Jet Propulsion Laboratory
California Institute of Technology

Materials for Advanced Lithium and Lithium-ion Batteries for NASA's Future Missions

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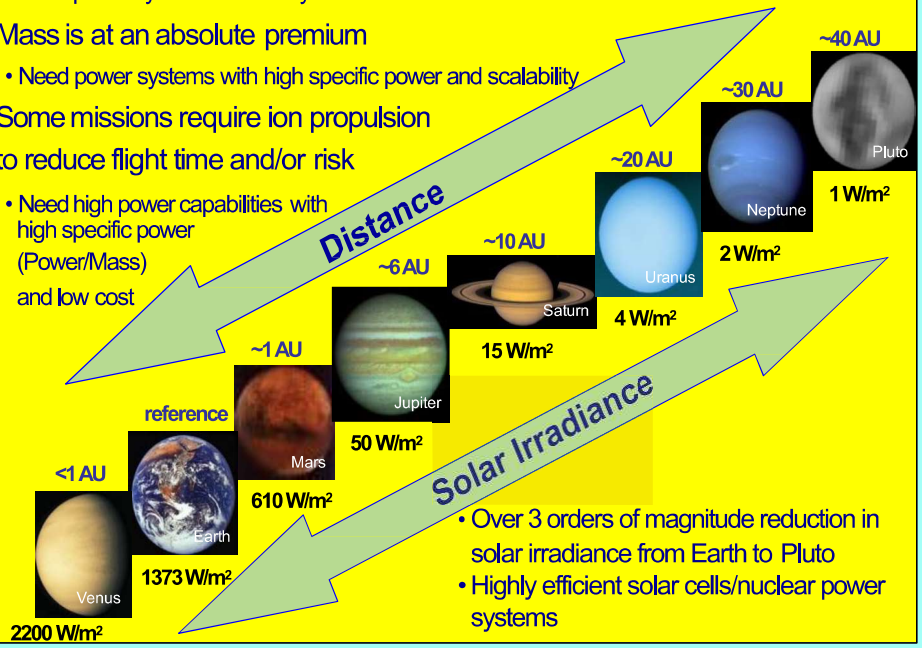
Power Generation Technologies in Planetary Missions

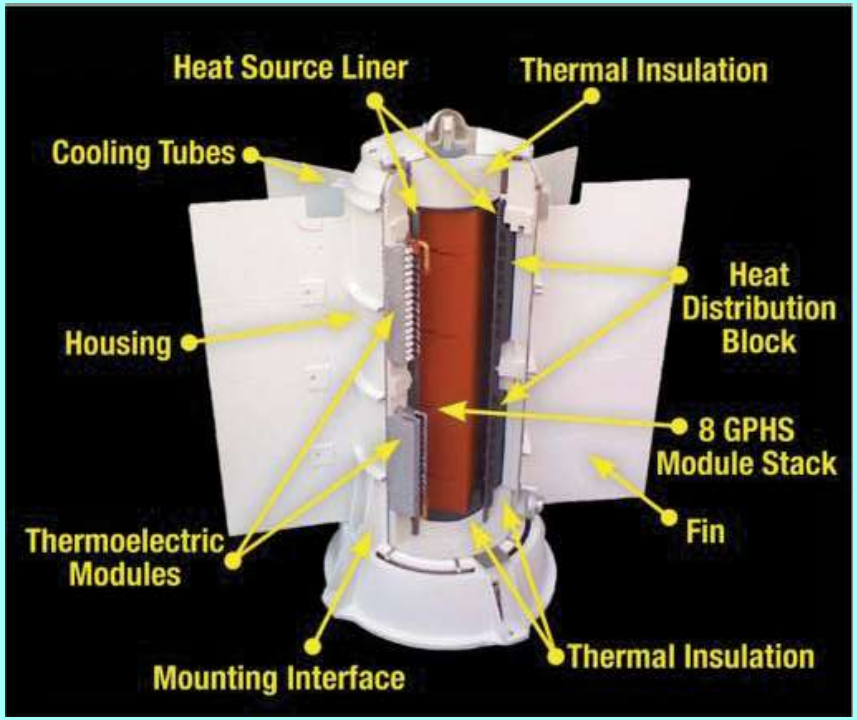
Solar Array for Near Planets

- Flight times are long
  - Need power systems with >10 years life
- Mass is at an absolute premium
  - Need power systems with high specific power and scalability
- Some missions require ion propulsion to reduce flight time and/or risk
  - Need high power capabilities with high specific power (Power/Mass) and low cost



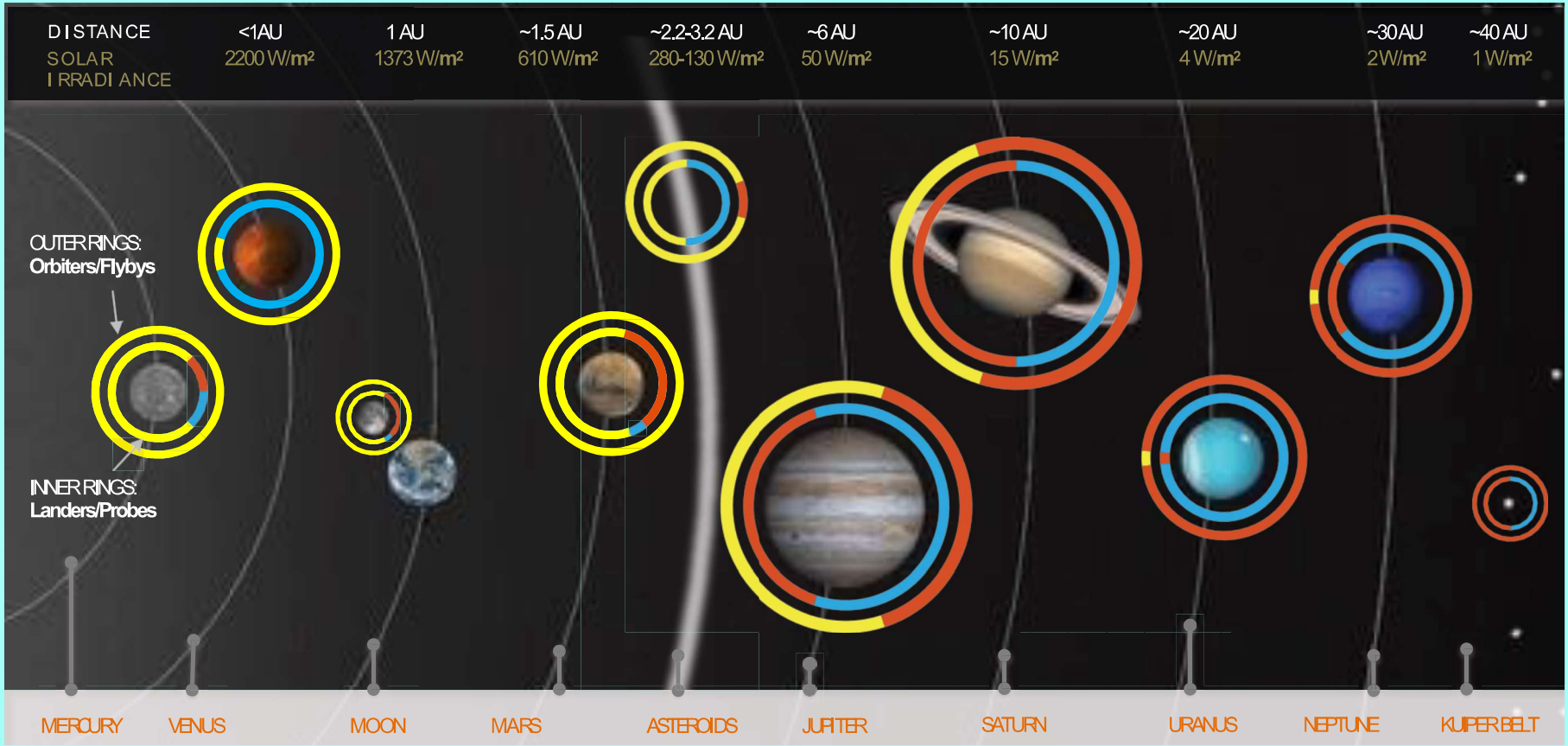
- Over 3 orders of magnitude reduction in solar irradiance from Earth to Pluto
- Highly efficient solar cells/nuclear power systems

Radioisotope Thermoelectric Generators (RTG) for Deep Space Missions



- Low solar irradiance at Jupiter and beyond.
- Most deep space mission concepts to Jupiter and beyond would use radioisotope power systems (Radioisotope thermoelectric generator or RTG)

Power Generation Technologies in Planetary Missions



Notional mission applicability based on expert opinion developed in JPLA-Team study in August 2015. Updated 2017.

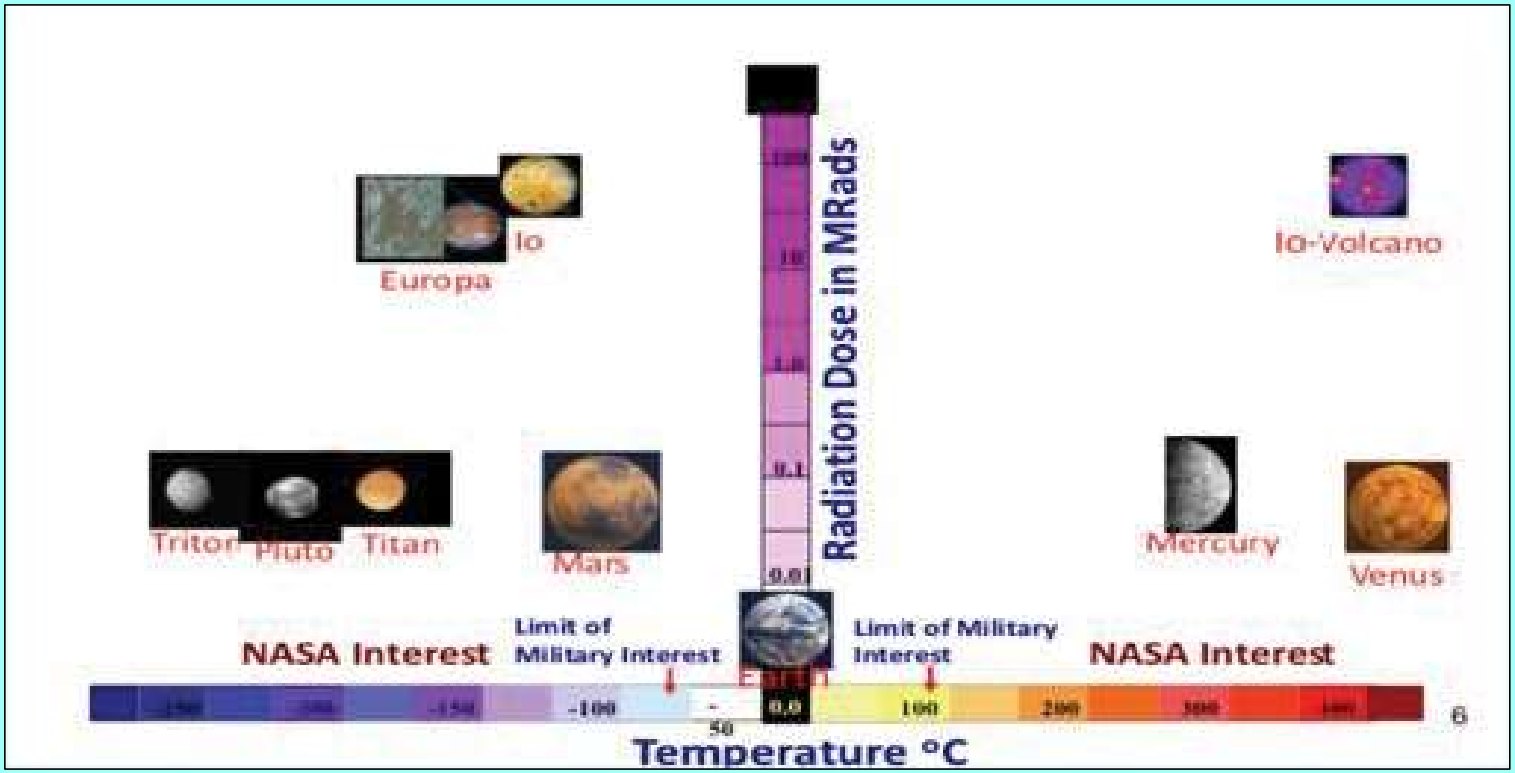
Solar/Rech. Bat
RPS
Primary Battery

Pre-Decisional Information —For Planning and Discussion Purposes Only

Functional requirements of batteries

- Energy storage devices used in robotic planetary science missions include primary (non-rechargeable) batteries, secondary (rechargeable) batteries, and capacitors.
- Rechargeable batteries are used to:
  - Power to the spacecraft during launch before deployment of the solar panels.
  - Power during cruise anomalies (Trajectory Control Maneuvers).
  - Power to the spacecraft, its equipment, and instrumentation during Sun eclipse periods.
  - For Load leveling in radioisotope powered missions during peak power operations such as telecoms, sample drilling and surface mobility.
  - Missions include used in planetary orbiters (Mars Global Surveyor, and Mars Reconnaissance Observer), Mars landers (Mars Pathfinder, Phoenix Lander), and Mars rovers (Spirit, Opportunity, and Curiosity)
- Primary batteries are used in:
  - Missions that require a single use of electrical power for a period of a few minutes to several hours.
  - Mission where a rechargeable battery is not desirable or no energy source is available for recharging
  - Such missions include planetary probes (Galileo, Deep Impact, and Huygens), sample return capsules (Stardust and Genesis), Mars Landers (MER), and Mars Rovers (Sojourner)
- Capacitors are used in
  - Applications requiring repeated high power and short duration pulses (seconds).
  - The Galileo and Cassini missions used capacitors for firing pyros and stepping motorized instrument platforms.

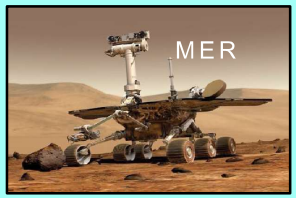
Environmental challenges for Power Systems in Solar Missions



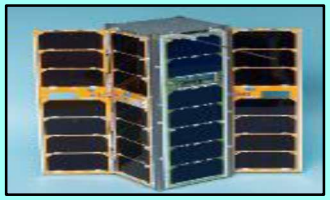
- Challenging environments (temperature and radiation)
- Ability to operate under vacuum (low-g environments) and high CO_2 pressures for Venus
- High degree of reliability (and safety)
- Resilience to vibration (launch), shock (pyro) for the battery

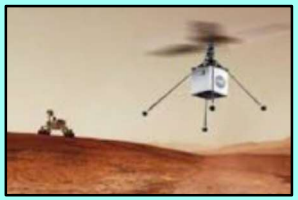
Types of Planetary Missions

Flyby or Orbiter

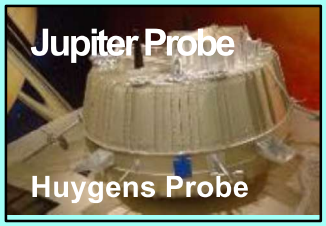


Lander or Rover





Cubesats and Helicopter



Probes

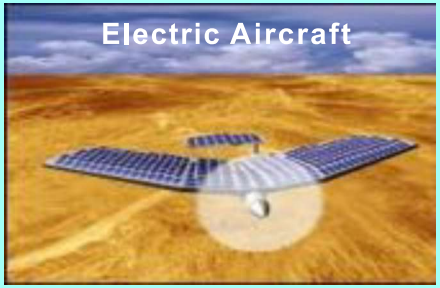
EVA

Need for Wh/kg & Wh/l Increase

Technology Drivers

- High Specific energy
- High Energy Density
- Good Low temperature Performance
- Long Calendar Life
- Low Self Discharge
- Safety and
- High reliability

Need for Cycle life Increases



Pre-Decisional Information —For Planning and Discussion Purposes Only

Battery Systems in Space Missions

Space Exploration	Mission	Technology Drivers	Relevant Technology
Earth	Geosynchronous Earth Orbit Satellite	Long Life (1000 deep discharge cycles) and Long Calendar life (10 years)	Rechargeable Battery; Mostly Nickel-Hydrogen, Being replaced by Li-ion batteries
	Low Earth orbit (LEO) Satellite	Long Cycle Life (60,000 cycles @ 40% DOD) and Long Calendar life (5-10 years)	
	ISS		
Planetary mission	Surface Missions (Landers and Rovers)	High Wh/Kg and Wh/l; Wide temperature performance	Ag-Zn (in 1996) and currently Li-ion
	Orbiters	Long Cycle Life (60,000 cycles @ 40% DOD); Long Calendar life (5-10 years)	Rechargeable Battery; Mostly Nickel-Hydrogen, Being replaced by Li-ion batteries
	Micro-probes	Low temperature performance; Impact tolerance, Compact and Lightweight;	Lithium Primary Battery
Comet/Asteroids	Sample Return	Long Shelf life and High Wh/Kg, Wh/l	Lithium Primary Battery
Jovian Planets	Orbiters and Landers	High radiation tolerance and Long Calendar life (> 6 years)	Previously Capacitors, Being replaced by Lithium-Ion
Outer Planets (Pluto)	Fly-by	High radiation tolerance and Long Calendar life (> 6 years)	Lithium-Ion

- **High gravimetric and volumetric energy densities are always important to reduce the launch costs and increase the science payload.**

Mars Orbital Missions

- Support four science themes of the Mars Exploration Program:
  - Climate, geology, life, and preparation for human exploration.
- Identify scientifically interesting landing sites for further study Assist in Communications and Navigation
  - A key role as communications relays for rovers, landers and probes
  - Assist with navigation of other spacecraft approaching Mars.

Viking
Operated for 2-4 years
Ni-Cd batteries
Four 8 Ah, 28V

Mars Global Surveyor
Operated for ~ 9 years
Ni-H_2 batteries
20 Ah, 2-CPV 8S2P

Mars Odyssey
Operating since 2002
Ni-H_2 batteries
16 Ah, 2-CPV 11S1P
Will support Mars 2020

Mars Express
Operating since 2004
Li-Ion batteries
67.5 16 Ah,

Mars Reconnaissance Orbiter (MRO)
Operating since 2006
Ni-H_2 batteries
50 Ah 2-CPV, 2P11S
(Will support Mars 2020)

MAVEN
(Mars Atmosphere and Volatile Evolution)
Operating since 2013
28V,110Ah Li-Ion

- Until recently, the long-life missions used Nickel hydrogen batteries, because of long cycle life and calendar life.
- Other examples Stardust, Genesis, Dawn, OCO and all satellites.
- Outer planetary missions were powered by RTG, e.g., Galileo, Cassini. Capacitors were used instead of batteries

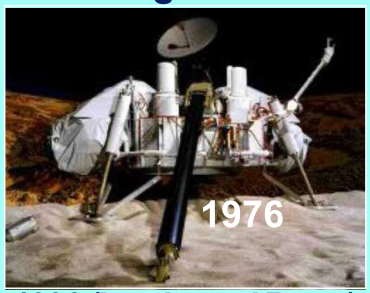
RTG Only (570W)

Li-ion batteries have started being used in long-life missions

Mars Surface Missions (Through 90s)

- The first Mars Lander, Viking Landers (I and II), had an RTG and Ni-Cd batteries for peak power.
- Mars Pathfinder and Sojourner (Lander and Rover) 1996
- Lander had Silver-Zinc Battery: 27 V and 40 Ah (actual 55Ah) from BST
  - Battery Challenges: i) Inverted orientation during ATLO/launch, ii) Fourteen month total wet stand including cruise, and 40 operational cycles without electrolyte leakage.
  - Supported through 84 Sol 84, albeit at reduced loads (goal : 30 sols).
- Sojourner rover had a primary battery ($Li\text{-}SOCl_2$) with a solar array supported 84 days (goal: 4 sols)

Viking Lander



1996 (Lander and Rover)

A battery with high specific energy and long life was sadly missing!

Mars Surveyor Program (MSP01) Lander (2001)

- NASA - DoD consortium set up in 1995 to develop large-format Li-ion cells within US.
  - Technology developed together with NASA Laboratories (JPL and GRC) and Industry (Yardney and SAFT)
- Li-ion cells of 5-55 Ah, 120 Wh/kg and long-life and with improved low temperature performance
- Batteries were built and successfully qualified. Mission was, however, cancelled.
  - Would have been the first planetary mission to utilize lithium-ion battery.
- Resurrected later as Phoenix lander mission (2007)
- Two parallel batteries each with eight 31 Ah Li-ion cells (8S2P)
- Helped in generating valuable data to validate the technology for future missions (Mars Exploration Rover)

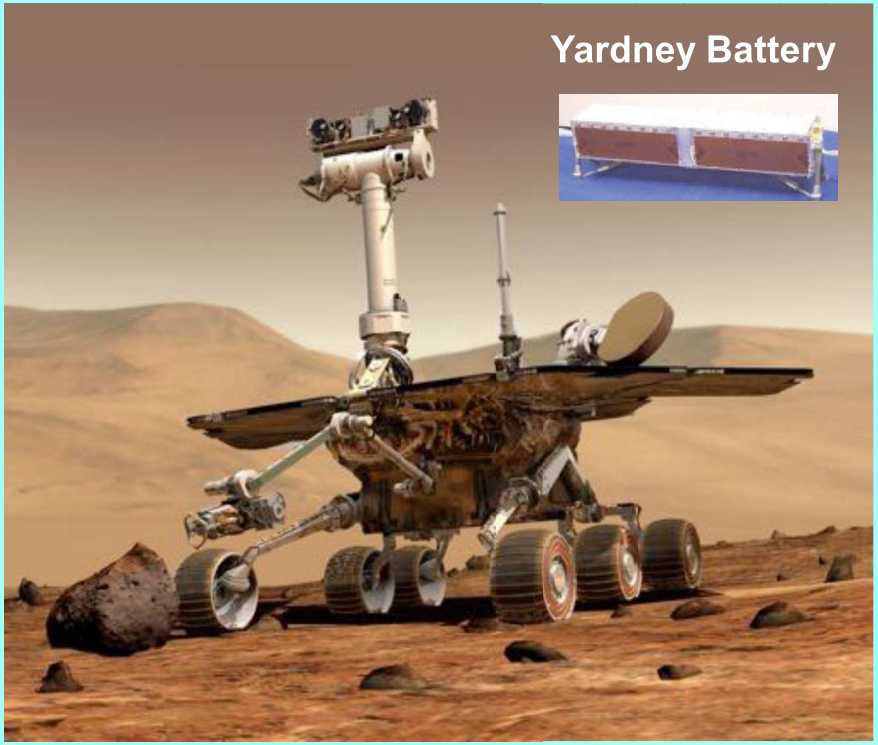
Chemistry

- **MCMB anode and $LiNi_{0.8}Co_{0.2}O_2$ cathode**
- **JPL's Gen1 low temperature electrolyte**
- **Flat Plate Prismatic Custom cell**

- **Battery: 32 V: 62 Ah**
- **Specific energy : 104 Wh/kg**
- **Temperature: -20 to 40°C**

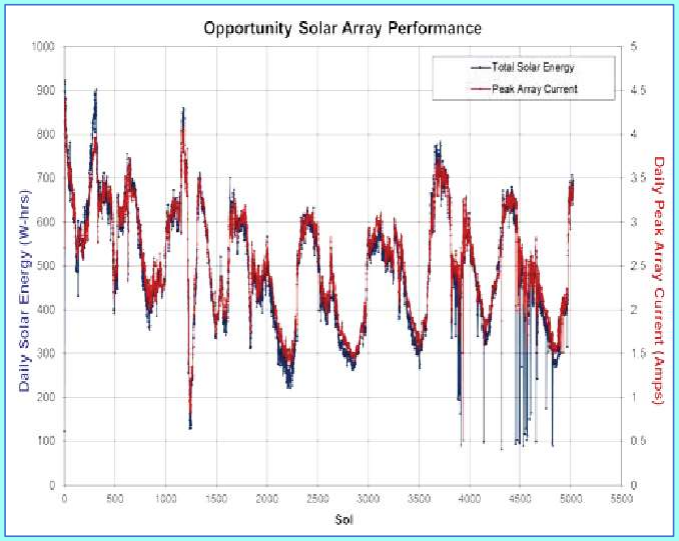
Mars Exploration Rover- Spirit and Opportunity (2003)

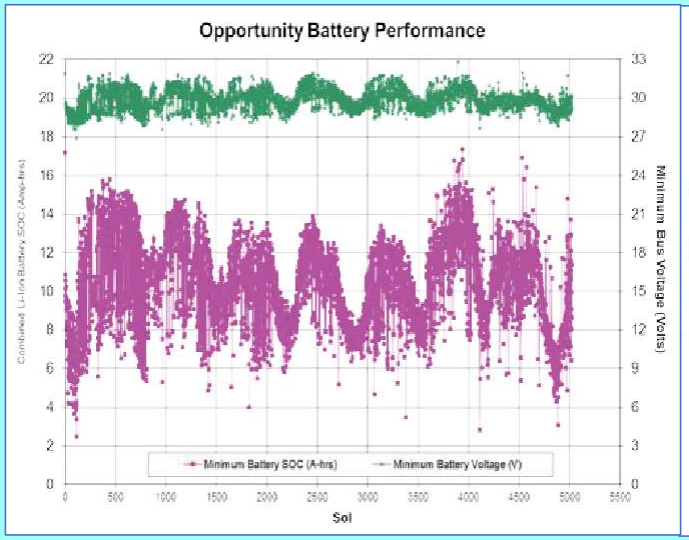
- First major NASA mission with Li-ion batteries
- Two six-wheeled, solar-powered robots standing 1.5 m high, 2.3 m wide and 1.6 m long and weighing 180 kg
- Energy Source: Triple-junction solar array with a BOL energy of 1000 Wh/sol
- Excellent performance from the Li-ion Battery, both in cycle life and Calendar life (against 90 days of design life) with astounding scientific findings.
  - Spirit Operated over 9 years
  - **Opportunity rover is still operational with over 5000 Martian sols and 10 km**
- Mission enabling: Alternate battery technologies were not viable.
  - Ag-Zn battery would have limited the life to six months or less and a Ni-H_2 battery would be about four times heavier (7.5 kg vs 28 kg)
- Cell balancing methods utilized to prevent overcharge.
- Led to the use of Li-ion batteries on several missions not only within JPL but across NASA (e.g., GSFC missions).

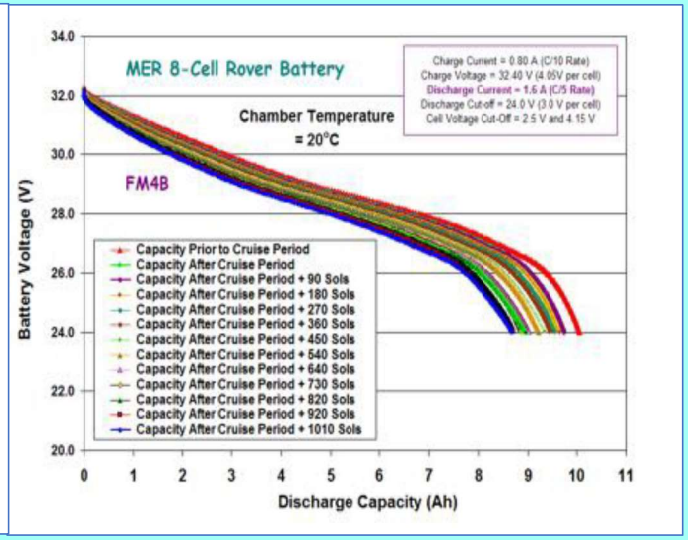


- Chemistry Same as MSP 01 with NCO Cathode, MCMB anode and JPL 1st Generation low temperature electrolyte
  - Cell: Custom 10 Ah; Battery: 32 V, 20 Ah; Specific energy : 90 Wh/kg
  - Temperature:-20 to 30°

Mars Exploration Rover- Spirit and Opportunity (2003)



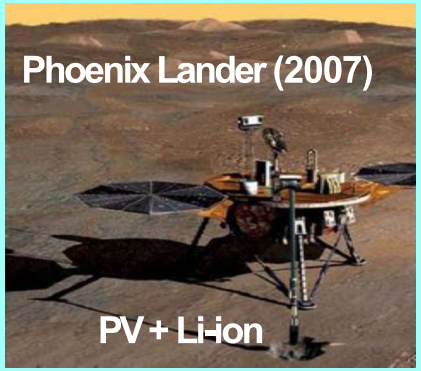




- Impressive performance of Li-ion batteries (30 V, 20 Ah) on the Mars Exploration rovers, demonstrating great resilience and longevity
  - Spirit survived through 1000 sols
  - Stable voltages on spacecraft (45% Depth of discharge)
  - 70% capacity retention in laboratory tests.

- **Opportunity still operating (14 years, 5000 sol, >10 km)**

Missions Using Based on Large Prismatic cells



- Custom prismatic cells of capacities 10-50 Ah from Yardney Technical Products
- Chemistry (MCMB (graphite) anode, NCO (or NCA) cathode and low temperature electrolyte.
- Mars 2020 Rover has graphite anode and NCA) cathode and the same low temperature electrolyte

Mission to Jupiter (JUNO) (2011)

- First solar powered S/C to Jupiter.
- Launched in August 2012, Juno is in orbit and studying the planet's composition, gravity field, magnetic field, and polar magnetosphere.
- Entered Jupiter orbit July 2016, and with its infrared and microwave instruments will measure the thermal radiation emanating from deep within Jupiter's atmosphere to assess the abundance and distribution of water, and oxygen.

Battery Challenges

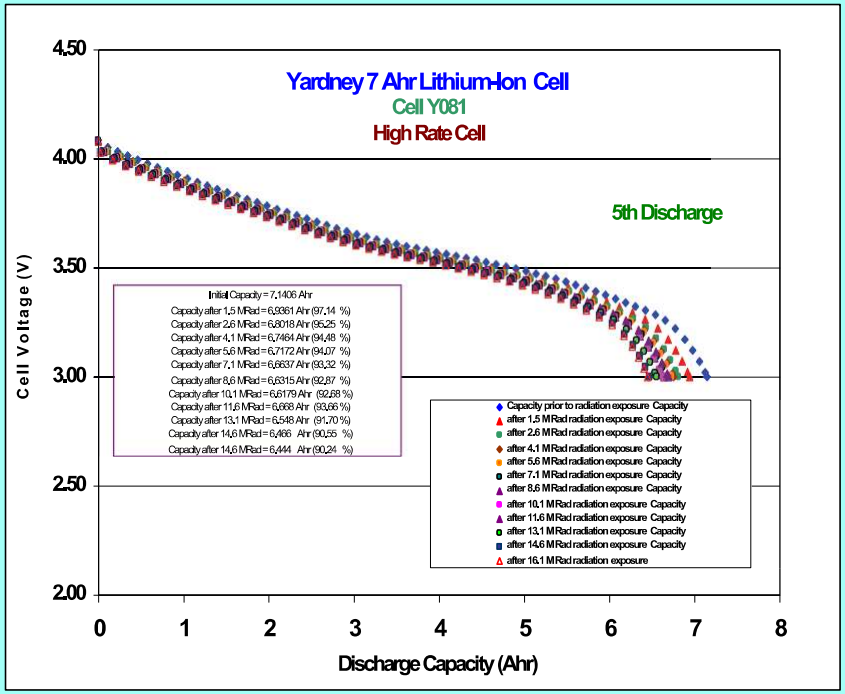
- Required batteries with long calendar life (over six years) and radiation tolerance.

Li-Ion Battery

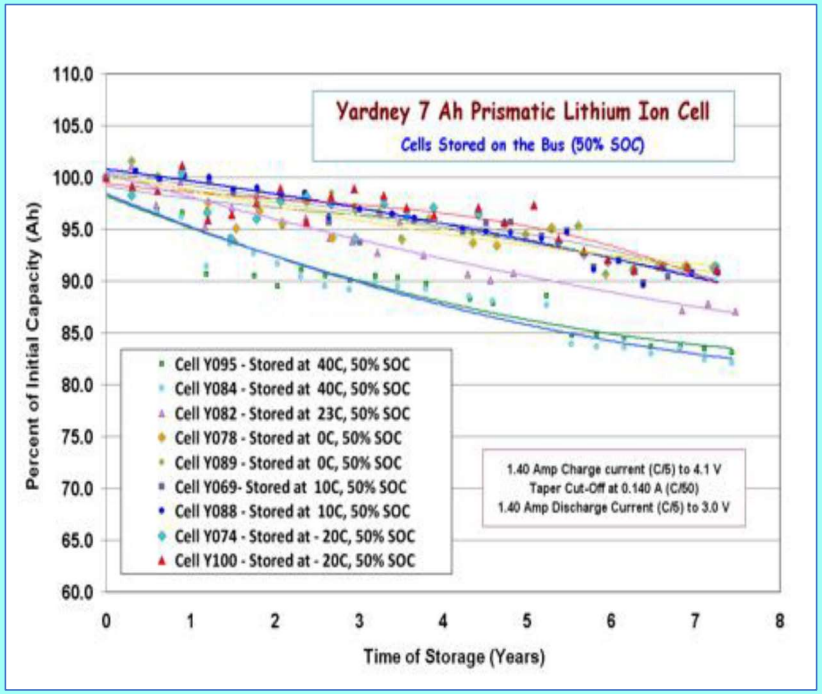
- **Chemistry (Same as MER)**
- **Cell: Custom 55 Ah**
- **Battery: 32 V, 110 Ah**
- **Specific energy : 105 Wh/kg**
- **Temperature:-20 to 30°C**

Validation of Li-ion Batteries for Juno

Radiation Tolerance of Li-Ion Cells



Storage of Li-Ion Cells



- Demonstrated tolerance of Li-on cells to high-intensity radiation environments (Cobalt-60). Cells retained >95% capacity after exposure to 18 Mrad.
- Calendar Life demonstrated through real-time testing

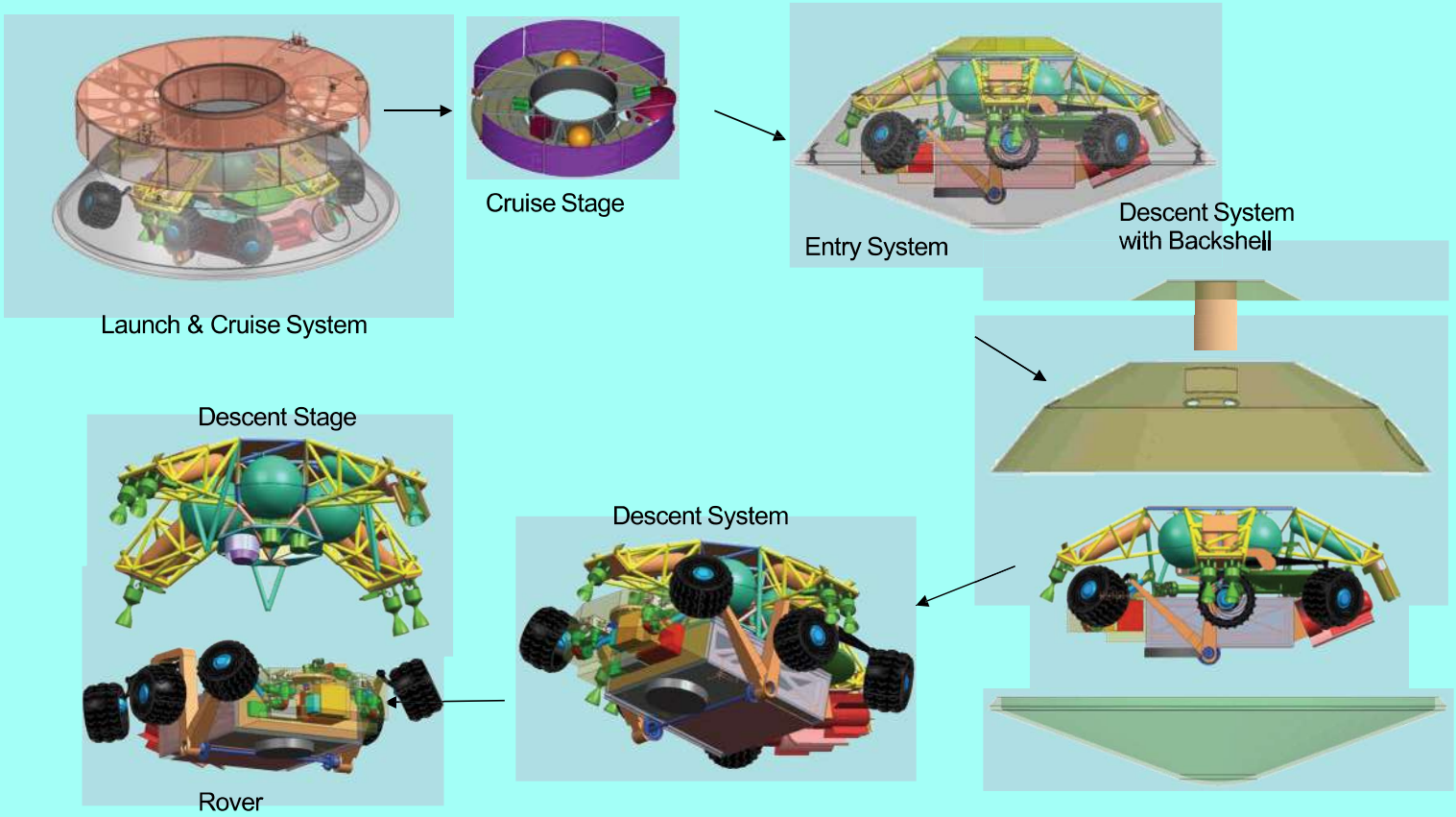
Mars Science Laboratory (MSL) Curiosity Rover

- **Science Goals**: To assess habitability: whether Mars ever was an environment able to support microbial life.
  - The biggest, most advanced suite of instruments ever sent to the Martian surface.
  - Analyze dozens of samples scooped from the soil and cored from rocks in the onboard laboratory to detect chemical building blocks of life (e.g., forms of carbon) on Mars.
- Landing: Parachute assisted and powered descent, lowered on tether like sky crane.
- **Programmatic Goals** : To demonstrate the:
  - Ability to land a very large, heavy rover to the surface of Mars
  - Ability to land more precisely in a 20-kilometer (12.4-mile) landing circle
  - long-range mobility (5-20 kilometers or about 3 to 12 miles)
- **Highlights:**
  - **Curiosity has operated over 1500 Sols to-date**
  - After 2 years and almost 9 km of driving, Curiosity has reached the base of Mount Sharp
  - During the first year, the rover fulfilled its major science goal of determining whether Mars ever offered conditions favorable for microbial life.
  - **As of Sol 1507, Curiosity has driven 9.16 miles (or 14.75 kilometers)**

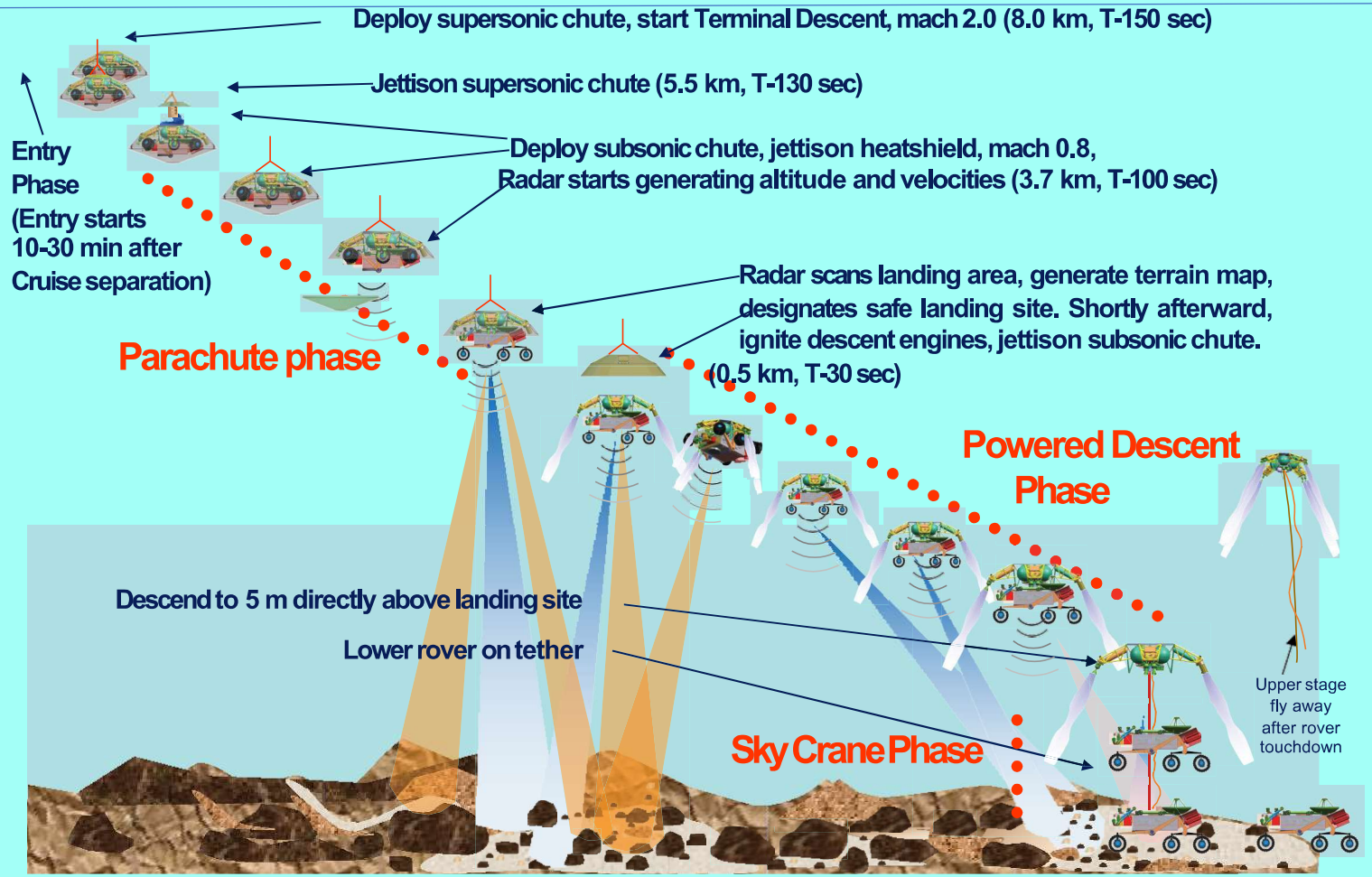
Battery Details

- Two 8-cell batteries in parallel (8s2p).
- 24-32.8 V, 86 Ah (MER, Grail, Juno Chemistry)
- Qualification Temperature range: -30° to +40°C.
- Operating Temperature Range: -20° to +30°C
- **Required Life: ~ 4 years**
- **Surface Life: 670 Sols of operation.**
- Battery temperature controlled with a combination of heaters and radiators

MSL Major Spacecraft Assemblies



MSL Entry, Descent, and Landing Timeline

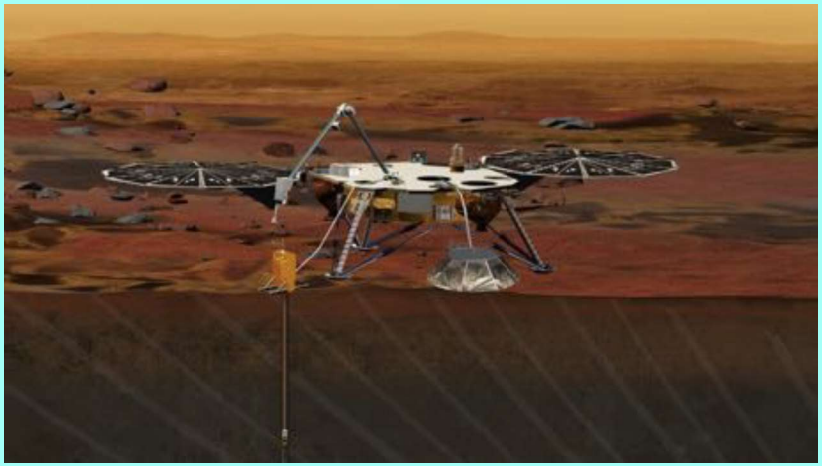


NASA's Mars InSight Lander

- InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) is a NASA Discovery Program mission that will place a single geophysical lander on Mars to study its deep interior.
- Mission will consist of a spacecraft based on a design that was successfully used for NASA's Phoenix Mars lander.
- Science Goals:.
  - InSight is a terrestrial planet explorer that will address the processes that shaped the rocky planets of the inner solar system (including Earth) more than four billion years ago
  - InSight will probe beneath the surface of Mars, detecting the fingerprints of the processes of terrestrial planet formation

– Launched in May 5, 2018.

– Landing: Nov. 26, 2018



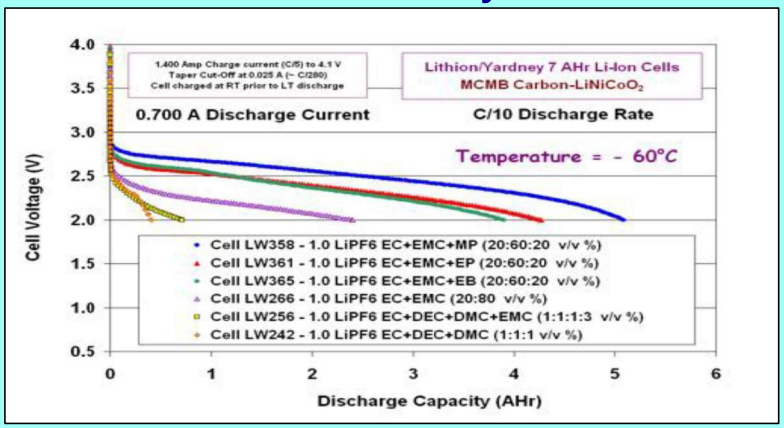
Battery Details

- Two 8-cell batteries (connected in parallel)
- Manufactured by Eagle-Picher Technologies / Yardney Division
- 24-32.8 V (Phoenix Battery Design)
- Qualification Temperature range: - 40°C to +50°C.
- **Operating Temperature Range: -30° to +35°C**
- **Required Life: ~ 4 years**
- **Surface Life: 709 Sols of operation.**

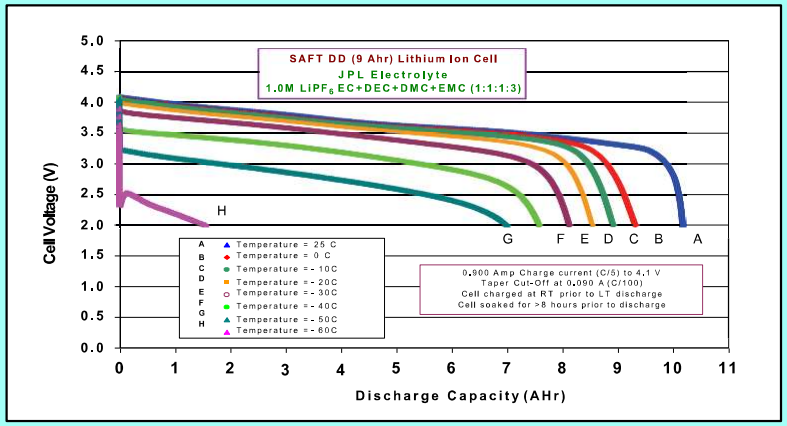
Low Temperature Electrolytes in Li-ion Cells

- Wide Operating Temperature Electrolytes (NASA Supported)
  - Planetary Rovers and Landers Applications
  - Early Generation Ternary Electrolyte (-20 to +40°C)
  - Quaternary Carbonate-Based Electrolytes (-40 to +40°C)
  - Low-EC formulations
  - Use of Ester-Based Co-Solvents (-60 to +40°C)
  - Use of Electrolyte Additives with Ester-Based Electrolytes
    - VC, VEC, LiBOB, FEC etc
- Electrolytes for Automotive Applications (DOE Supported)
  - Wide Operating Temperature Electrolytes (-30 to +60°C)
  - High Voltage Electrolyte Systems

Ester Blends-Yardney Cells



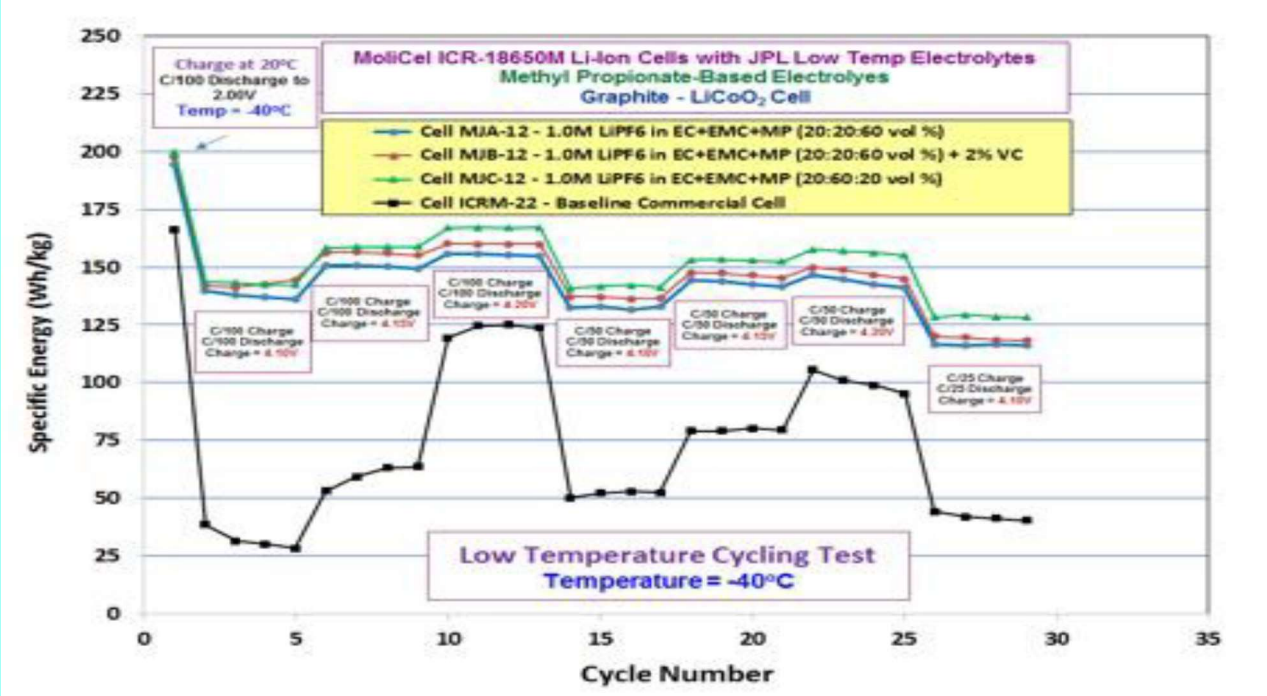
Low-EC All Carbonate -SAFT Cells



- At a moderate discharge rate at –60°C (C/10), the methyl propionate-based electrolyte was observed to deliver ~ 52 Wh/Kg, vs. only ~4 Wh/kg for the ternary blend.

Performance of E-One Molicel ICR-18650 M Custom Cells

Continuous cycling at -40°C: Effect of charge voltage and charge rate

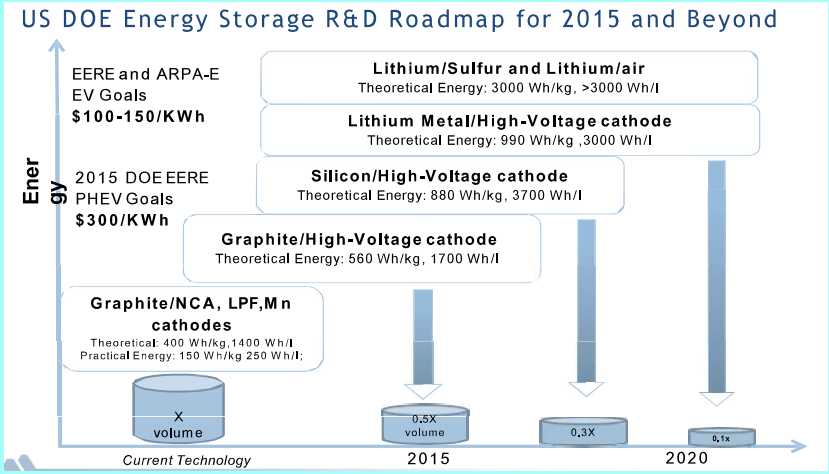


- Excellent specific energy at -40°C observed using a low rate charge and discharge (C/100) (i.e., > 167 Wh/kg).
- Cells have been continuously cycled at -40°C since 10/22/2015 (over 5.5 months of operation)

- **The custom Moli ICR-M cells with JPL electrolytes display improved cycling performance at -40°C compared to the baseline. A number of cells containing JPL electrolytes have been demonstrated to meet programmatic target of >100 Wh/kg (both charge and discharge at -40°C).**

Applications Requiring High Specific Energy Batteries

- High specific energy 400 Wh/kg cells for Extra-Vehicular Activities (EVA)
- Develop advanced Li-ion batteries with high specific energy and improved safety for future NASA missions, e.g., PLSS (portable Life Support Systems for EVA(Extra vehicular Activity) – Similar to DoE's approach
  - Si-C anode with 1000 mAh/g and 100 cycles,
  - NMC cathodes with a sp. capacity of 250 mAh/g and 100 cycles and
  - Low-flammability electrolytes.
- Demonstrate > 200 Wh/kg in prototype cells with C-NCA baseline chemistry, 230 Wh/kg with Si-NCA cells and 250 Wh/kg with Si-NMC cells



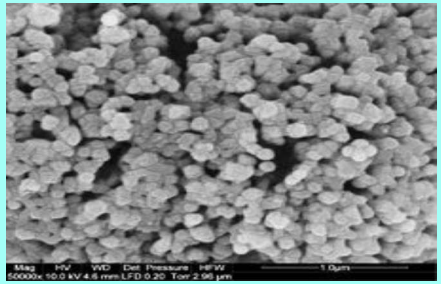
Performance Goals

Characteris*c	Requirement
Battery Energy (Wh)	1000 Wh/cycle
Battery Voltage	28 v DC
Battery Mass	6.8 kg (15 lb max)
Battery Volume	4 liter(12''x4''x5'')
Operating time	> 800 h over > 100 cycles
Energy Density (Packaged)	> 150 Wh/kg
Temperature	10-30°C
Battery Shelf Life	>730 days.
Battery Cycle Life	>100 recharge cycles.
Battery Recharge Time	< 10 h

ASPS- High Specific Energy Cathodes for Li-ion cells

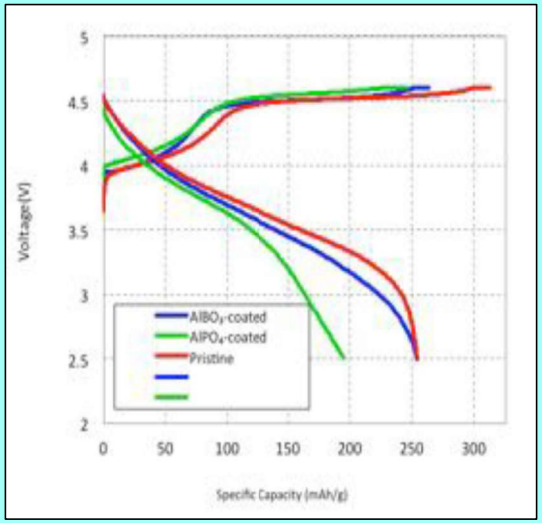
- **Lithium- excess Layered-Layered composites of Li_2MnO_3 and $Li(Mn,Ni,Co)O_2$**
  - High capacity > 250 mAh/g achieved from optimized composition of transition metal ratio and Li content and scaled up by DoE.
  - High tap densities (1.5-2.0 g/cc) and spherical morphology realized from hydroxide precursor synthesis.
  - Demonstrated improved performance (high reversible and low irreversible capacity, and cyclic and thermal stability.
  - Developed a new surface coating ($AlBO_3$), which improves the performance of high voltage cathodes. Can also be used against conventional cathodes.
  - Challenges: High Irreversible Capacity, Poor cycle life, Poor power capability, voltage fade

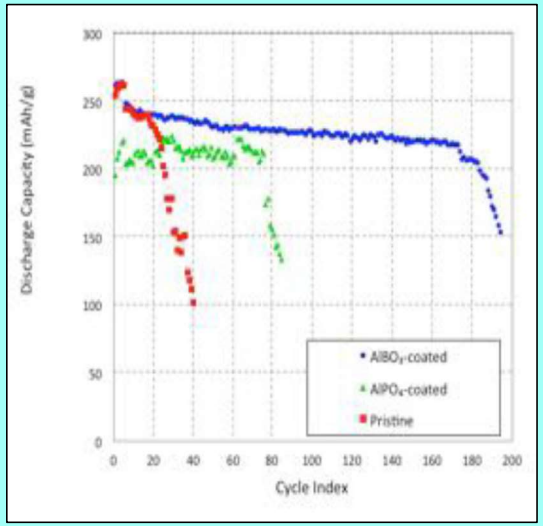
Material Scaled up at ANL(DoE)



Analysis		Results
Particle Size Distribution	D10 (μm)	3.8
	D50 (μm)	6.3
	D90 (μm)	10.6
Specific Surface Area (m^2/g)		2.52
Tap Density (g/cc)		1.81
Element mol %	Li / (Ni+Co+Mn)	1.47
	Ni / (Ni+Co+Mn)	0.15
	Co / (Ni+Co+Mn)	0.17
	Mn / (Ni+Co+Mn)	0.68

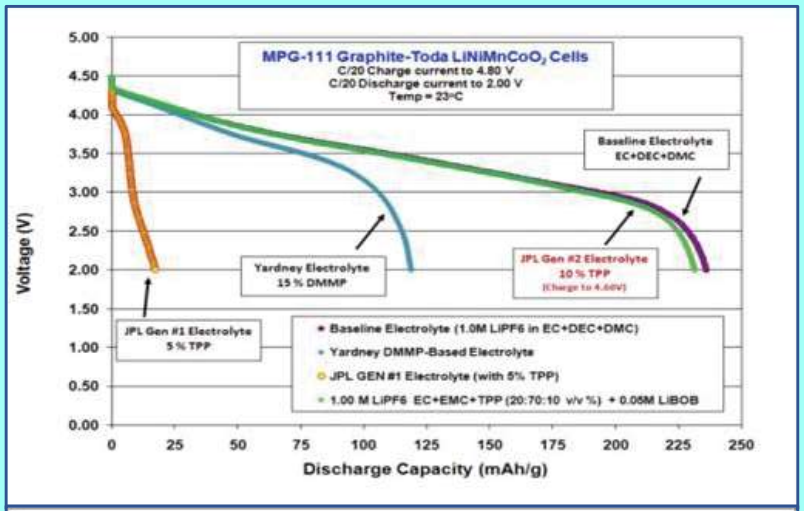
New coating (AlBO3) for high voltage cathodes

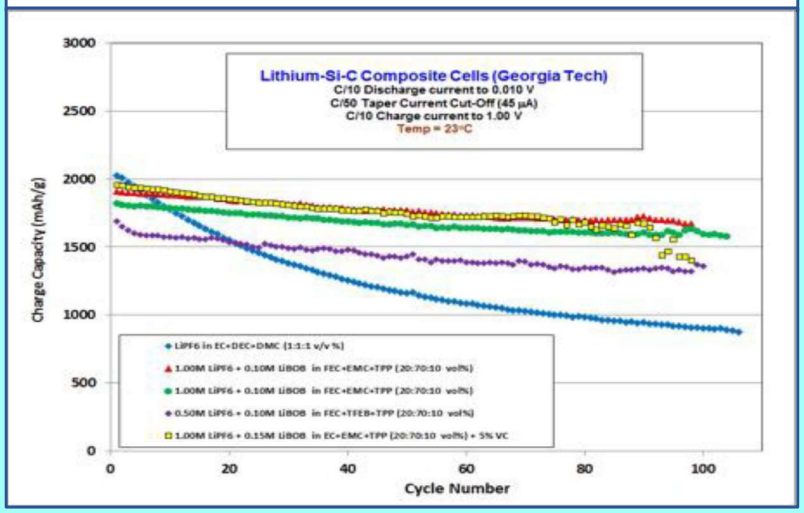




ASPS-Low Flammability and High-Voltage Electrolytes

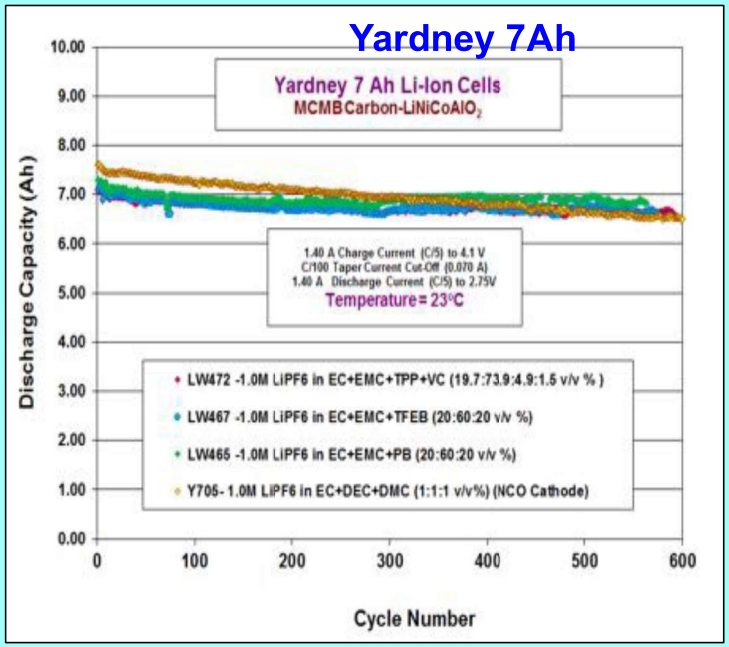
- Developed new electrolytes with reduced flammability (and thus enhanced safety) and high voltage compatibility for Li-ion cells.
  - Various amounts of flame retardant additive (triphenyl phosphate – 5-15%) with 'no loss' in performance.
  - Developed low flammability electrolytes with improved performance over baseline electrolytes with Si anodes.
  - Evaluated three different Si anode technologies (Amprius, Physical Sciences and 3M)
  - Reduced (to ~30%) flammability achieved from electrolyte solutions.

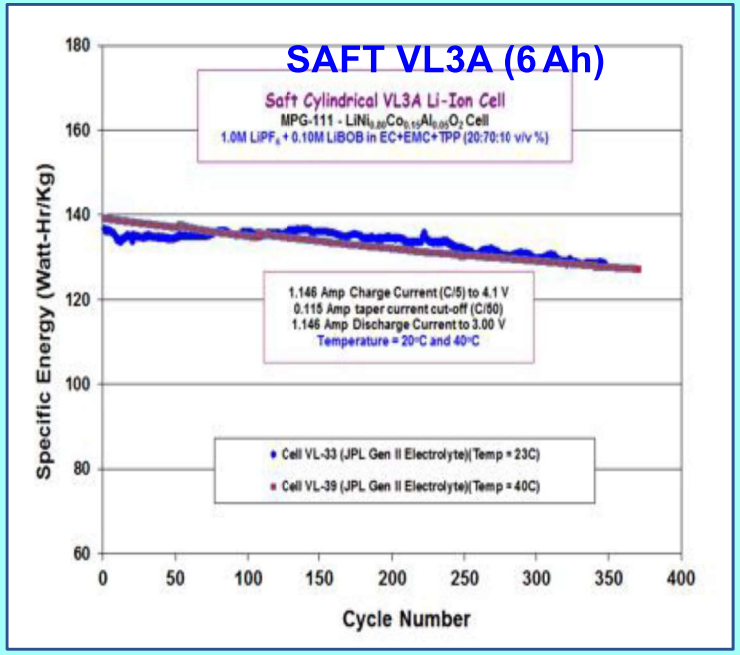




Low Flammability Electrolytes for the SOA Li-Ion Cells

- Demonstrated excellent cycle life and rate capability of low flammability electrolytes in prototype cells for various aerospace Li-ion chemistries
  - Yardney Cells with MCMB anode and $LiNi_{0.8}Co_{0.2}O_2$ cathode
  - SAFT chemistry with MPG111 graphite anode and $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ cathode





- *Low Flammability electrolytes do not compromise the performance of Li-ion cells*

Adaptation of Commercial Li-Ion Cells for Space Missions

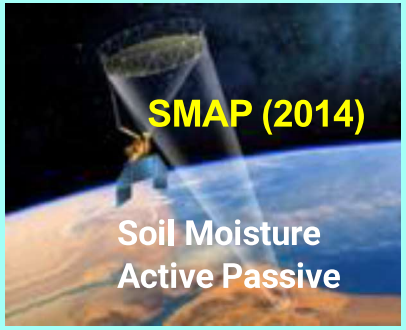
Flight Batteries using commercial 18650 cells (ABSL)

- Sony Hard Carbon – Lithium Cobalt Oxide
- – Built-in protection devices: PTC(thermal fuse) CID (Current Interrupt device), vent
- – Consistent cell fabrication by Sony
- – Further, the cells are well matched using proprietary methods by ABSL
- *No need for cell balancing electronics based on the cell uniformity*
- Redundancy from multiple parallel strings.
- Several new high energy cells available

Several Battery Deigns Available (ABSL) (8S10P, 8S16P, 8S52P)

Analogy with EV batteries using 18650 cells

LI-Ion Batteries with COTSCells for Space Missions

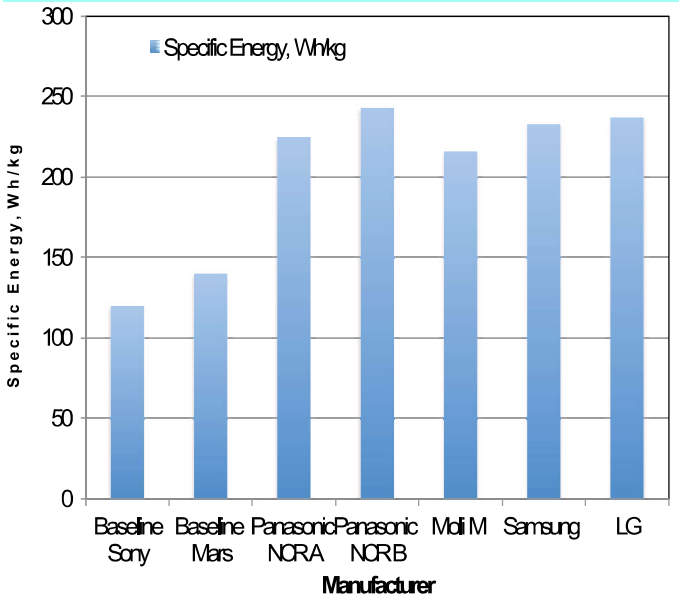


- All these missions used batteries using Sony HC18650 cells (hard carbon–$LiCoO_2$) (110 Wh/kg) in series –parallel configuration of different sizes
- For the upcoming Europa Clipper, we are planning to use E-One Moli M cells (220 Wh/kg)

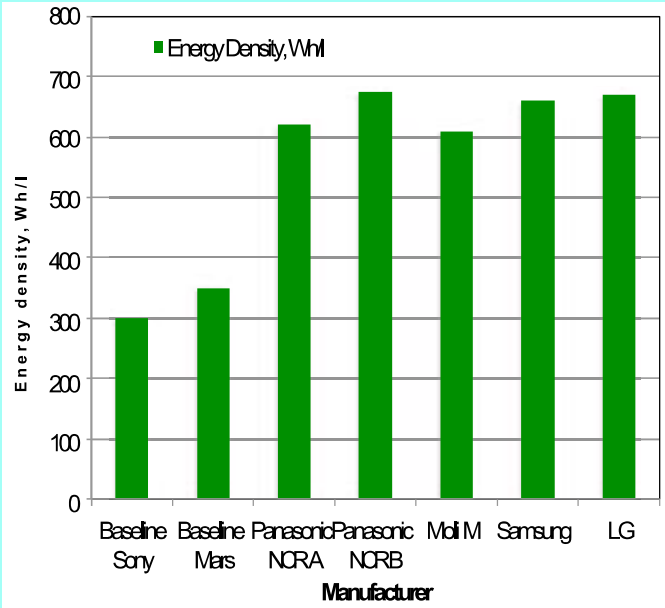
Commercial Cells are Continuing to Get Better

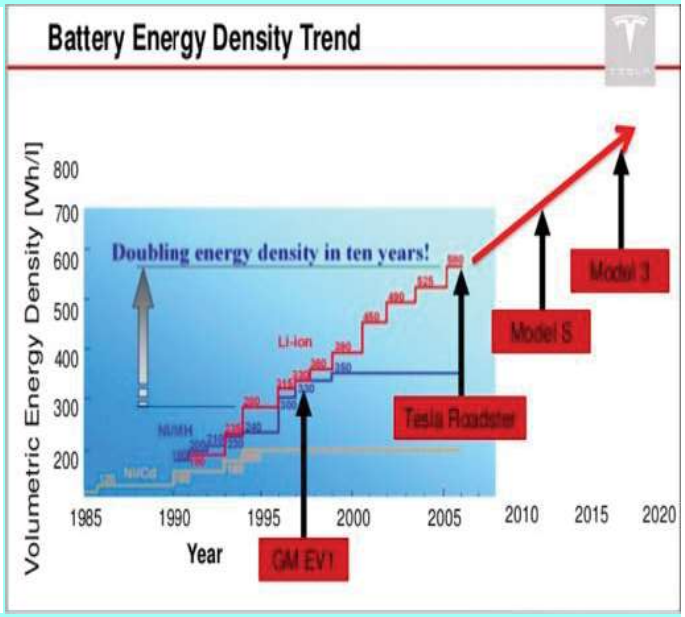
- Commercial manufacturers have traditionally focused on small cells (cylindrical 18650 cells and pouch cells).
- With improved cell designs (dense electrodes, thin separators), many commercial manufacturers have achieved significant energy improvements.

Specific Energy



Energy Density

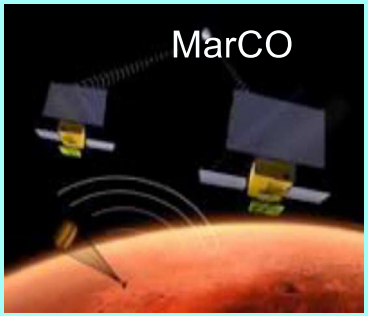


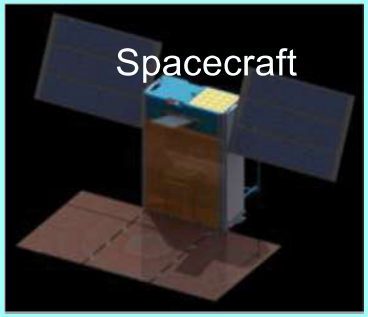


Not quite Moore's Law (computing power tends to approximately double every two years) but impressive growth nonetheless (energy density doubles each ten years).

Mars Cube One (MarCO)

- The twin communications-relay CubeSats, constitute a technology demonstration called Mars Cube One (MarCO) on InSight.
  - A Technology Demonstration of communications relay system for mission-critical events such as the 2016 InSight entry, descent, & landing.
- The basic CubeSat unit is a box roughly 4" square.
- MarCO's design is a six-unit CubeSat, with a stowed size of about 14.4" x 9.5" X4.6"
- The redundant 6U CubeSats will separate from the Atlas V booster after launch and travel along their own trajectories to the Red Planet, independent of the InSight spacecraft, with its own course adjustments on the way.
- Launch: May 5, 2018; Arrival: Nov. 26. 2018

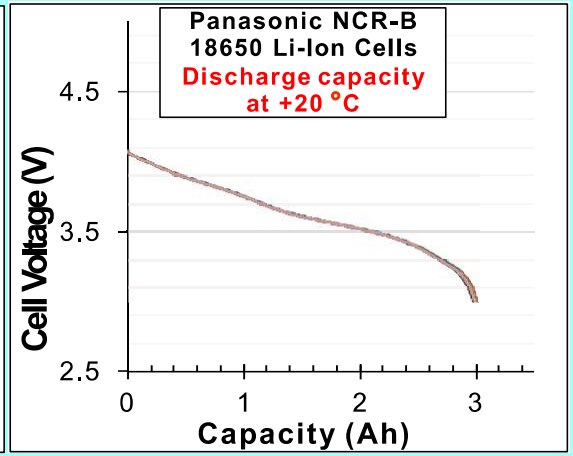




Battery with Panasonic Cells

Cell matching

- 20 °C charge/discharge
- 20 °C impedance measurement
- 0 °C charge/discharge
- 0 °C impedance measurement
- Room Temperature 72 hour stand test
- Weighted sum of z-scores

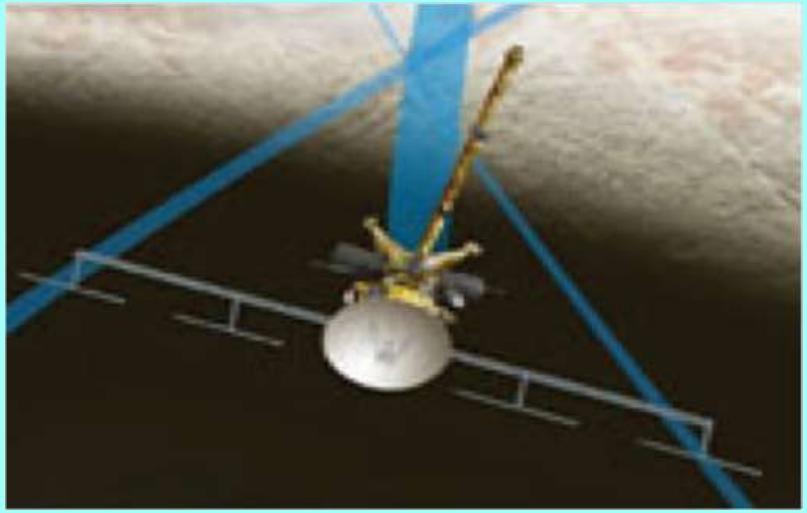


Europa Clipper Mission

Mission Objectives

To explore Europa, investigate its habitability and aid in the selection of future landing sites. Europa Clipper will orbit around Jupiter and will have~ 32 flybys as low as 25−100 kilometers to achieve a medium-quality global topographic survey, including ice thickness. Specifically, the objectives are to study:

- Ice shell and ocean: Confirm the existence, and characterize the nature, of water within or beneath the ice,
- Composition: Distribution and chemistry of key compounds and the links to ocean composition.
- Geology: Characteristics and formation of surface features, including sites of recent or current activity.

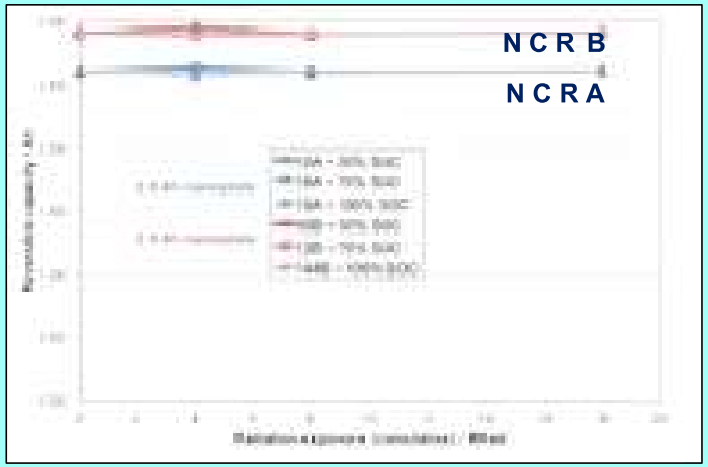


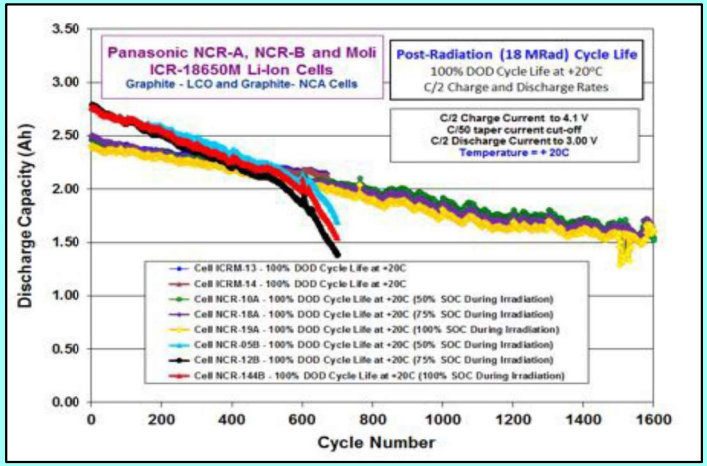
Mission Summary (JPL/APL)

- Launch date: NET 2022
- Launch vehicle: Atlas V 551 or SLS[3]
- Mission duration: Cruise: 6.4 years
- Science: 3.5 years[5]
- Orbits : 32 to 48
- Power: Solar cells (450 W). Solar panels of 90m^2, challenges: Radiation, Low Intensity and Low Temperature (LILT)
- Batteries: 3 x 8S72P Li-ion batteries (30V, 330 Ah) (E-One Moli M cells)

Europa Clipper Li-Ion Battery Technology Validation Testing

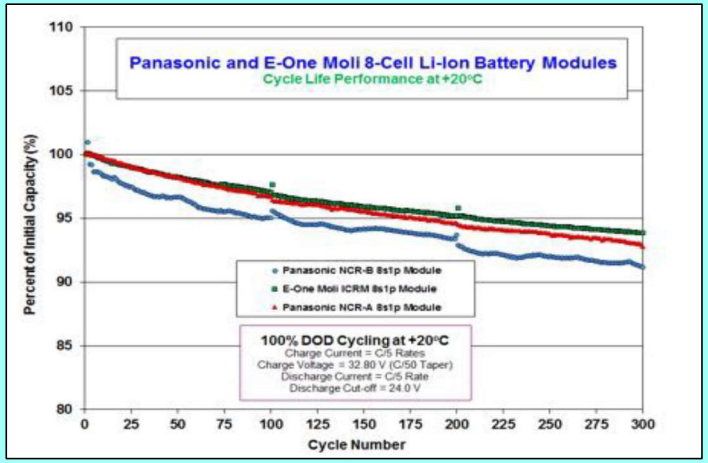
Capacity after 18 Mrad of ^{60}Co irradiation

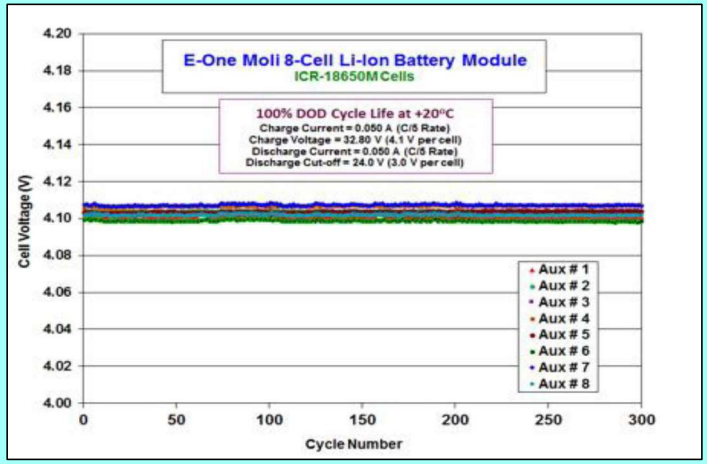




Cycle life after 18 Mrad of ^{60}Co irradiation

Module Cycling at 0C



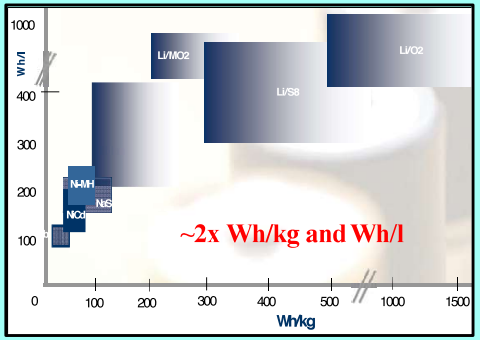


Module cycling – Cell Dispersions

Pre-Decisional Information — For Planning and Discussion Purposes Only

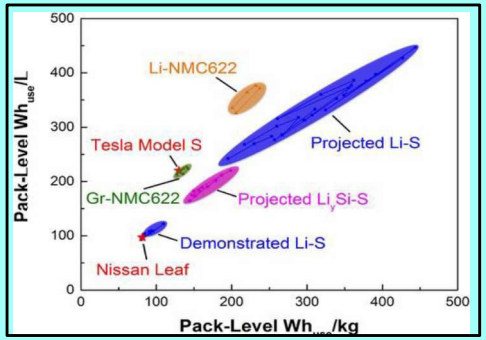
Long-Life and High Energy Li-S Battery for NASA and DoD Applications

Theoretical



- High specific capacity of 1670 mAh/g vs <300 mAh/g for Li-ion cathodes;
- High theoretical specific energy of 2567 Wh/kg vs ~1200 Wh/kg for Li-ion

Experimental



- Low experimental energy density due to low sulfur loading (1-2 mg/cm^2)
- High loading (7mg/cm^2) –> 400 h/kg, which is the objective here

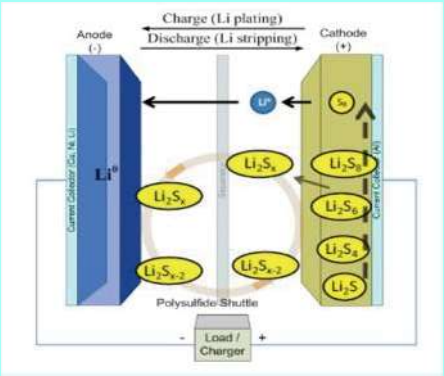
Objective:

To develop a high energy and long-life rechargeable Li-S battery with i) 400 Wh/kg and 400 Wh/l at C/10 at cell level, ii) cycle life of > 200 cycles, iii) wide temperature (-10 to +30 °C) and safe operation.

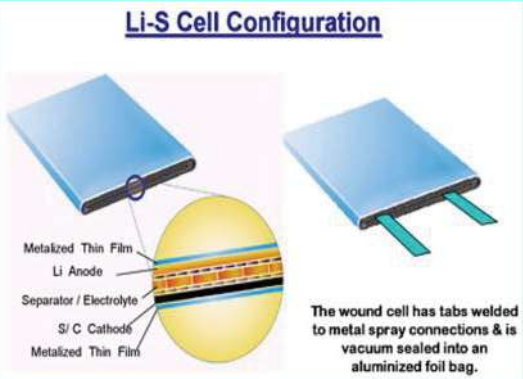
Approach:

- New sulfur cathodes with transition metal sulfide blends (MoS_2 and TiS_2) with the sulfur cathode and/or with the coatings of metal sulfides.
- Ceramic-coated separators as Polysulfide Blocking Layers to minimize the crossover of polysulfides
- Protected Li anode with a thin coating of AlF3 by Atomic Layer Deposition or various polymer electrolyte coatings
- New electrolytes which will minimize polysulfide-related shuttle effects and promote sulfur kinetics (Solvated or concentrated electrolytes)
- New techniques to determine the polysulfides in the electrolyte

Challenges

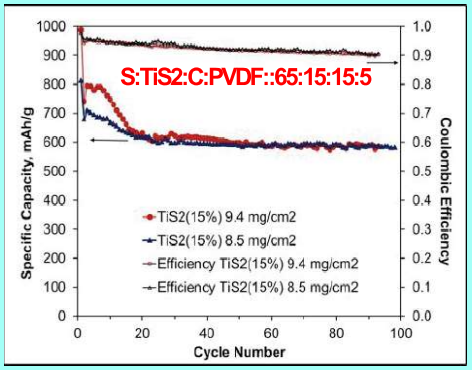


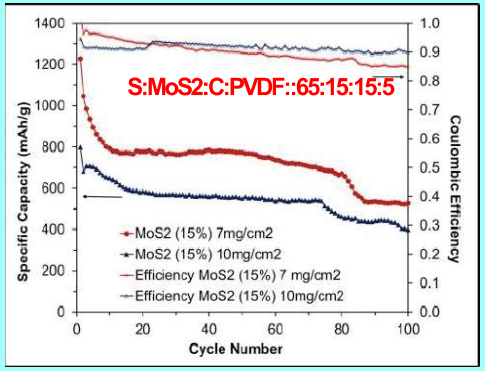
- Dissolution of lithium polysulfides (reduction products) forming redox shuttle and affecting cycle life , anode interface and efficiency



- Current developmental cells are 'Pouch cell) with 250-400 WH/kg.
- Higher the Wh/kg lower would be the cyclelie

Sulfur Cathodes with High loadings (9 mg/cm^2) and high proportion (65%)



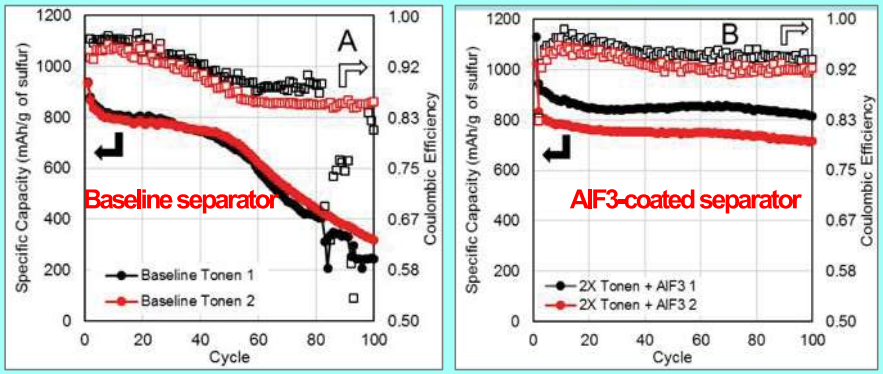


- TiS_2 participates in the redox reaction, but MoS_2 does not undergo such transition in the voltage range.
- Area specific capacity is 8 mAh/cm^2 (3-4X of Li-ion)

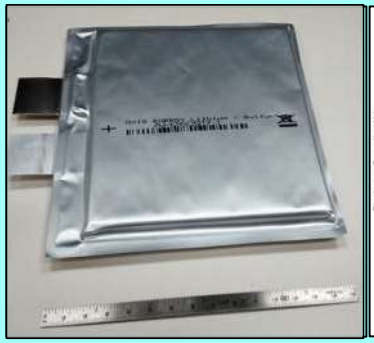
PI: Kumar Bugga; Phone: 818-354-0110,: ratnakumar.v.bugga@jpl.nasa.gov

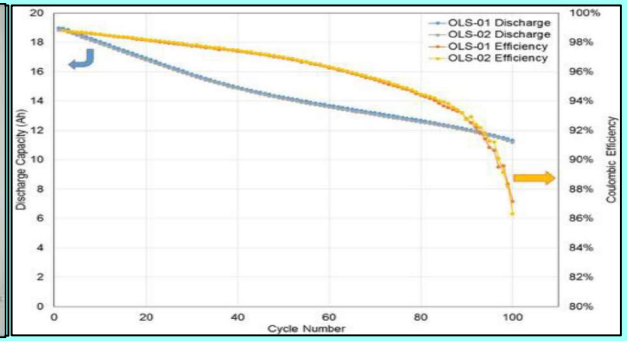
Long-Life and High Energy Li-S Battery for NASA and DoD Applications

Ceramic-coated separators



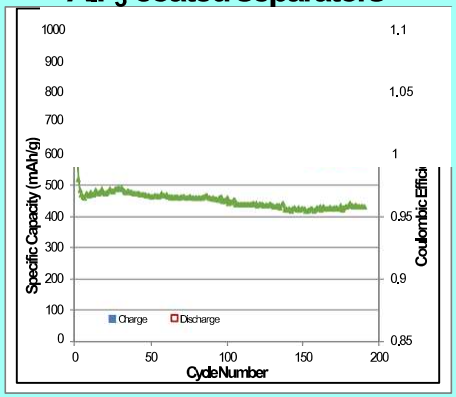
- Coating of the separator with a ceramic material (alumina or aluminum fluoride) improves cycle life (blocks polysulfide migration)





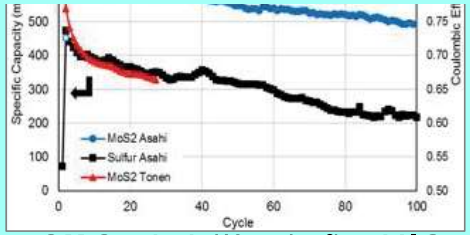
- Specific energy if 300 Wh/kg
- 70% f the capacity retained through 100 cycles, with an efficiency of > 94%
- Performance is good till -10°C, but drops to 25% at -20C.

AlF_3-coated separators



- AlF3 coated onto Tonen by doctor-blade (with 5% PVDF)–Standard sulfur cathode

Pouch Cells



- S-MoS_2 cathode (10 mg/cm^2) and Al_2O_3-coated separator superior
- High Area Specific capacity of 8 mAh/cm ^{2}

Papers, Presentations and Patents

Publications

- In the J. Electrochemical Society on the metal sulfide-blended sulfur cathodes
- In the J. Electrochemical Society on the ceramic-coated separators
- New in-situ technique for determining the dissolved polysulfides in Li-S cells, communicated to the J. Phys. Chem. Letters

Conference Presentations

- Presented at the Lithium-Sulfur Materials, Modeling and Mechanism meeting (2017, 2018), MRS meeting (2018), ECS meeting (2017 and 2018) and International Battery Seminar (2018) and the Power Sources Conference (2018).

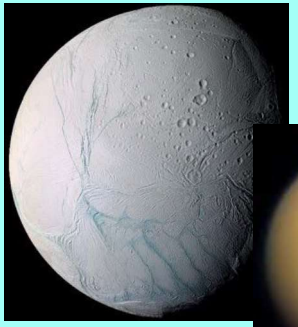
Patents

- One patent on the metal sulfide blended high capacity cathodes and two NTRS on on the sulfide blended cathodes and ceramic coated separators

PI: Kumar Bugga; Phone: 818-354-0110,: ratnakumar.v.bugga@jpl.nasa.gov

Life Beyond Earth – In Ocean Worlds

- Planetary Habitats Theme: “Beyond Earth, are there contemporary habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now?”



Enceladus

Titan

Europa

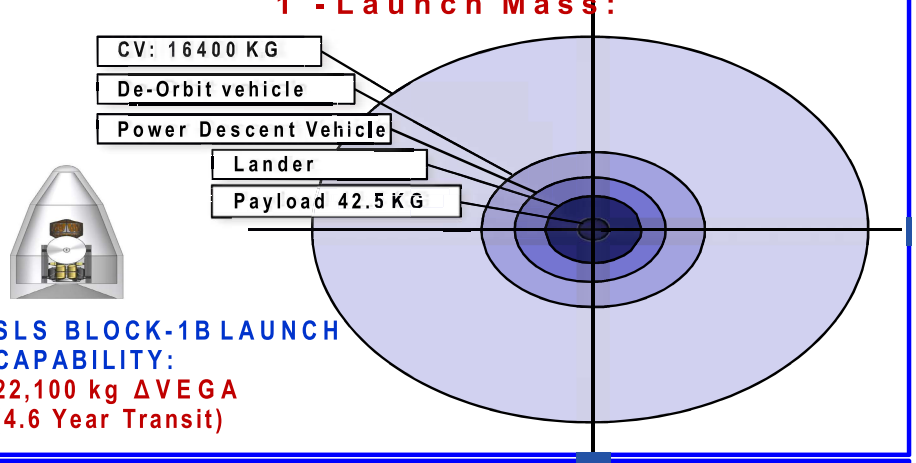
Europa Lander Mission (Concept)

Pre-Decisional Information — For Planning and Discussion Purposes Only

Four Significant Challenges

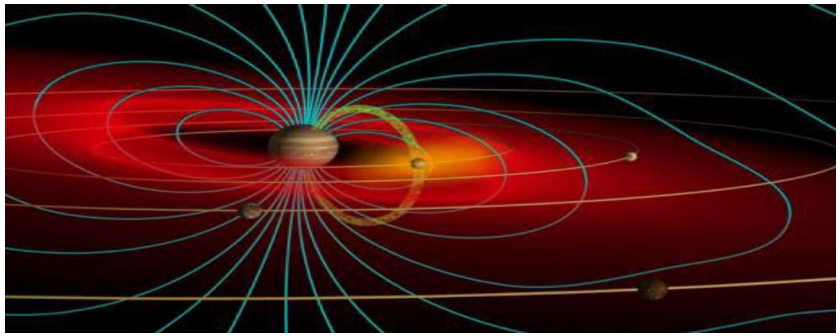
What makes the Europa Lander more challenging than Mars or Lunar landers

1 - Launch Mass:



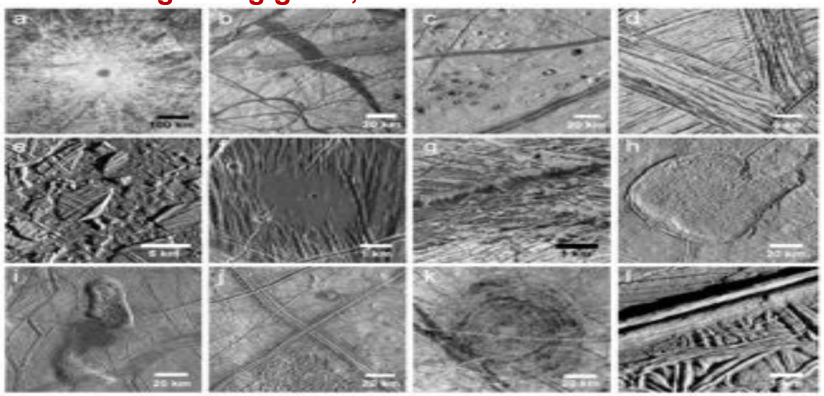
SLS BLOCK-1B LAUNCH CAPABILITY:
22,100 kg ΔVEGA
(4.6 Year Transit)

3 - Jovian Radiation Environment:



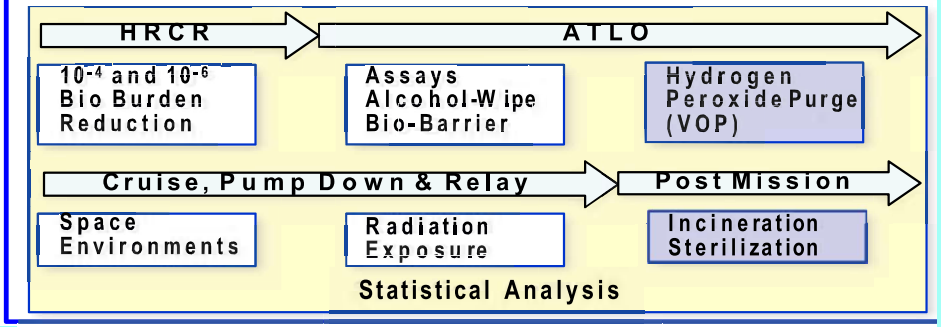
- Drives short surface mission duration ~ 30 day Relay Orbiter
- Vaults provide a 150 kilo-rad environment with a RDF of 2.0

Galileo Images Show Europa Having Rugged, Unusual Terrain



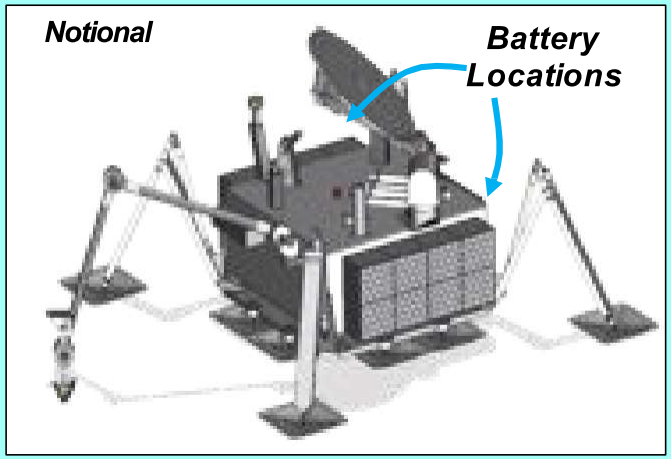
4 - Planetary Protection:

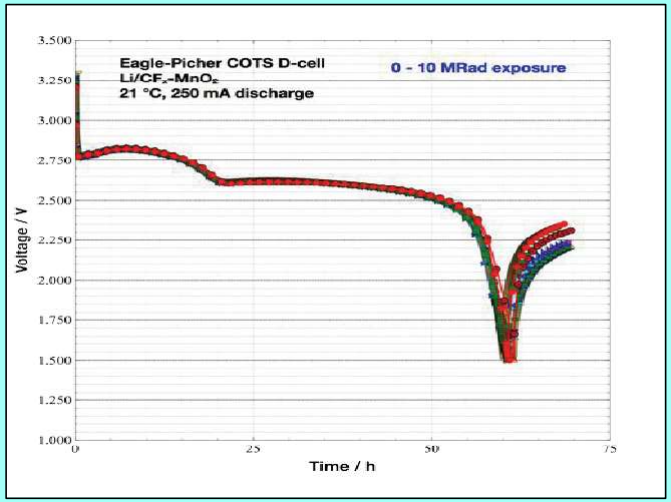
Europa Lander must have a less than 10^{-4} probability of introducing a single "Viable Organism" to any Europa habitable zones – Drives ATLO



Europa Lander Mission Concept Enabled by Li-CF_X

- 500 Wh/kg at the battery level to support 20-day mission (low discharge rate)
- Li-CF_X chemistry has been demonstrated to meet these requirements
  - High electrical energy density (730 Whr/Kg)
  - Significant battery self heating keeps battery and vault warm
- Battery temperature 0 to +60ºC
- 90 kg battery mass allocation
- Power: 50 -600 mA/cell
- Challenges
  - Radiation tolerance and planetary protection
  - Space qualification





Cell Chemistry	Cell Specific Energy (Wh/kg)	Vendor(s)	Flight Heritage
Li/SO_2	270	Saft	Huygens, Galileo Probe
$LiSOCl_2$	350	Saft	MER, Deep Impact
Li/MnO_2	210	Saft, Ultralife	None
Li/CF_x-MnO_2	560	Eagle-Picher	None
Li/CF_x	730	Ray-O-Vac, Eagle-Picher	None

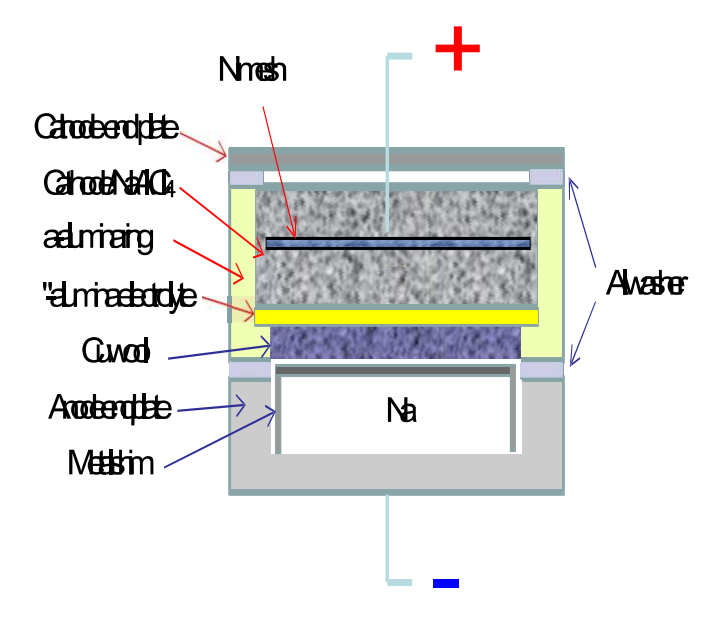
Pre-Decisional Information — For Planning and Discussion Purposes Only

High Temperature Rechargeable Batteries for Venus Missions

Based on molten salt electrolyte and/or sodium beta alumina solid electrolyte

Characteristic	LiAl-FeS_2	Na-Nickel Chloride	Na-S
Operating Temp Range, °C	400 - 475	220 - 500	290 - 450
Open Circuit Voltage, Volts	1.73	2.58	2.08
Discharge Voltage Range, volts	1.2 – 1.8	2.1 to 2.5	1.7 – 2.0
Theoretical Specific Energy	490	800	755
Specific Energy for Cells, Wh/kg	90-130	100-130	130-180
Specific Energy for Batteries, Wh/kg	Near 100	90-130	80-120
Energy Density for Cells, Wh/l	150-200	150-190	
Energy Density for Batteries, Wh/l	Near 150	70-130	90-150
Specific Power for Cells, W/kg	90-300		180-390
Specific Power for Batteries, W/kg	Near 150	40-100	100-150
Cycle Life, cycles	>1000	>1000	2000
Energy Efficiency, %	About 80	About 80	About 80

Planar Sodium- Nickel Chloride Cell



Acknowledgments

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