# Battery Fault Tolerance & Safety in High Reliability Autonomous Applications

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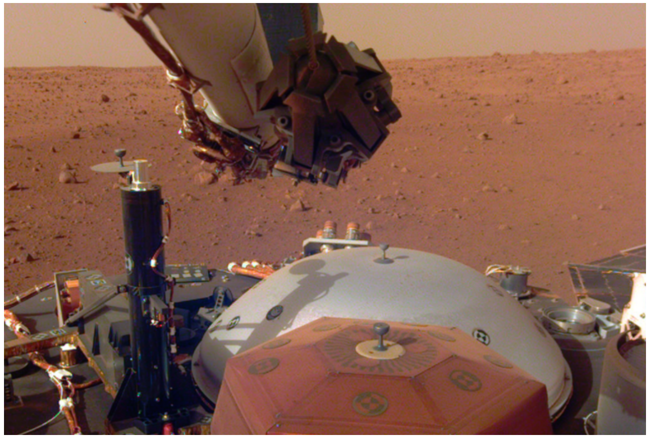
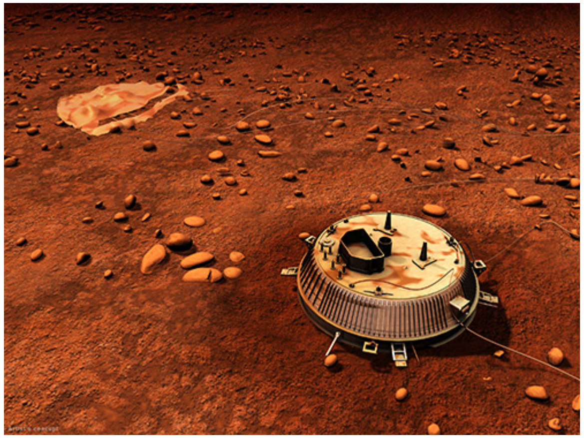
# Challenges with Power for Unique Remote Autonomous Systems

- One-of-a-kind applications, with limited or no user in the loop
- Unlike DOD/military applications, one time use
- No provision for re-work or replacement
- No extensive “field testing” or user feedback prior to deployment
- Requires extensive up-front consideration of risks
- Requires extensive test program and modeling/simulation of worst case scenarios
- Can be very high value (>$1 B)



**InSight Lander (Mars)**



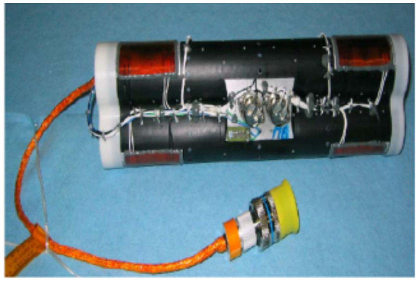
**Huygens Probe (Titan)**

**Europa Lander (Proposed)**

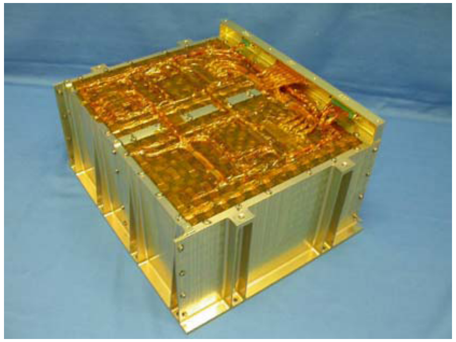
# Three Main Classes of Space Batteries

- **Thermal Batteries (Minutes of discharge time, one time use)**
  - High power, one time use for critical events such as Entry/Descent/Landing
- **Primary (Hours of discharge time, one time use)**
  - Typically for short duration probes in extreme environments
- **Secondary (Hours of discharge time between recharge cycles)**
  - Requires suitable power sources for recharging (solar or radioisotope)

**Thermal**

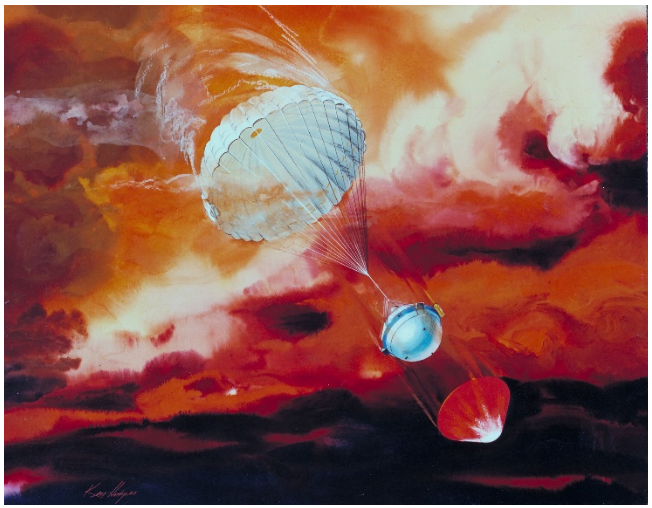


**Primary**

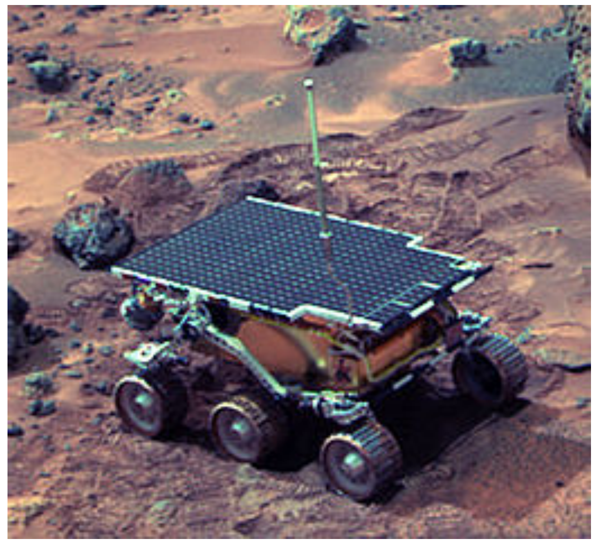


**Rechargeable**

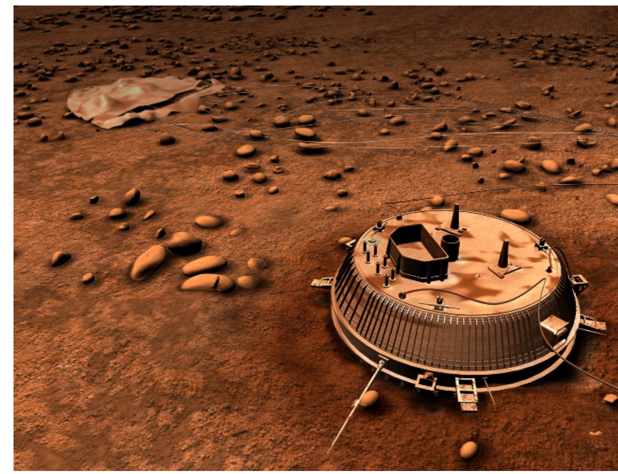
# Primary Battery Applications



**Galileo Probe**
1989



**Sojourner Rover**
1996



**Huygens Probe**
1997

**Typically support hours of run time for smaller probes/missions in extreme environments**

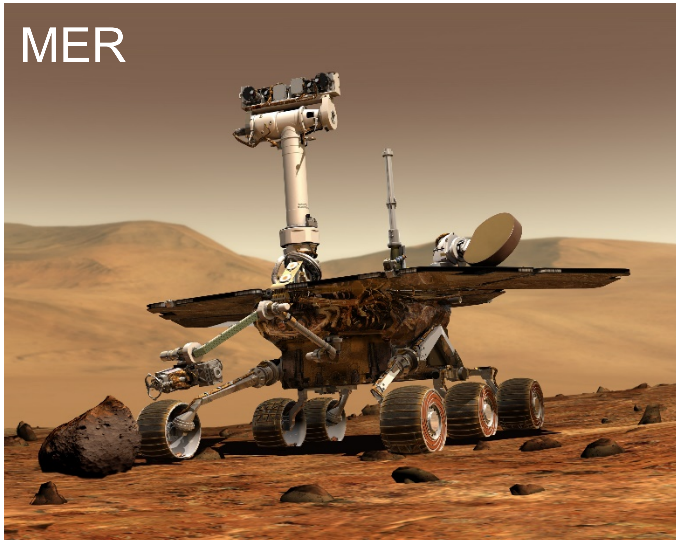
# Primary Batteries for Space Missions

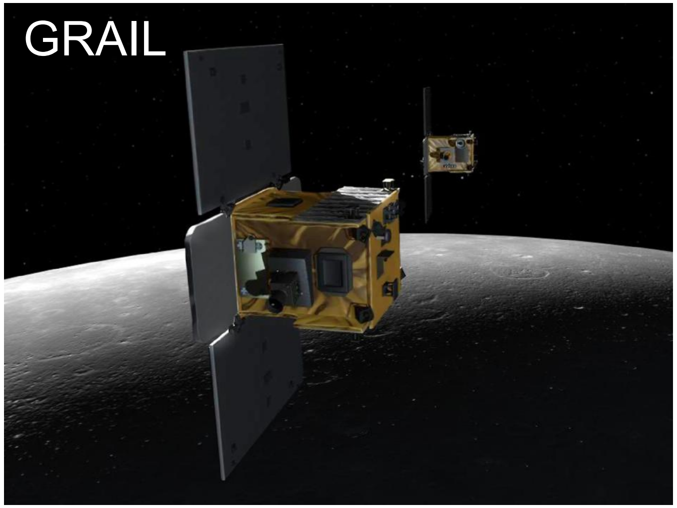
- Primary batteries are a proven option used by missions such as Galileo Probe, Huygens Probe and Sojourner Rover
- Offer relatively wide temperature operation when solar arrays or radioisotope power sources are not available
- Limits operations to hours or days (based on size of battery and discharge current)
- Emerging technologies based on advanced chemistries offer potential for retaining significant capacity at low temperatures and high discharge currents

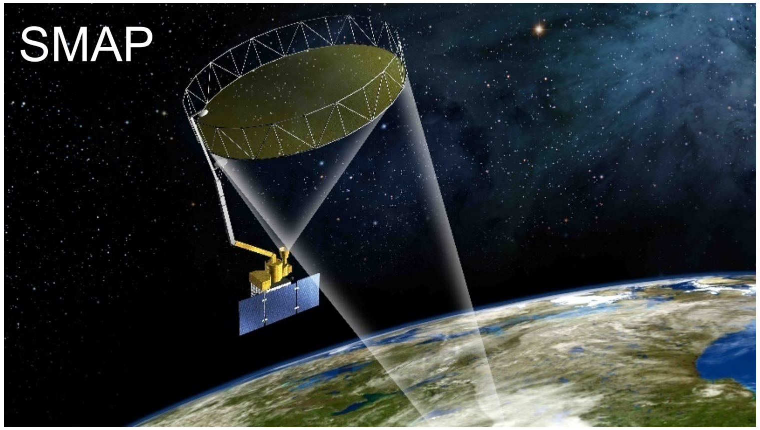


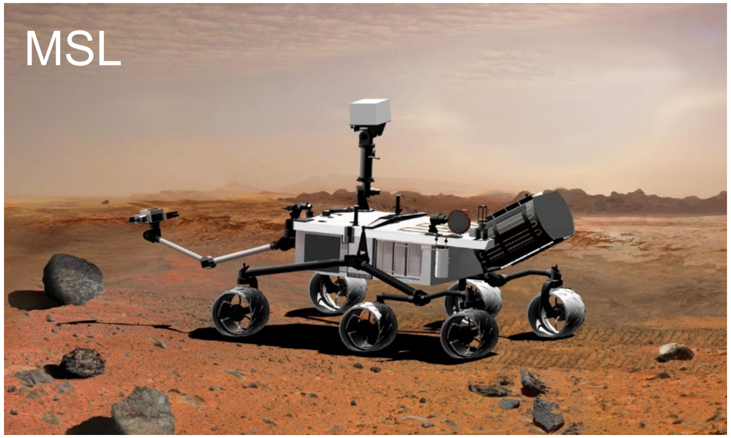
| **Metric** | $Li/SOCl_2$ (State-of-the-art) | $Li/SO_2$ (State-of-the-art) | $Li/CF_x$ (Advanced) |
|---|---|---|---|
| Specific Energy at +25ºC (Watt-hr/kg) | 590 | 260 | 720 |
| Low Temperature Operating Limit (ºC) | -80 to -55 | -40 to -55 | -40 to -55 |
| Capacity Delivered at Low Temperatures (Relative to +25ºC) | Low relative capacity delivered at moderate currents | Moderate relative capacity delivered at moderate to high currents | Highest specific capacity of all options at moderate temperatures; need further development for low T/high rate operation |

# Li-Ion Battery Applications for Space



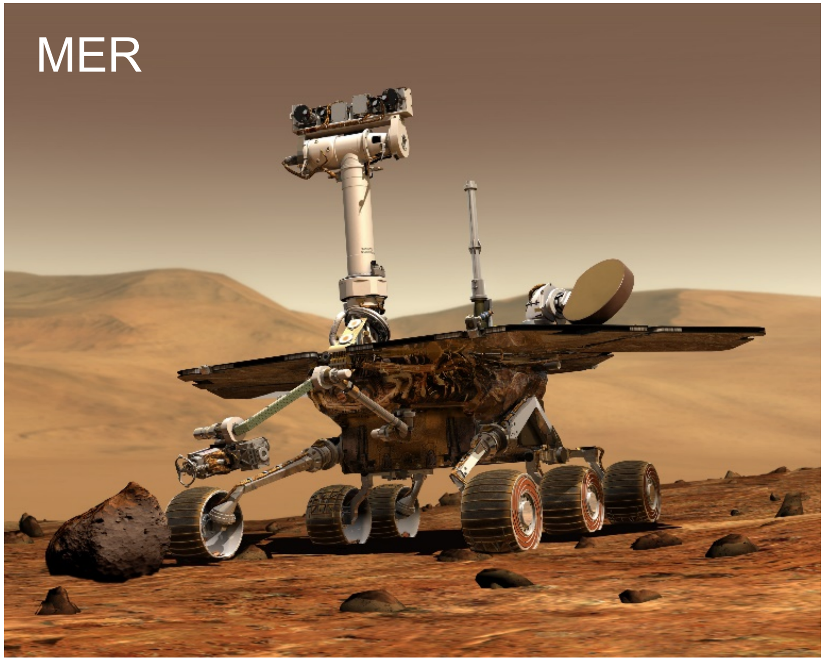




Rechargeable batteries provide power during launch, and power during eclipses and night time operations with solar arrays, and for load-levelling with both solar arrays and radioisotope thermoelectric generator power sources

# Early Adoption of Li-Ion Batteries for Solar System Exploration

- Mars Exploration Rover Battery Assembly Unit (RBAU)
- Prismatic cells were used ($LiNiCoO_2$ cathode and MCMB anode with custom electrolyte)
- Two eight-cell batteries in parallel, with independent battery control boards
- Limited tolerance to faults and fault propagation
- Cells are mechanically pre-loaded and in intimate contact
- Loss of a battery string would mean a degraded mission
- Radioisotope heating units used for thermal management, along with redundant survival and warm-up heaters
- Excellent performance over 15 year life





Prismatic cells

Battery Pack with RHUs installed

# Evolution from Custom Prismatic Cells to Commercial Cells for Space Applications

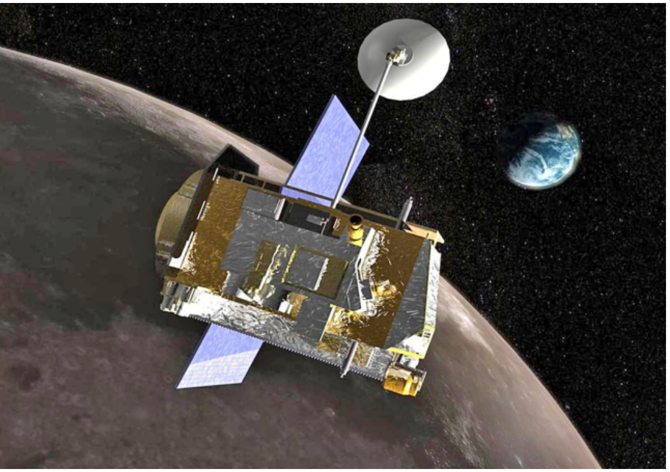
- **Large, custom prismatic cells**
  - Perceived volume advantage
  - Ability to customize
  - Lot traceability of all components
  - QA inspection possible during both cell and battery assembly
  - Little provision for fault tolerance
  - Large size makes risk mitigation more difficult
  - Configuration control and improved maintenance of heritage
  - Higher cell purchase price


**Prismatic Cells**

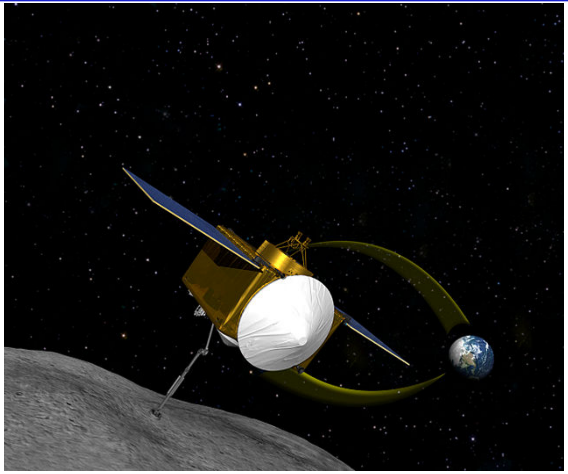

**Cylindrical Cells**

- **Small, COTS cylindrical cells**
  - Leverage mature Li-ion manufacturing capability
  - Lower cell purchase price
  - Little provision for customization
  - Limited traceability of lots and no component traceability
  - No provision for independent QA inspection during cell assembly
  - Requires extensive lot acceptance testing, followed by cell screening/matching
  - More options for fault tolerance at the cell and pack levels (internal safety devices, less energy per cell in case of cell thermal runaway, greater cell-to-cell spacings, etc.)
  - Reduced cell monitoring and balancing requirements

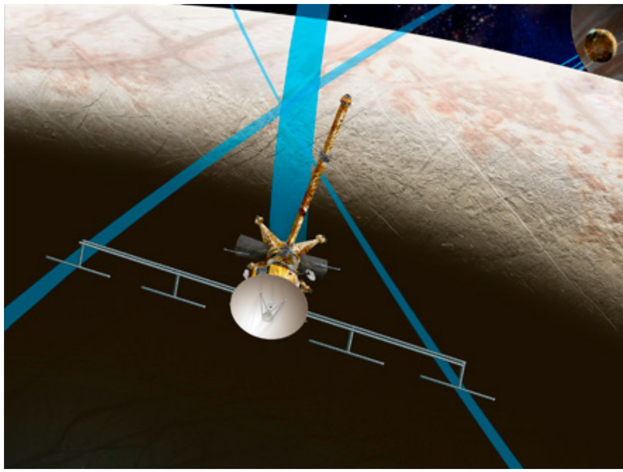
# NASA Planetary Missions Using Small Cell Technology



**Lunar Reconnaissance Orbiter (LRO)**



**Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer (OSIRIS REX)**



**Europa Clipper**

- State-of-the-art small cell technologies can support **higher** specific energy batteries relative to heritage large cell approach
- Batteries based on today's commercial cells can enable ~160 Wh/kg batteries vs. ~110 Wh/kg for batteries based on large cells (26 to 32.8V at 25$^{o}$C)
- Small cell battery >300 Wh/l (Europa Clipper) vs. large cell battery ~275 Wh/l (MSL)
- Ongoing testing of commercial small cells reveals suitable performance in space environments
  - Acceptable low temperature performance for many future missions
  - Good radiation tolerance at high total doses (similar to large cells)

# Mitigating Battery Related Risks

- **How do we keep personnel and critical hardware safe and ensure mission success, for all phases and all classes of robotic missions?**

- **Develop fault tolerant approaches to using and implementing energy storage**
  - Eliminate and reduce single faults and fault propagation
  - Extensive consideration and analysis of risk factors
  - Implementing "lessons learned" following failures
  - Extensive testing and careful selection of cell level technology
  - Extensive qualification, screening and matching of flight cells
  - Proper design and qualification of flight battery
  - Robust operating principles for safe and reliable operation

- **Safety and reliability concerns related to batteries for space**
  - During ground testing
  - For large "flagship" robotic missions
  - For smaller/augmentation missions (CubeSats, etc.)

# Safety During Ground Testing

- **Selection of appropriate COTS cell technology requires extensive performance testing of cells over relevant temperatures and environments**

- **<u>Multiple levels</u> of protection and fault tolerance during testing**
  - Dedicated, limited occupancy test facility
  - Storage of cells not under test in external climate controlled environment
  - Proper thermal control of cells control during testing
  - Use of redundant voltage taps and thermocouples on battery hardware to ensure appropriate charging levels
  - Implementation of inhibits in test schedules for overvoltage, over-temperature, faults with any sensor data, etc.
  - Vented, pressure relief valves and locking doors on test chambers
  - Integrated fire detection and suppression in test chambers
  - Building level water sprinkler system
  - Direct alarm/notifier to onsite fire department

# Excerpts from NASA Standard for Launch Payload Safety Requirements (8719.24)

- All systems shall be designed to tolerate a minimum number of credible failures
- The number of inhibits to prevent an overall failure or mishap is based on the failure or mishap results
- If a failure may lead to a catastrophic hazard, the system shall have no less than three inhibits (dual fault tolerant)
- Each design inhibit shall be independent of any other inhibit
- Each design inhibit shall be verifiable after installation through a process of pre-installation testing and implementation of written procedures…

These apply mainly to human spaceflight and are tailored for robotic missions

# Approaches to Achieving Fault Tolerance in Flight Batteries

- **Approaches that don't increase mass (or very little)**
  - Careful analysis of risk and establishment of requirements
  - Extensive cell chemistry/design screening
  - Lot qualification and cell matching
  - Burst to vent testing
  - Adequate cell safety features (CIDs, PTCs, shutdown separators)
  - Proper vent placement, vent paths
  - Robust power sub-system architecture with voltage and current regulation, safety inhibits and redundancy

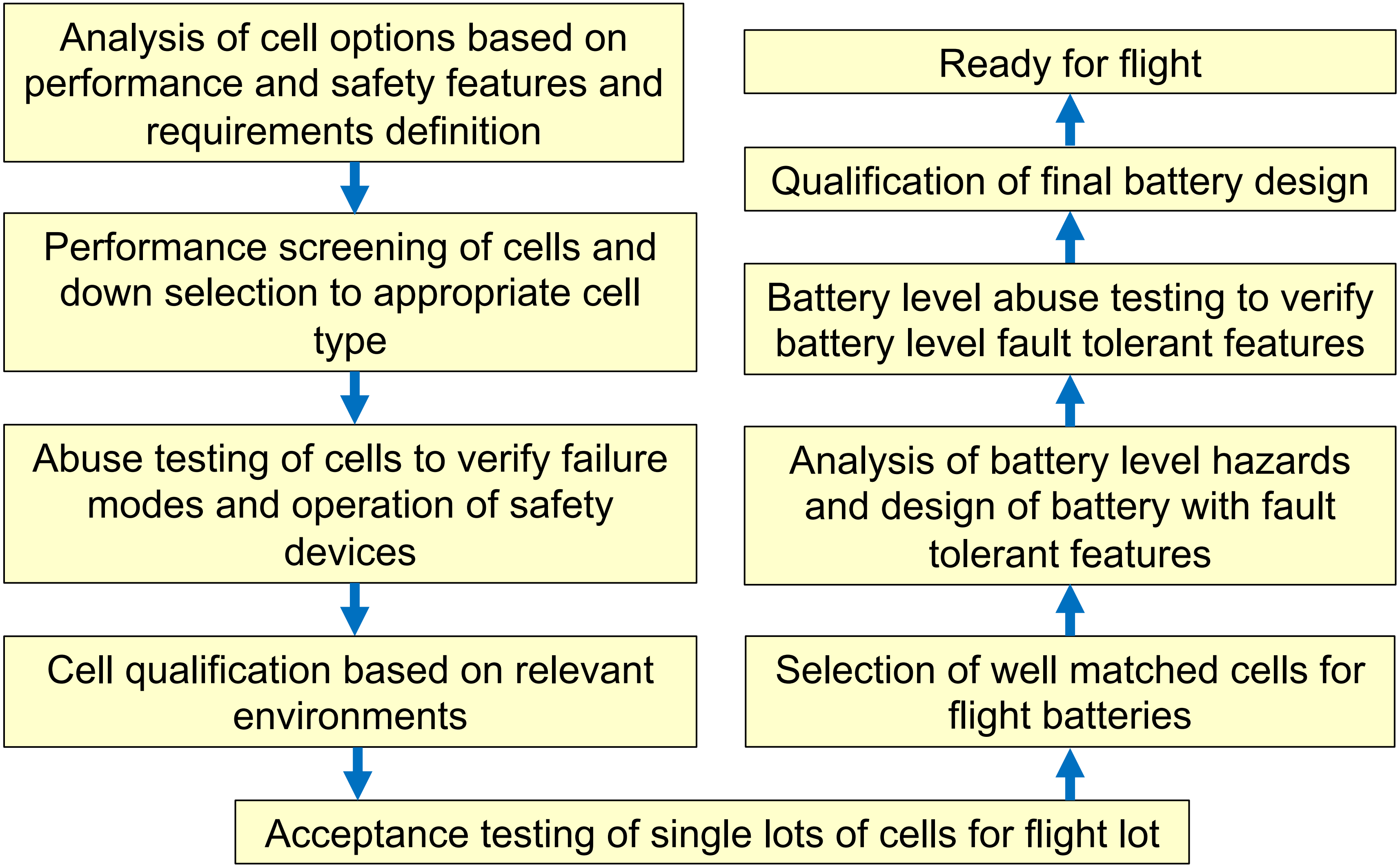
- **Approaches that do increase mass and volume**
  - Increased cell-to-cell spacing
  - Fusing of parallel cells
  - Interstitial heat spreaders/sinks for thermal dissipation and to prevent sidewall ruptures
  - Capture plates to prevent spread of cell ejecta

<u>Robotic Missions</u>
- More mass sensitive
- Higher risk tolerance

↓

<u>Human Missions</u>
- Less mass sensitive
- Lower risk tolerance

# Simplified Flight Battery Development Flow





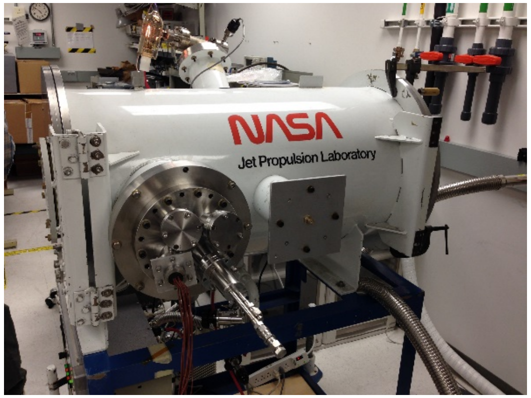

*Implementation of specific elements depends on class of mission (i.e., Flagship vs. CubeSat)

# Reducing Risk through Analysis and Establishment of Requirements

- Establish fault containment regions (FCR) and prevent faults from propagating beyond its FCR boundaries
- Consider cell level safety features such as shutdown separators, vents, current interrupt devices and PTC devices
- Consider string level and module level features, such as fuses
- Separate battery into physically separate modules for redundancy
- Use of established design principles: e.g., specify ability to meet mission success with loss of string
- Establish safe operating parameters through extensive testing (i.e., minimum and maximum charging currents, appropriate voltage and temperature range)
- Consider mitigation of unique environmental concerns (temperature, radiation)

# Cell Screening and Lot Acceptance Testing

- **Screening of cells**
  - Capacity, energy over relevant temperatures
  - Typically performed at JPL
- **Lot acceptance of cells**
  - Use single cell lot for flight batteries
  - Lot size at least 50% greater than number required for flight batteries
  - Typically performed by vendors; have proprietary approaches
  - JPL developing internal standards, particularly for small missions
- **Cell qualification and final cell selection**
  - Thermal vacuum (TVAC) testing
  - Pyro-shock and random vibration
  - Also performed by vendors using internal processes
  - Safety testing
  - For small cell approach, qualification at both the cell and battery levels




# Abuse and Safety Testing

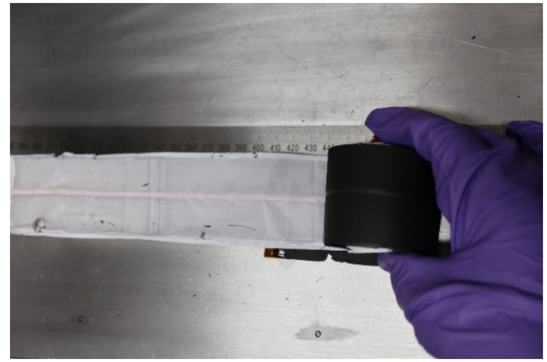
- JPL does not perform abuse/safety testing of cells or batteries
- Performed by vendor or via external partnering with NASA Johnson Space Center, Sandia National Labs, Navy Crane, etc.
- Leverage availability of existing test results, where possible
- Particularly critical to evaluate safety devices exposed to extreme environments (temperature, radiation)
- Human missions implement both cell and battery level abuse testing, whereas robotic missions typically implement cell level abuse testing only

**Typical proposed test plan (tailored for lithium-ion vs. lithium primary batteries)**

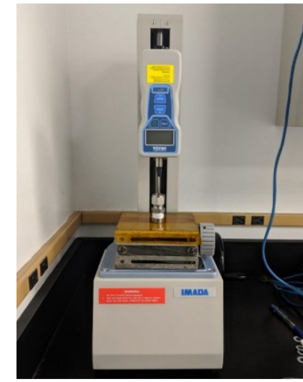
- **Thermal ramp testing:** Cells will be heated at 5 °C/min to thermal runaway or 250 °C.
- **External short circuit testing:** A resistive load (shunt) of will be applied to the cell for 60 minutes.
- **Overdischarge tests:** The cell will be discharged from full charge to -150% total state of charge (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 CID triggered or thermal runaway/venting is observed.

# Example of Component Level Screening

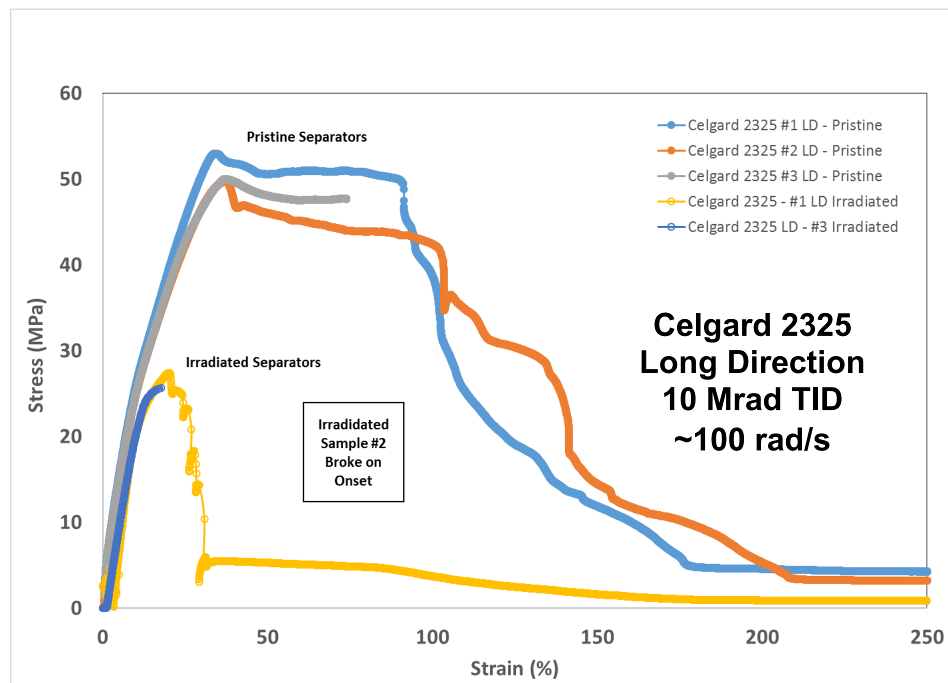
- Separators are of particular interest, due to key role in cell safety
- Prevent shorting and provide shutdown function
- How does exposure to extreme environments affect performance?
- Testing
  - Dynamic mechanical analysis
  - Puncture testing
  - Thermal testing



**Analysis of extracted components**



**Puncture testing on pristine vs. irradiated separator samples**



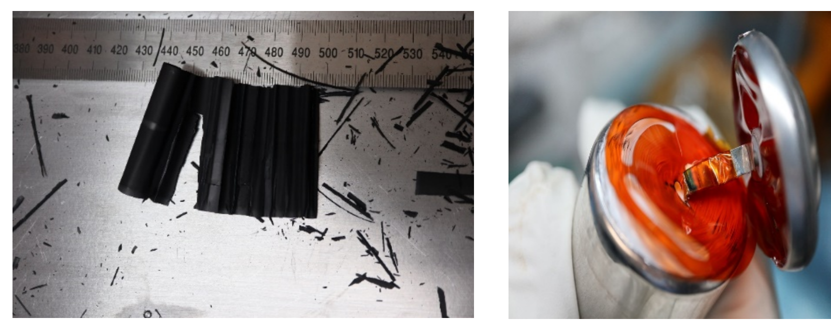
# Evaluating Destructive and Non-Destructive Methods for Detecting Defective Cells

- Identifying methods to supplement standard “stand tests” to identify internal shorts

- CT Imaging of Cells
- Magnetic Resonance Imaging
- Micro-calorimetry
- Precision Coulometry
- Impedance Spectroscopy
- Destructive Physical Analysis of components, and correlation with non-destructive methods

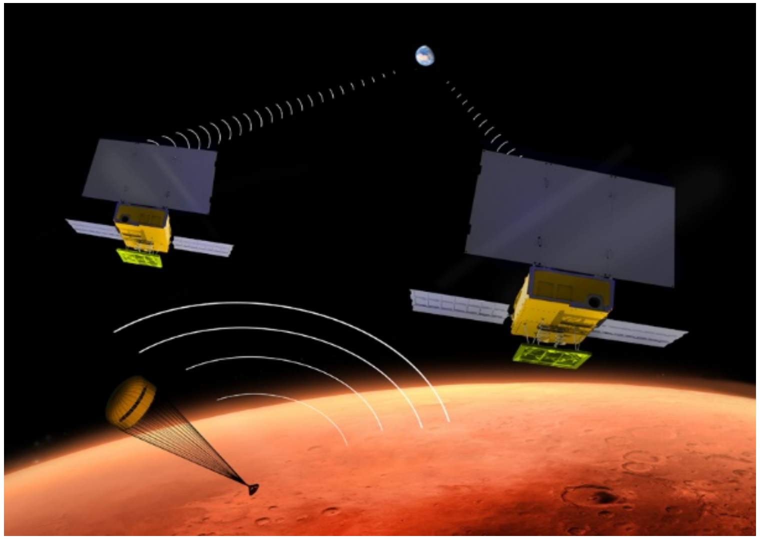
**CT Scanning**


**Micro-calorimetry**

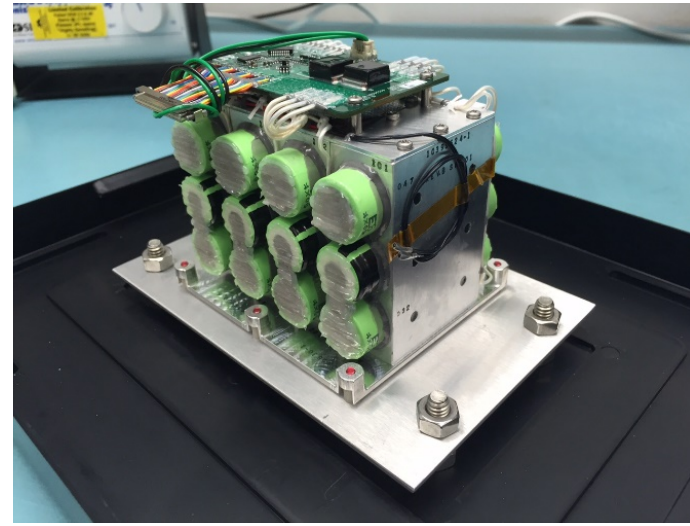



**DPA of cell components**

# Safety and Reliability for Small Missions

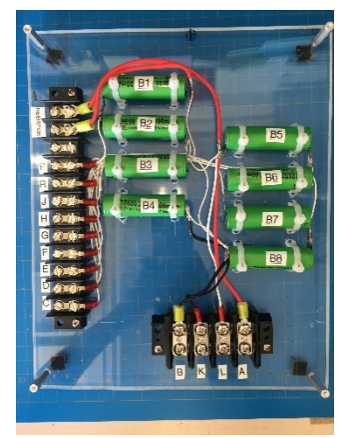


MarCO (6U CubeSat) successfully demonstrated in Nov. 2018



MarCO battery pack

- CubeSats are much smaller spacecraft (1U = 10 cm x 10 cm x 10 cm and 1-2 kg)
- NASA and JPL are incorporating these spacecraft into more missions
- High risk tolerance now, but will likely play more critical role in the future
- Small volume presents significant constraints to battery design
- Proximity of smaller spacecraft to higher value flight hardware must also be considered
- Establishing adequate cell screening processes to support more resource constrained missions
- Establishing design guidelines for these batteries




Lunar Flashlight CubeSat Battery Prototype

# Evolution from Prismatic to Cylindrical Cells Li-Ion Technology to "Beyond Li"

- **Moderate specific energy/low temperature technology**
  - Based on large prismatic cells
  - 140 Watt-hour/kg cells at +20°C
  - -30 to +35°C discharge limits
  - TRL 9 (InSight)

- **High specific energy/moderate temperature technology**
  - Based on small cylindrical cells
  - 220 Watt-hour/kg at +20°C
  - -10 to +40°C discharge limits
  - TRL 5 (Europa Clipper)


**<u>Still needed</u>: A high specific energy cell (>>200 Wh/kg at +20°C) that can be discharged and safely charged at low temperatures (-30 to -60°C)**

# Looking Ahead

- **Safety and Reliability for Human Missions**
  - Battery must be safe for ground personnel and crew members to handle and use
  - Safe to be used in the enclosed environment of a crewed space vehicle
  - Safe to be mounted or used in unpressurized spaces adjacent to habitable areas
  - To what extent do we adopt human flight battery fault tolerant approaches required to address these requirements, for autonomous robotic missions?

- **Future "beyond lithium" batteries under consideration for future missions**
  - May involve lithium metal, and share characteristics with primary batteries
  - Currently developing more detailed approaches to handle lithium primary cells and batteries
  - How do we address fault tolerance and propagation in increasingly higher energy content smaller cells, taking into account the unique constraints of human vs. robotic missions?

# Acknowledgements

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**Jet Propulsion Laboratory**
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