Solar Power and Energy Storage for Planetary Missions

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August 25, 2015

Topics

- Background
- Solar Arrays
- Solar Cells
- Batteries
- Power electronics
- Emerging technologies
- Applicability to New Frontiers
- Summary

2002

2004

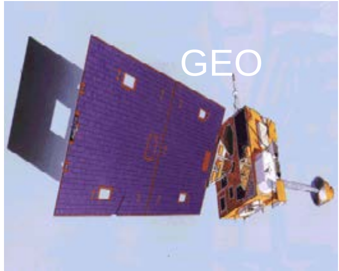
Photovoltaic Power Systems

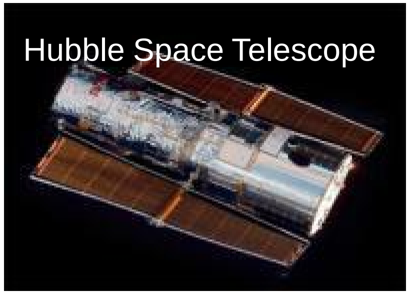
- A photovoltaic power system converts input solar illumination to electricity directly through the photovoltaic effect. Key components are:
  - solar cells,
  - substrate/panel,
  - array structure and deployment mechanisms
  - energy storage

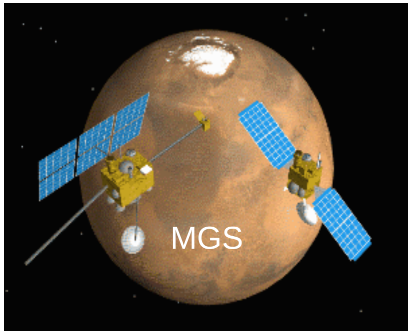
Photovoltaic power systems have been widely used in robotic science and human exploration missions

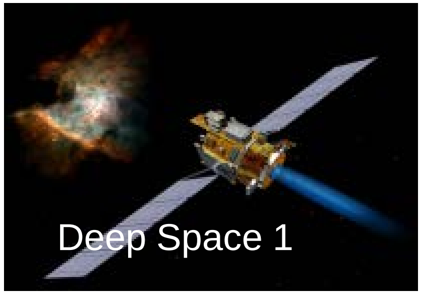
Applications of Photovoltaic Power Systems

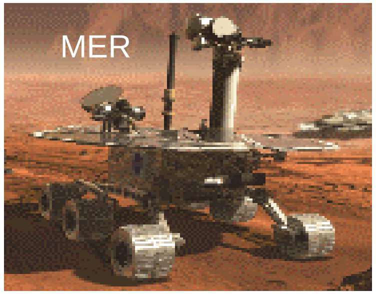
- Used on >99% of the space missions launched to date:
  - Earth Orbital : GEO, LEO, MEO
  - Planetary Orbital/fly byes
  - Ion Propulsion Missions:DS-1
  - Mars, Jupiter, Venus, Mercury,
  - Planetary Surface: Mars, Moon
  - Human Exploration: ISS

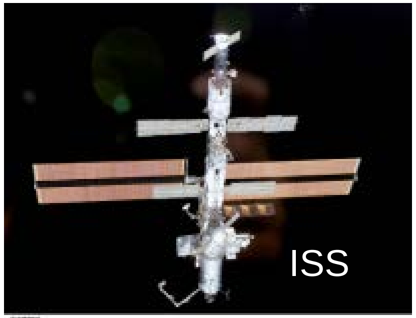






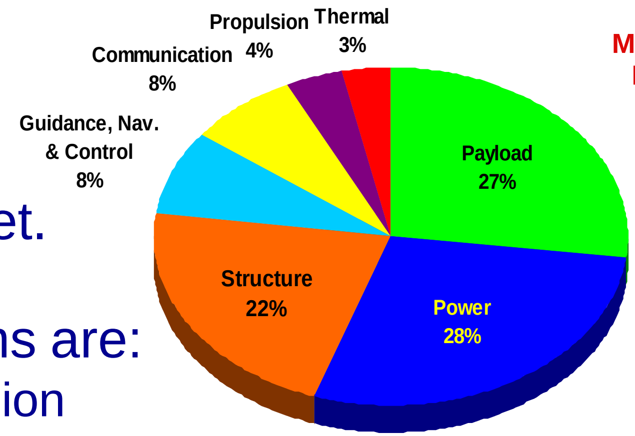


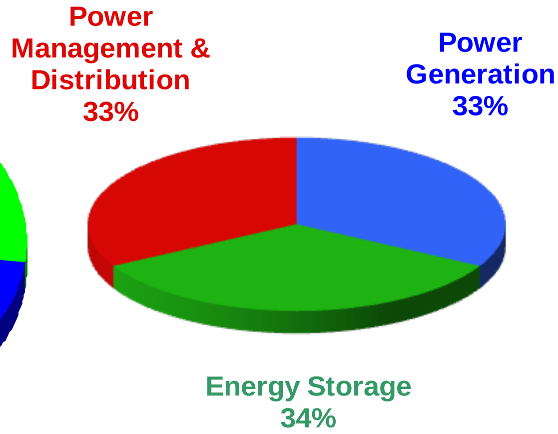




Space Power Technology Area Overview

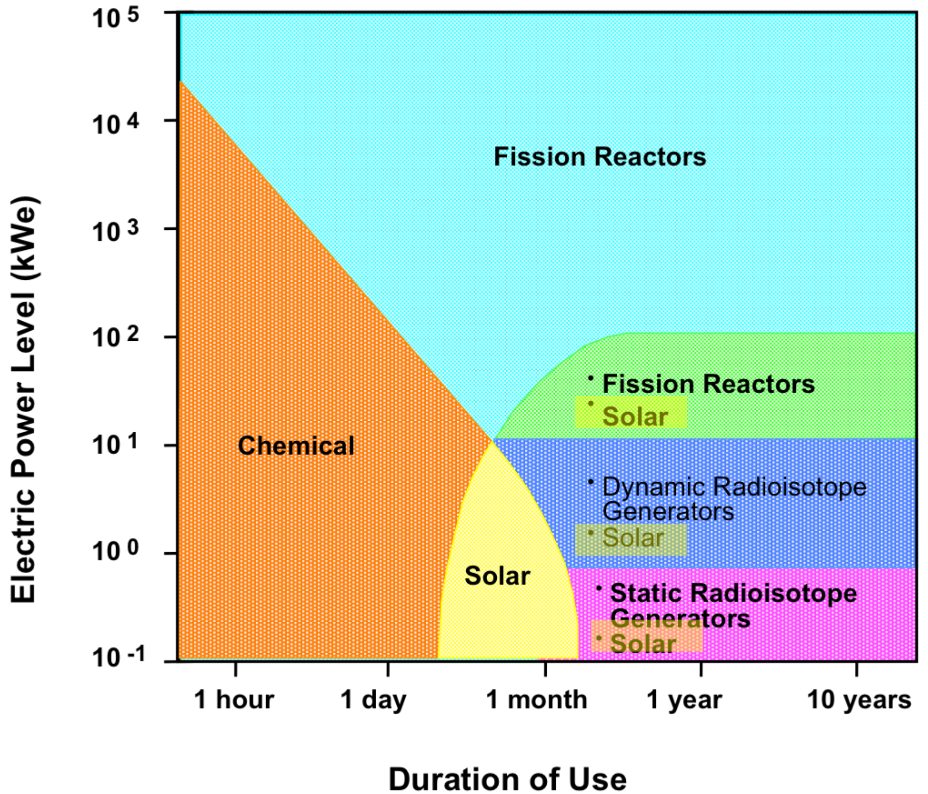
- Power system is 20-30% of spacecraft mass and costs 20% of the spacecraft budget.



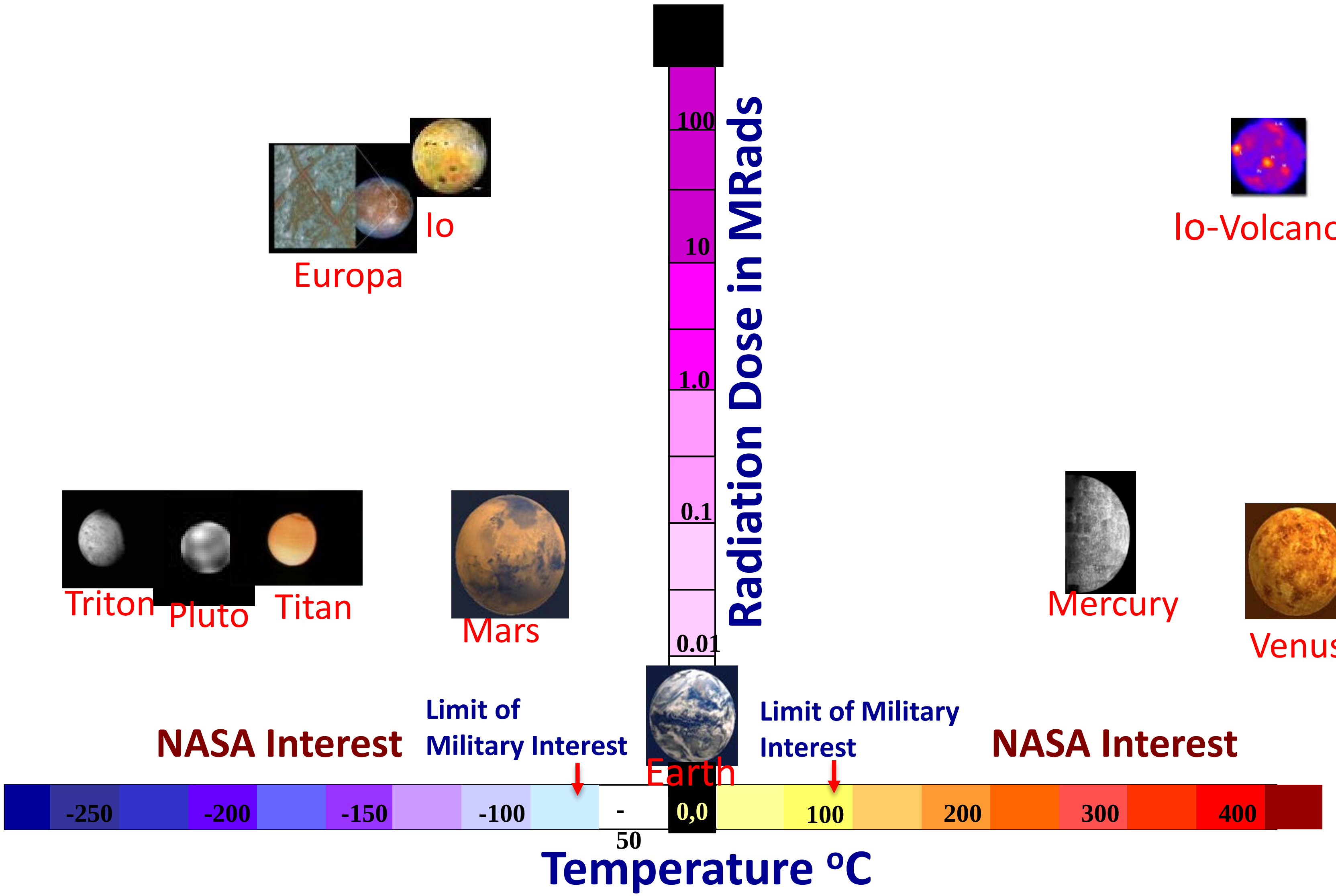


- The major power subsystems are:
  - Power Generation/Conversion
  - Energy Storage
  - Power Management and Distribution

- Space missions need a variety of power solutions
  - Solar power systems
  - Nuclear power systems
  - Batteries
    - primary and secondary (rechargeable)
  - Fuel Cells
  - New Technologies

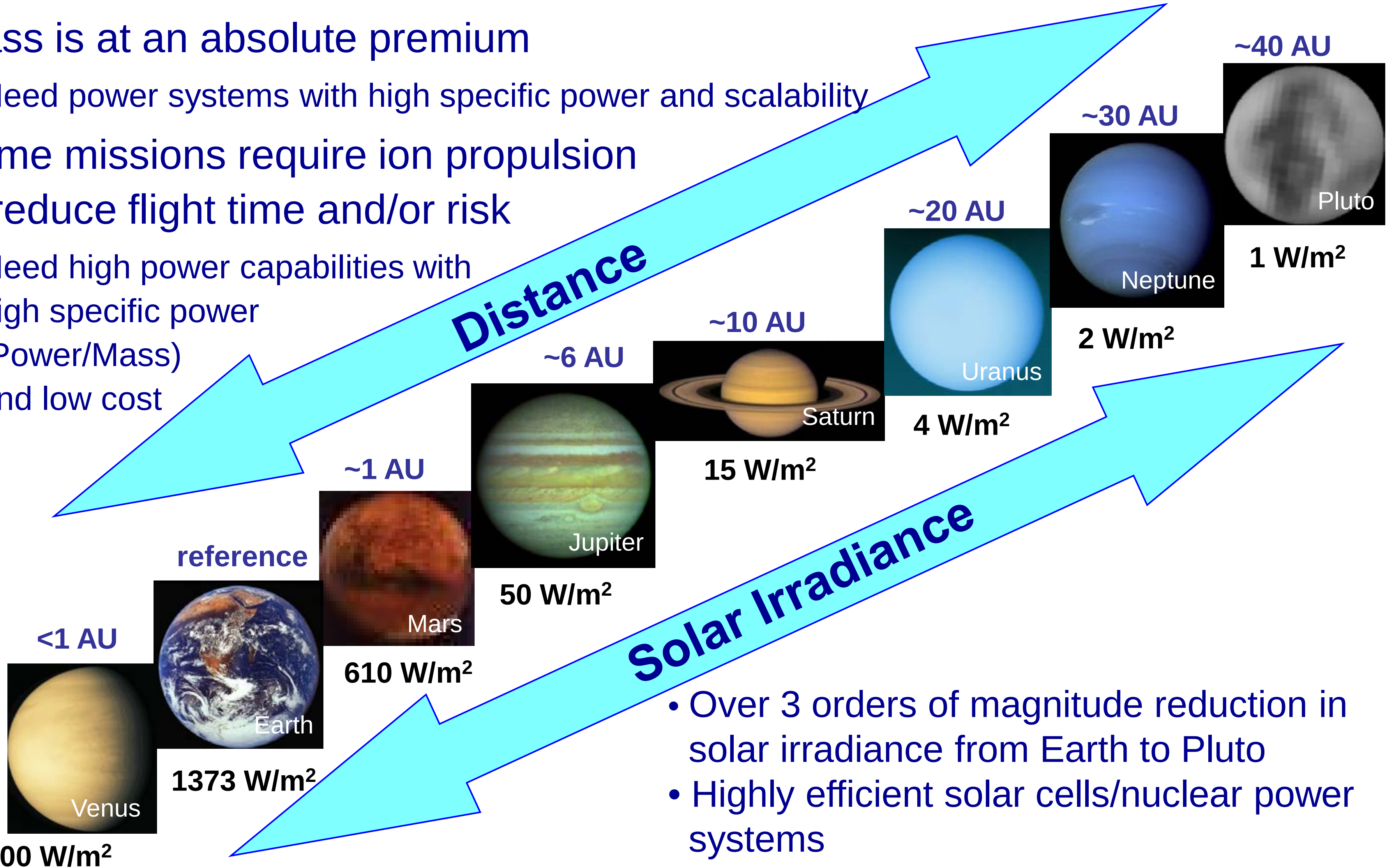


Major Challenges of Planetary Missions – Extreme Environments



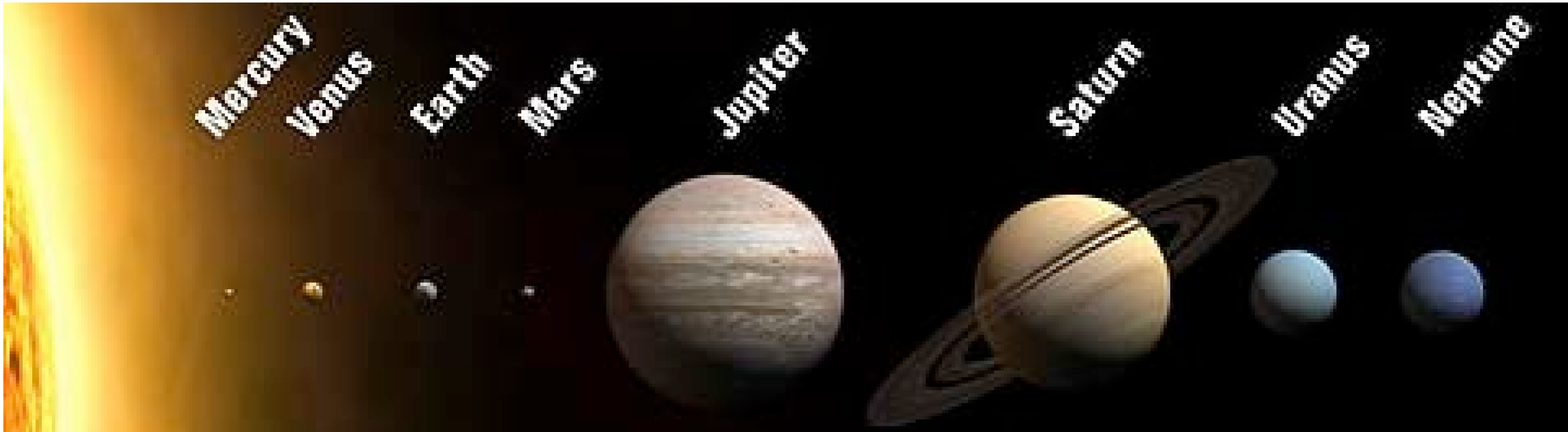
Major Power Challenges of Solar System Missions

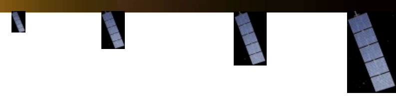
- Flight times are long
  - Need power systems with >10 years life
- Mass is at an absolute premium
  - Need power systems with high specific power and scalability
- Some missions require ion propulsion to reduce flight time and/or risk
  - Need high power capabilities with high specific power (Power/Mass)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

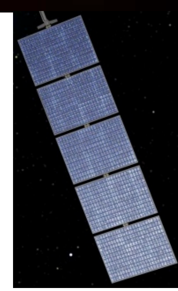


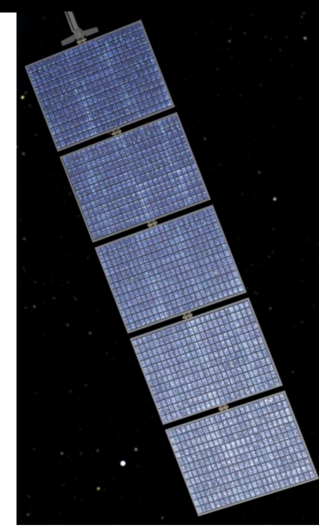
- Over 3 orders of magnitude reduction in solar irradiance from Earth to Pluto
- Highly efficient solar cells/nuclear power systems

Solar array size for planetary missions









Earth: 300 W/m^2

Jupiter: 6 W/m2

Saturn: 3 W/m2

Juno

L= 9 m W= 2.7 m/panel

A > 60m^2, Mass = 340kg

Total number of solar cells: 18,698

Total power output at Earth = ~14 kW BOL

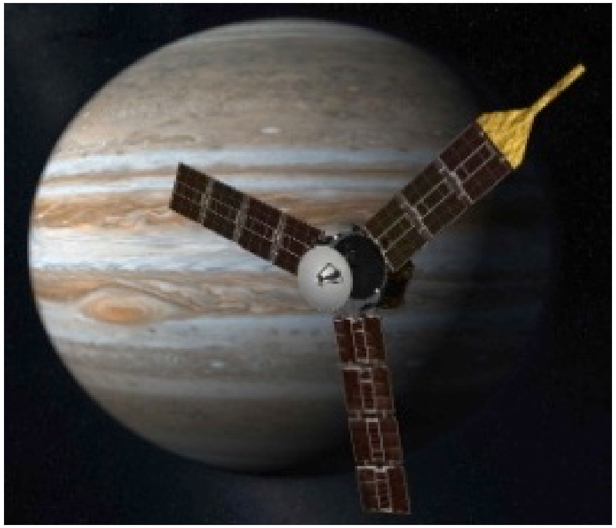
Total power output at Jupiter = ~450 W

Specific power = ~50 W/kg at Earth BOL

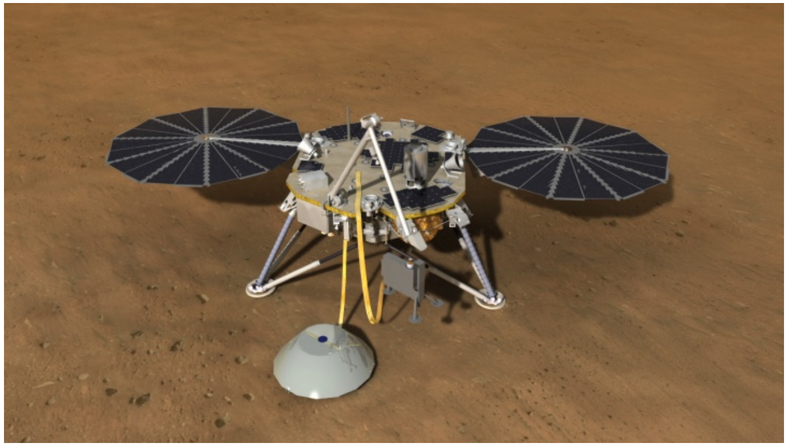
Array size increases with the square of the distance from the sun.

Continuing Development of Solar Power Systems

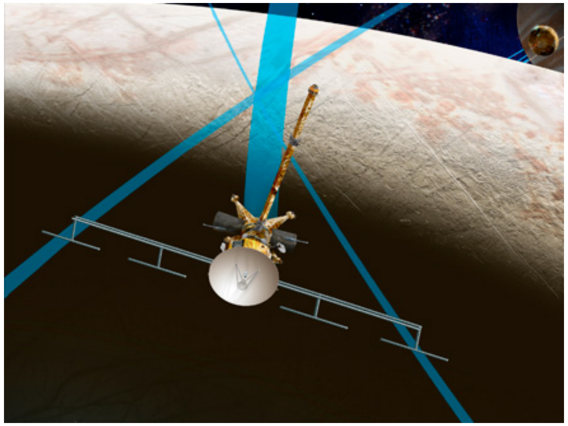
MER: Long cycle life rechargeable batteries (>1,000 cycles for >10 years)



Juno: LILT selected, high radiation solar arrays with long calendar life batteries (5 year cruise time)



InSight: Light-weight, deployable solar arrays ***with*** lower temperature batteries (-30°C)



Europa Fly-by Mission Concept: LILT baselined, higher radiation solar arrays with high specific energy, radiation tolerant batteries (~200 Watt-hr/kg)

Solar Arrays for Planetary Missions

Spacecraft Power needs:

Operating loads = ~ 200 W

Payload = ~ 100W

Propellant heat = ~ 100-200 W

TOTAL = ~ 400-500 W

at planetary body

Mission	BOL Power (kW)	Specific Power (W/kg)	Specific Cost ($/W)
DS1 (1998)	2.5	42	Provided by DOD
Dawn (2007)	10	80	~900
Near-Term	10 to 30	> 150	< 500
Far-Term	> 100	> 300	< 250

Solar Arrays

- Primary Drivers
  - Power Level
  - Cost
  - Risk (real and perceived)
  - Specific Power (W/kg)
  - Low Intensity Low Temp. (LILT)
- Secondary Drivers
  - Natural Frequency/strength
  - Packaging

- ISS arrays are about 27 W/kg and $3,500/W

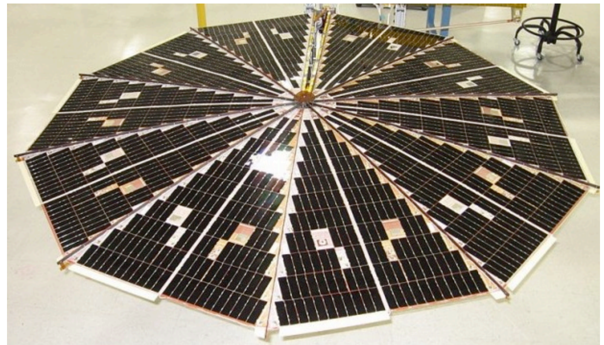
- **Need low-risk, light-weight solar arrays in the 10- to 30-kW range.**
- **At 30 kW, a 200W/kg array saves > 200kg relative to an 80 W/kg array.**

Solar Array technologies

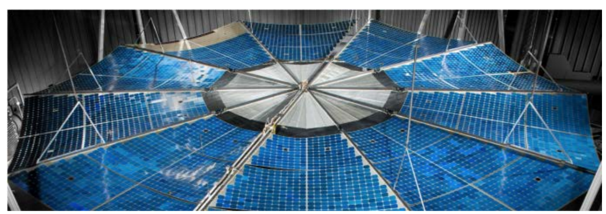
State of the practice

Large area, lightweight, reduced stowed volume

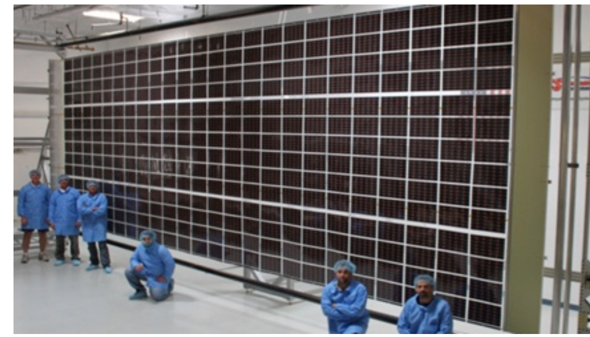
Rigid panels
~50-80 Watts/kg at 1AU
TRL 9 (Dawn, Juno)



ATK Ultraflex/Megaflex
~150 Watts/kg at 1AU
Top: TRL 9 (Phoenix - Ultraflex)



Bottom: TRL 6 – Megaflex



Deployable Space Systems (DSS)
Rosa/Megarosa
~150 Watts/kg at 1AU
TRL 6

State of the Art

Solar Arrays for Outer Planets

Background:

- Outer-planet mission arrays operate at Low Irradiance Low Temperature (LILT)
- Vendors develop their solar cells for Earth orbit (1AU 28°C)
- Testing all cells for LILT is (costly and time-consuming) impractical.

Current Process:

- Characterize statistically significant cell quantity under LILT/radiation
- Use that data to obtain screening parameters and array-design data
- Vendor screens all cells at low irradiance and room temperature (LIRT)
- Eliminate cells that do not meet screening criteria, ~50% rejection rate
- Oversize the array to account for uncertainty in screening effectiveness
- Build and test the array at nominal Earth orbit conditions

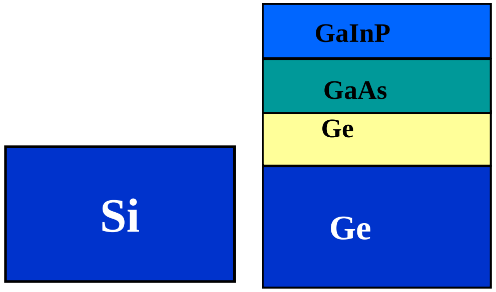
Improved process needed, but not currently funded:

- Develop LILT-optimized cells with predictable/consistent LILT performance
- Eliminate need for LIRT screening and array oversizing and associated costs

SOA Solar Cells & Arrays - Overview

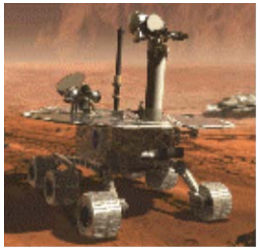
- **Solar Cells**
  - Multi Junction Solar Cells are presently being used in space missions and high efficiency Silicon was used on Rosetta

Cell Type	Efficiency
High Efficiency Si Cells	16 %
Multi Junction Solar Cells	29 %

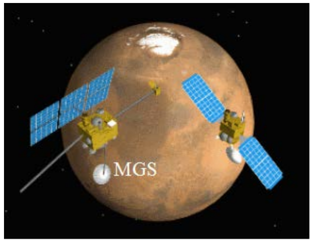


- **Solar Arrays**
  - Body mounted, rigid panel and flexible deployable arrays are currently being used in many spacecraft.
  - These arrays have been used for low–medium power (0.5-20 kW) applications

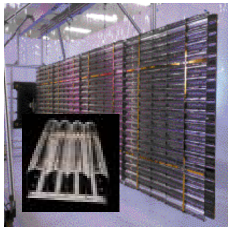
Array Type	Specific Power (W/kg)
Rigid Panel Array	30-40 (3 J)
Flexible Foldout Arrays	30-50 (Si)
Concentrator Arrays	30 -60
Flexible foldout Arrays	80-150 (3 J)



Body-Mounted



Rigid Panel



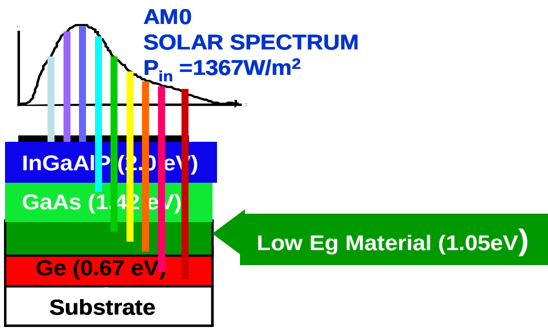
Concentrated Array

Flexible Foldout Array (Ultraflex)

Solar cell efficiencies

State of Practice:

- Flight-qualified solar cells are triple junction cells from 2 U.S. vendors
- 29% conversion efficiency at 1AU and 28^{o}C
- Significant variation in cell performance under LILT conditions
- Screening required to obtain reduced variation in conversion efficiency out to Saturn (10AU)
- Radiation losses of ~15% (Juno) to ~25% (Europa)



Multi Junction Crystalline Cell
Status:30%
Goal: 39%

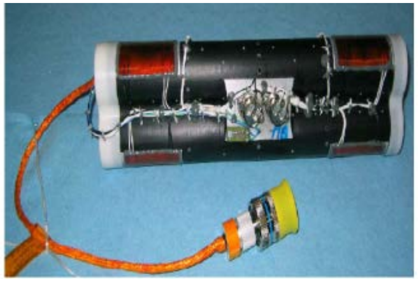
Advanced Solar Cells:

- Industry is currently developing 4 to 6 junction cells
- With funding, 33 to 36% efficiency projected with qualification by $\geq$2017
- Characterization of advanced cells need to be done under LILT conditions to understand and improve yields
- Opportunity to engage/incentivize vendors to consider LILT conditions and radiation during development to ensure increased efficiency for deep space missions. Will also reduce mass and volume.

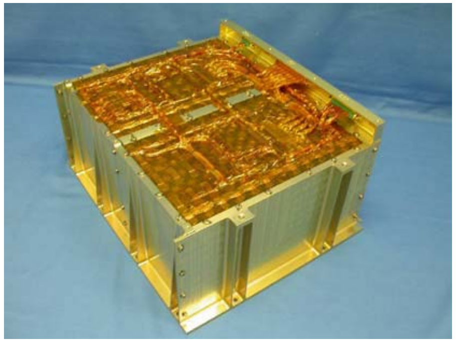
Three Main Classes of Batteries

- **Thermal Batteries (Minutes of discharge time, one time use)**
  - High power, one time use for critical events such as Entry/Descent/Landing
  - Missions: MER, MSL
- **Primary (Hours of discharge time, one time use)**
  - Two main chemistries: $LiSOCl_2$ and $LiSO_2$
  - Missions: Galileo Probe, Mars Pathfinder (Sojourner), Huygens Probe
- **Secondary (Hours of discharge time between recharge cycles)**
  - Lithium-ion battery chemistry (custom electrolytes possible)
  - Requires suitable power sources for recharging (solar or radioisotope)
  - Missions: MER, Juno, MSL

Thermal



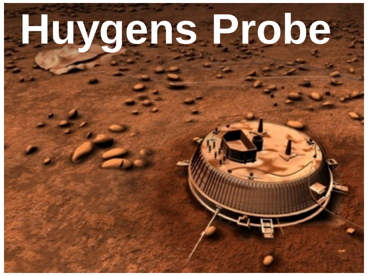
Primary



Rechargeable

Primary Batteries for Space

- 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 radio-isotope power sources are not available
- Limits operations to hours or days (based on size of cell and discharge current)
- Emerging technologies based on advanced chemistries offer potential for retaining significant capacity at low temperatures and high discharge currents



Metric	$Li\text{-}SOCl_2$ (State-of-the-art)	$Li\text{-}SO_2$ (State-of-the-art)	$Li\text{-}CF_x$ (Advanced)
Specific Energy at +25ºC (Watt-hr/kg)	590	260	520
Low Temperature Operating Limit (ºC)	-40 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	Potential for high relative capacity at high currents

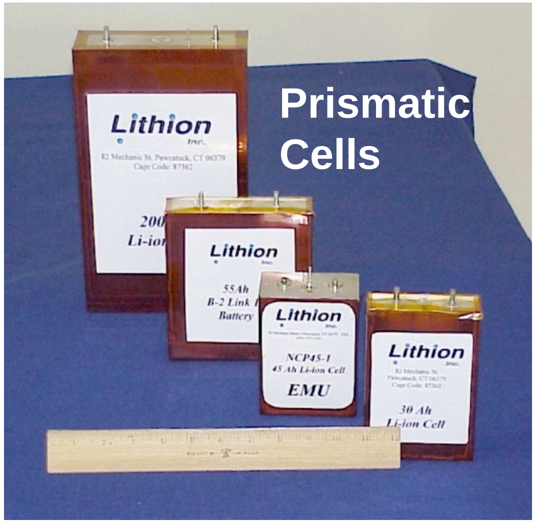
Secondary Battery Performance Must Target All Four Metrics

- **Higher Specific Energy**
  - Target: >200 Watt-hour/kg
  - Goal is greater energy stored per unit mass
  - Translates to greater mass available for science payload
- **Wider Temperature Operation**
  - Target: <-30°C Charge and Discharge
  - Batteries have narrowest operating range of all avionics sub-systems
  - Wider limits means less power/mass needed for thermal control
    - Eliminates use of RHU's for thermal control and/or reduces electrical heating
- **Longer Life**
  - Target: 1000's of cycles with >10 year calendar life
  - Critical for long outer planets cruise times and extended missions
- **More Radiation tolerant**
  - Target: >15 Mrad
  - Supports Jupiter icy moon missions and other high radiation targets

Two Main Li-Ion Rechargeable Cell Types Used for NASA Planetary Missions

- **Battery is comprised of multiple cells**
  - Add cells in series to increase voltage
  - Add cells in parallel to increase capacity

- **Lithium-ion cell types used for planetary exploration**
  - Large Prismatic Cells (Yardney): Up to 55 Amp-hour capacity
  - Small Cylindrical Cells (Sony, Panasonic): 1-3 Amp-hour capacity

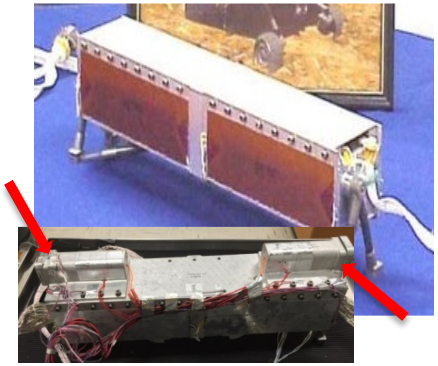


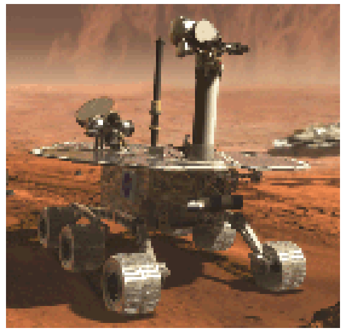
Prismatic Cells

Cylindrical Cells

NASA Planetary Missions Using Large Cell Batteries

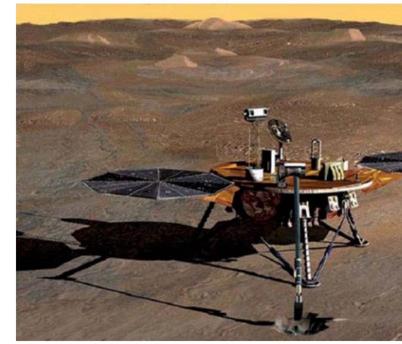
Mars Exploration Rovers (2003)





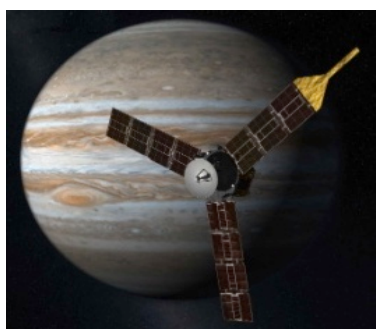
- **Battery specific energy: 90 Watt-hour/kg**
- **Operating on Mars Since Jan. 2004**

Mars Phoenix Lander (2007)



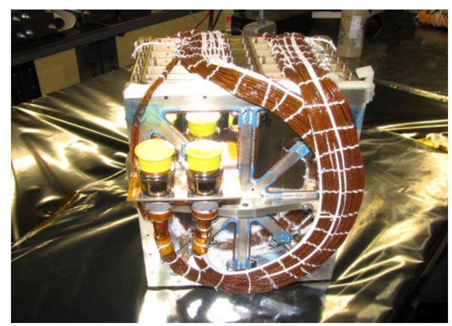
- **Battery specific energy: 105 Watt-hour/kg**
- **Successfully supported mission (90 days)**

Juno – Jupiter Orbiter (2010)



- **Battery specific energy: 110 Watt-hour/kg**
- **Cruising to Jupiter (8 year life proven)**

Mars Science Laboratory (2011)

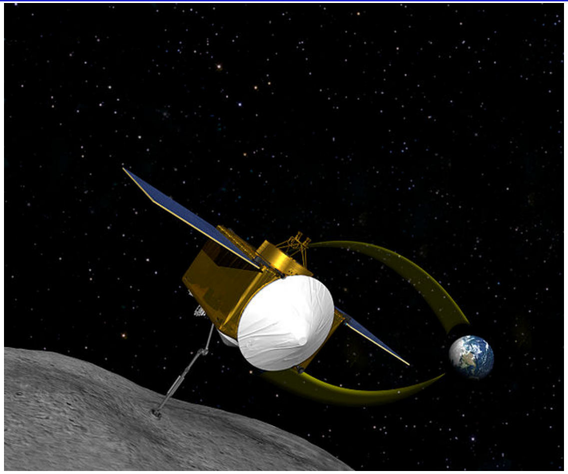


- **Battery specific energy: 104 Watt-hour/kg**
- **Operating on Mars since Aug. 2012**

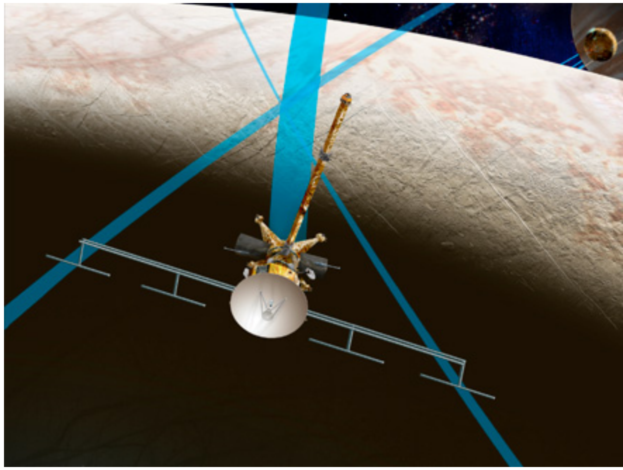
← RHU 's

NASA Planetary Missions Using Small Cell Batteries

Lunar Reconnaissance Orbiter (LRO)



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



Europa Fly-by Mission Concept

- 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 ~200 Watt-hour/kg batteries vs. ~110 Watt-hour/kg for batteries based on large cells
- Ongoing testing of commercial small cells reveals suitable performance in space environments
  - Acceptable low temperature performance for Europa Fly-by Mission concept allowable flight temperatures
  - Good radiation tolerance at high total doses

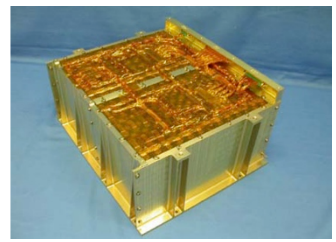
Evolution in Space Battery Chemistries

Increasing capacity and cycle life

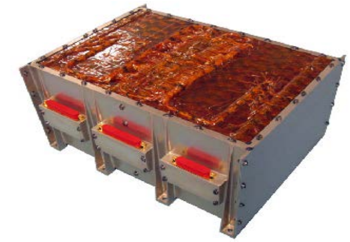
Ag-Zn
105 Watt-hour/kg
~100 cycles

Ni-Cd
40 Watt-hour/kg
>1000 cycles

Ni-H_2
55 Watt-hour/kg
1000's of cycles



Heritage Small Cell (ABSL/Sony) and Large Cell (Yardney) Li-Ion
~110 Watt-hour/kg
1000's of cycles



State-of-the Art Commercial Small Cell Li-ion
~200 Wh/kg
1000's of cycles

1980 1990 2000 2010 2020

Status of Battery Development

- **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 6 (InSight)

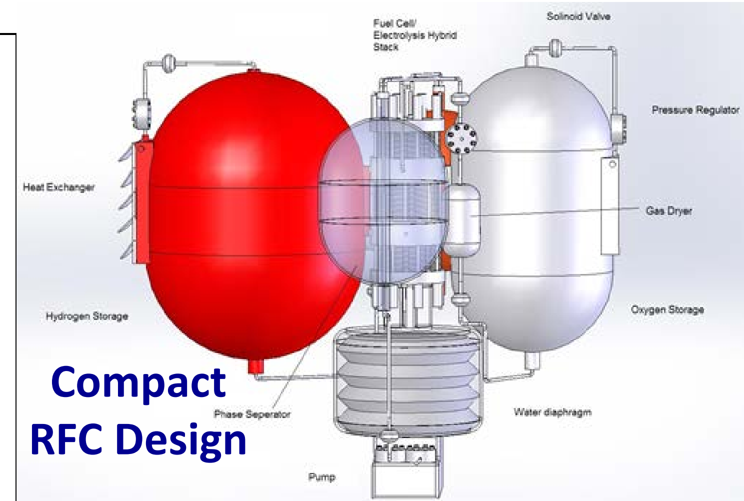
- **High specific energy/moderate temperature technology**
  - Based on small cylindrical cells
  - 220 Watt-hour/kg at +20°C
  - -10 to +40°C discharge limits
  - TRL 5 (Europa Fly-by Mission Concept)

<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)

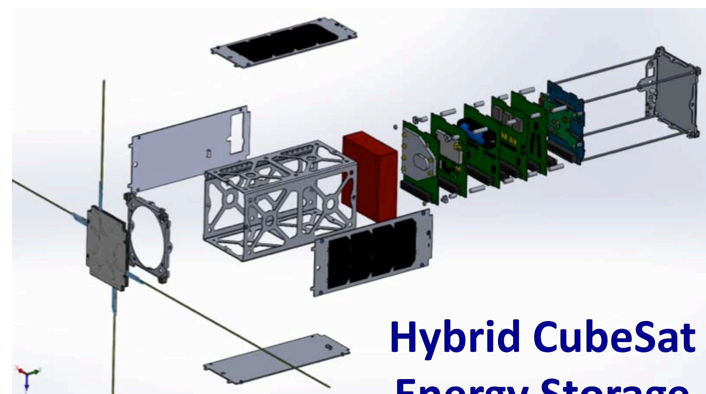
Emerging Energy Storage Technologies

- **Regenerative Fuel Cell (RFC) Systems**
  - Compact RFCs for very long duration (>100 hour) discharge times
  - Used for high power applications (>1kW)
  - Utilize waste heat from RFC system for thermal management
  - Currently under development for lunar applications and aircraft

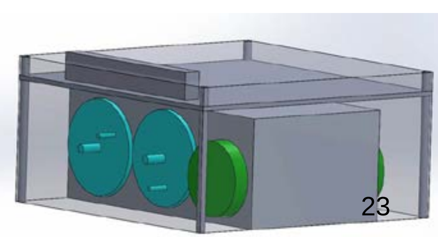
- **Hybrid Energy Storage Systems**
  - Combined Battery + Super-Capacitor
  - Battery provides energy storage
  - Super-Capacitor supports very high current pulses at low temperatures
  - Currently under development for CubeSat missions



Compact RFC Design



Hybrid CubeSat Energy Storage

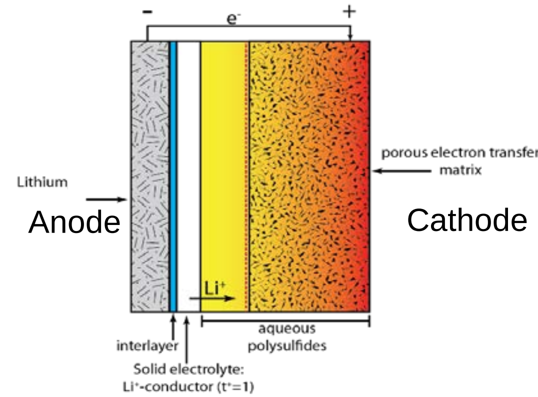


Enabling and Enhancing Power Technologies for New Frontiers Mission Concepts

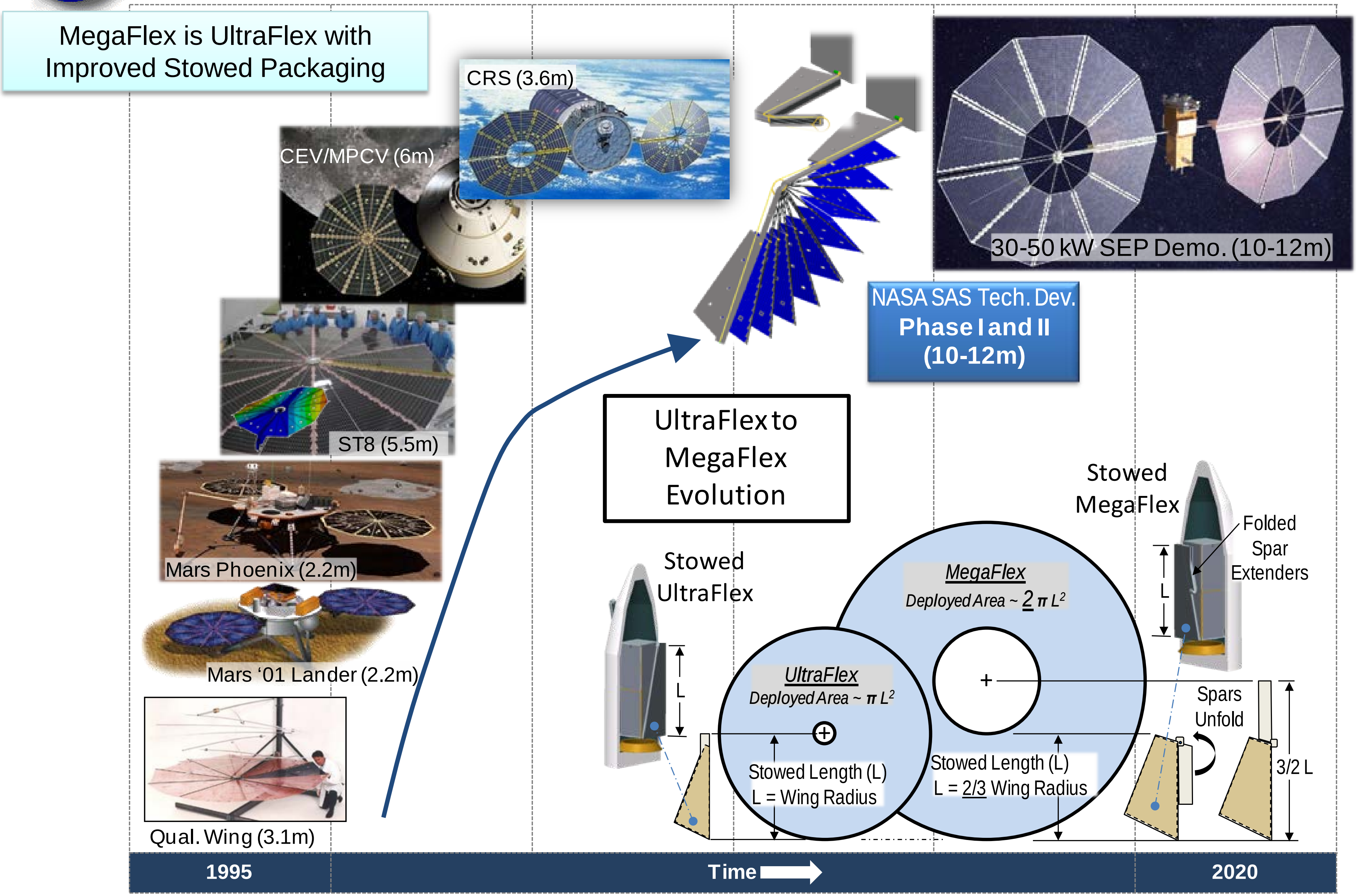
- **Lunar South Pole-Aitken Basin Sample Return & Lunar Geophysical Network**
  - Lower temperature batteries to support lunar night (~14 days) survival & reduce thermal management power
  - Keep-alive power to heat electronics and ascent vehicle propellant
- **Saturn Probe, Comet Surface Sample Return, Trojan Tour & Rendezvous, Io Observer**
  - Qualified light weight deployable arrays (Ultraflex/ROSA) to reduce array mass and stowed volume are being developed under STMD funding
  - Higher efficiency LILT cells to reduce solar array size, mass and volume
  - Lower temperature (-60°C) batteries to enable fully non-nuclear mission

BACK-UP

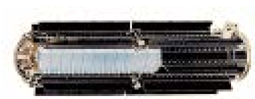
NASA Rechargeable Li/Li-Ion Batteries Projects

2003	2010-2014	2015
		
Li-Ion (SOP)	**Adv. Li-Ion**	**Adv. Li-Ion**
Chemistry: Carbon-$LiNiCoO_2$ Sp. Energy: 80-100 Wh/kg Cycle Life: > 2000 Cycles Operating Temp.: -20 to 40C Status: TRL 9 Heritage : Spirit, Opportunity Phoenix, Curiosity Sponsor: USAF, ARL, NASA-Code R Team: AFRL,JPL, GRC, Yardney	Chemistry: Silicon-$LiNiMnCoAlO_2$ Sp. Energy: 160-180 Wh/kg Cycle Life: > 100 Cycles Operating Temp.: 0 to 40C Status: TRL 4 Potential Applications: EVA Sponsor: NASA STMD Team: JPL, GRC, SAFT, UT	Chemistry: Li-S Sp. Energy: > 300-350 Wh/kg Cycle Life: > 100 Cycles Operating Temp.: -10 to 30C Status: TRL 2/3 Potential Applications: EVA Sponsor: NASA STMD Team: JPL, LIOX, EPI

UltraFlex to MegaFlex Evolution



SOP Technology Capabilities

Technology Element	Capability
Power System	Direct Energy Transfer 0.5 to 20 kW, Shunt Regulator/Radiator 28- 120 V dc
Power Electronics	 22- 120 V dc -55 to 75C, up to a 1Mrad > 85% converter efficiency
Radioisotope Power Sources	 GPHS RTG 4-5 W/kg 6.5 % eff
Solar Cells	  Si cells 9-15% eff, TJ Cells 24-28% *Rigid Panel 30-80 W/kg Flexible Fold Out Array : 40->100 W/kg
Rechargeable Batteries	  Ni-H_2 30-100 Wh/kg >10 years -10 to 30 C

*80 W/kg for rigid achieved with large solar arrays (~20 kW) and 40 w/kG for ISS arrays, which although very large, were built with old cell technology (Si) and with high stiffness/strength requirement

Batteries at Very Low TRL (SBIR)

Three current SBIR efforts all focused on solid state Li batteries, which is a very challenging technology:

- All-Solid, High-Performance Li-Ion Batteries for NASA's Future Science Missions - TH Chem, Inc.
  - In Phase I, THC has demonstrated the feasibility of the new battery technology by preparation of the proposed all-solid-state 3-D batteries via processing of electrode and electrolyte precursors, followed by electrochemical evaluation of the test cells. Phase II efforts will be focused on optimization of materials structures, electrode processing, and prototype cell fabrication and evaluations.

- High Energy Density Solid State Li-Ion Battery with Enhanced Safety - NEI Corporation
  - In Phase I demonstrated the processability of sulfide-based solid electrolytes, so that they can be cast in the form of a thin and flexible tape. The Phase II effort will incorporate the new solid electrolyte in an all-solid pouch cell.

- Ultra High Energy Solid-State Batteries for Next Generation Space Power - Solid Power, Inc.
  - Phase I will demonstrate the feasibility of surpassing 600 Wh/kg and 1000 Wh/L at the cell level which will give a 3-5X improvement over the best battery technologies planned for NASA missions today.