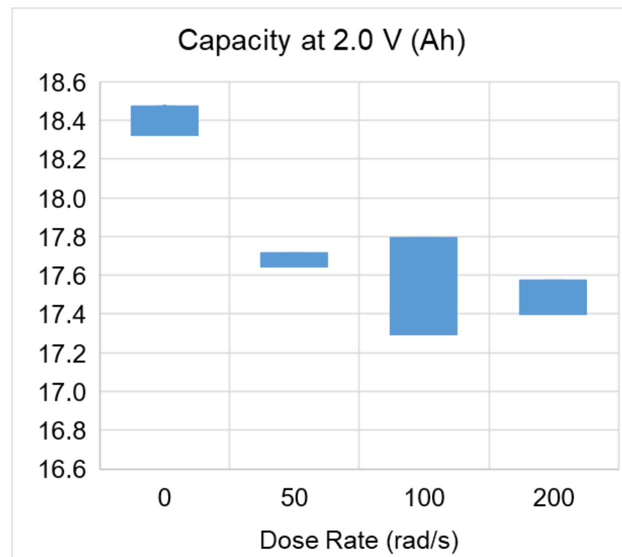
Cell Level Radiation Testing

- Collaboration with Sandia National Labs Gamma Radiation Facility
- Irradiating cells at Sandia, performance testing at JPL
- Environmental concern, as well as possible planetary protection sterilization protocols
- See also talk on first day of Space Power Workshop *“Lithium CFX Batteries for High Radiation Environments”* (J-P Jones, JPL)

Sandia Facility

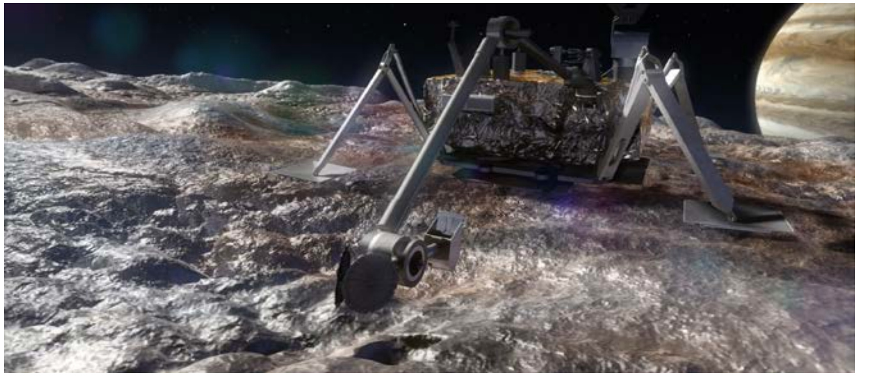


Delivered capacity vs. dose rate

JPL Test Facility

Summary

- Li/CF_x chemistry can meet emerging requirements for notional Europa Lander
- High specific energy (~700 Wh/kg) at moderate rates and temperatures
- Heat generation useful for spacecraft thermal management
- Radiation tolerance is promising
- Further work required to evaluate impacts of radiation on calendar life and component reliability
- Applications to other extreme environment missions



Pre-Decisional Information – For Planning and Discussion Purposes Only

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