Jet Propulsion Laboratory
California Institute of Technology

Advanced Energy Storage Technologies for Future NASA Planetary Science Missions

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Outline

- Study Overview
- Background
- PSD Mission Needs
- State of Practice of Energy Storage Systems
- Advanced Energy Storage Systems under Development
- Summary of Findings & Recommendations

Study Overview

Background

- Planetary Science Division (PSD) of NASA-SMD requested an assessment of advanced space solar power and energy storage systems that will enable/enhance the capabilities of future Planetary Science Missions (> 2025).
- Solar Power Systems:
  - Solar Cells
  - Solar Arrays
- Energy Storage Systems:
  - Batteries
  - Fuel Cells
  - Capacitors
  - Flywheels

Study Objectives
Energy Storage Technology Assessment

- Review the energy storage system needs of future planetary science missions
- Assess the capabilities and limitations of state of practice energy storage systems to meet the needs of future planetary science missions.
- Assess the status of advanced energy storage technologies currently under development at NASA, DOD, DOE and Industry and assess their potential capabilities and limitations to meet the needs of future planetary science missions.
- Assess the adequacy of on-going technology development programs at NASA, DoD, DOE and Industry to advance energy storage technologies that can meet the needs of future planetary science missions.
- Identify technology gaps and technology programs to meet the needs of future planetary science missions.

Review Team
Energy Storage Technology Assessment

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- Simon Liu, Aerospace
- Chuck Taylor, NASA HQ
- Christopher Iannello, NASA HQ
- Marshall Smart, NASA-JPL

Jet Propulsion Laboratory

Goddard Space Flight Center

Glenn Research Center

NASA -HQ

Presenters

Batteries

- ENERSYS
- Eagle Picher / Yardney Technical Products
- Amprius
- LMA
- Boeing
- SAFT
- University of Maryland
- SKC Power Technologies

Fuel Cells

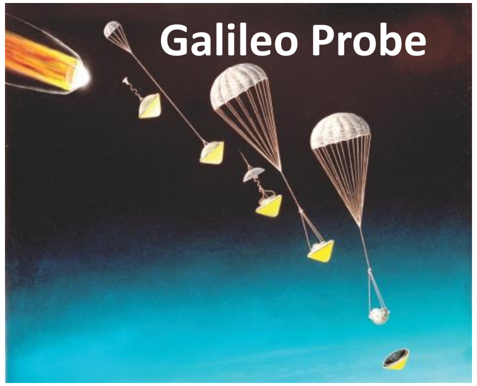
- Giner
- Infinity
- Teledyne
- Proton

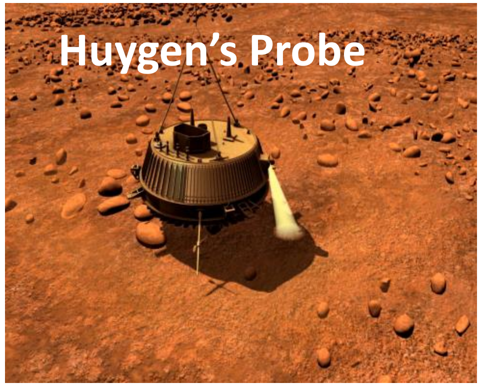
NASA/DOD/DOE

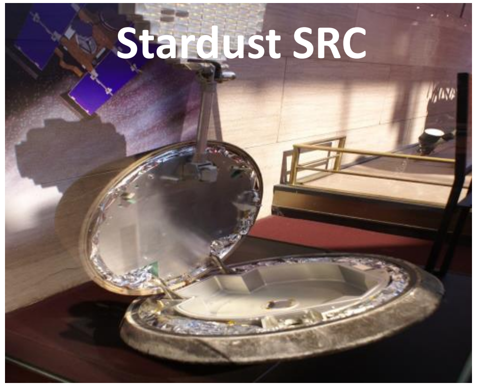
- NASA-GRC
- NASA-JPL
- NASA-GSFC
- Aerospace Corporation
- Navy Research Laboratory (NRL)
- Applied Physics Laboratory (APL)
- DOE

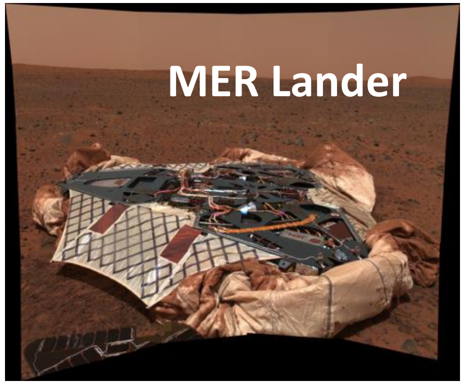
Background

PSD Missions Powered by Primary Batteries

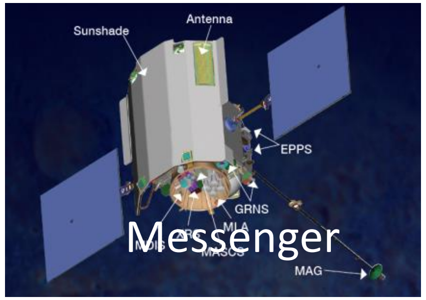


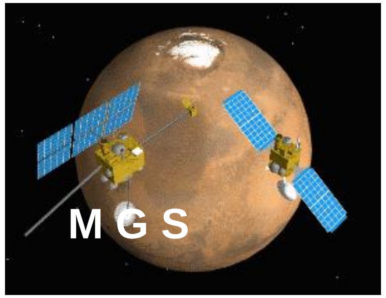


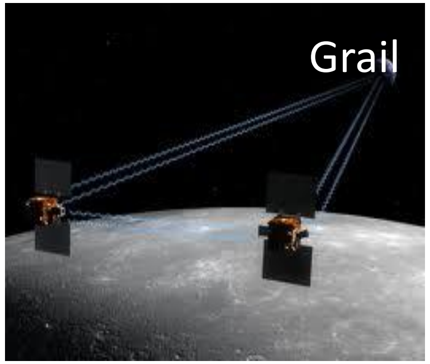


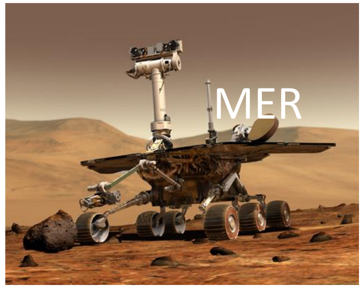


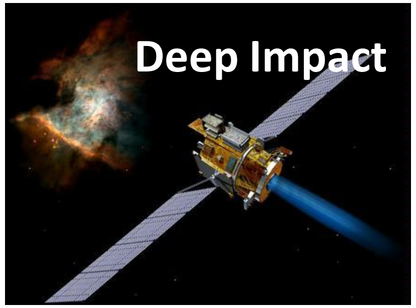
PSD Missions that used Rechargeable Batteries

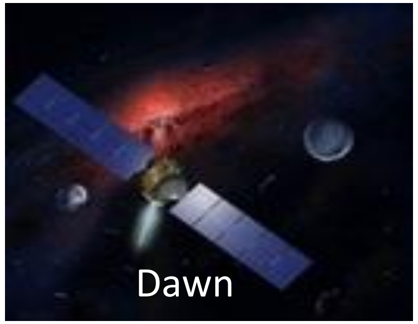


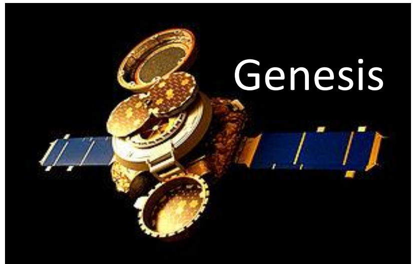


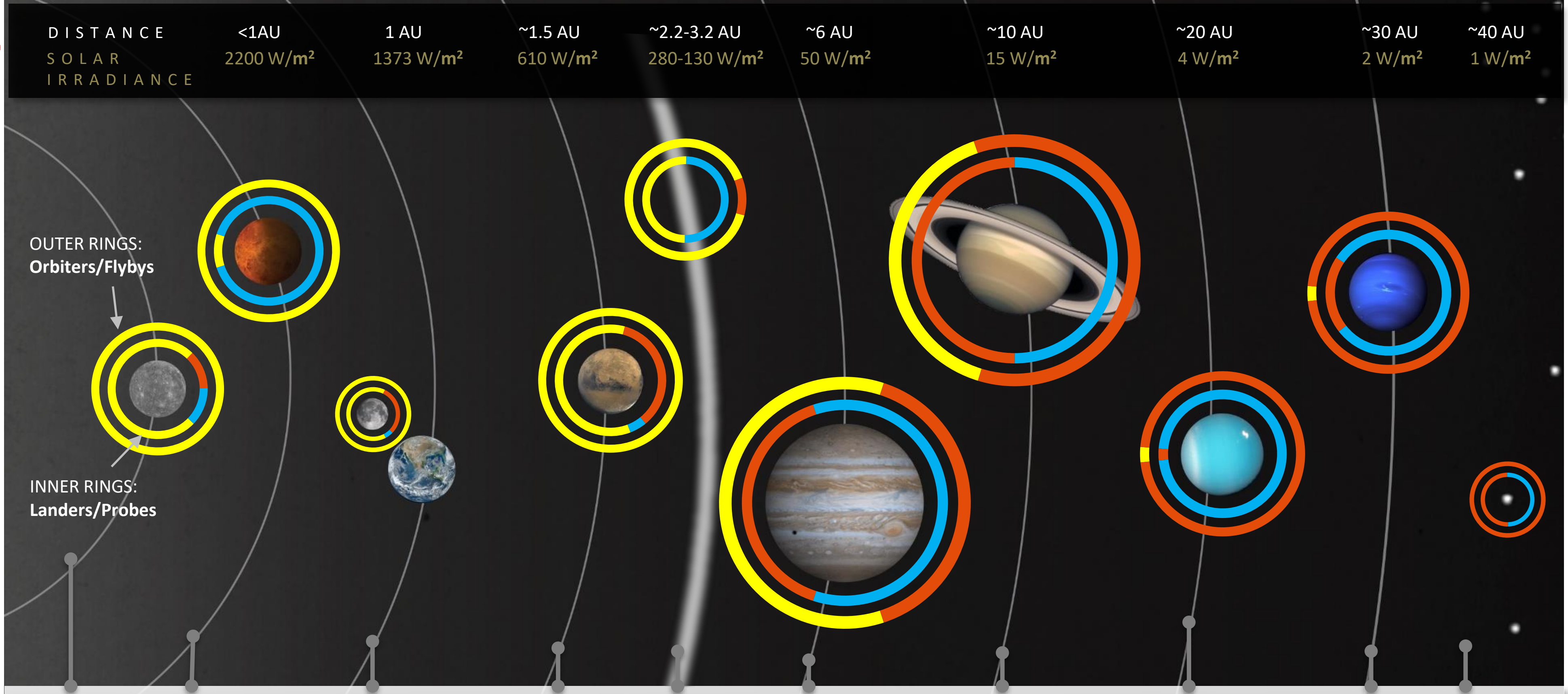












MERCURY

SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Polar Landers
- Long-lived Landers

BATTERIES
- Short-lived Landers

VENUS

SOLAR
- Orbiters
- Upper Atmosphere Probes*
- Surface Probes**

RPS
- Current RPS not operable in Venus surface environment

BATTERIES
- Atmospheric probes
- Surface Missions

MOON

SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Polar Landers
- Long-lived Landers

BATTERIES
- Short-lived Landers

MARS

SOLAR
- Orbiters
- Landers
- Rovers

RPS
- Long-lived Polar Lander
- Long-lived, high capability rovers

BATTERIES
- Short-lived surface missions

ASTEROIDS

SOLAR
- Sample Return
- Flybys/Tours
- Orbiters
- Landers

RPS
- May be necessary for Trojan asteroids

BATTERIES
- Short-lived surface missions

JUPITER

SOLAR
- Orbiters
- Flybys

RPS
- High capability
- orbiters
- Long-lived moon landers

BATTERIES
- Atmospheric Probes
- Short-lived landers

SATURN

SOLAR
- Flyby s/c
- Orbiters

RPS
- High-capability orbiter
- Ring observer
- Titan Montgolfier (MMRTG)
- Long-lived surface mission

BATTERIES
- Atmospheric probes
- Short-lived surface missions

URANUS

SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys
- Moon landers

BATTERIES
- Atmospheric probes

NEPTUNE

SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys
- Long-lived Triton Lander

BATTERIES
- Atmospheric probes

KUIPER BELT

SOLAR
Not likely to be practical

RPS
- Orbiters
- Flybys
- Landers

BATTERIES
- Short-Lived landers

*requires technology development for solar cells in corrosive environment
**requires technology development for high temperature

POWER TECHNOLOGIES APPLICABLE TO SOLAR SYSTEM EXPLORATION MISSION CONCEPTS AS OF 2015[1]

(1) Notional mission applicability based on expert opinion developed in JPL A-Team study in August, 2015. Updated 2017.

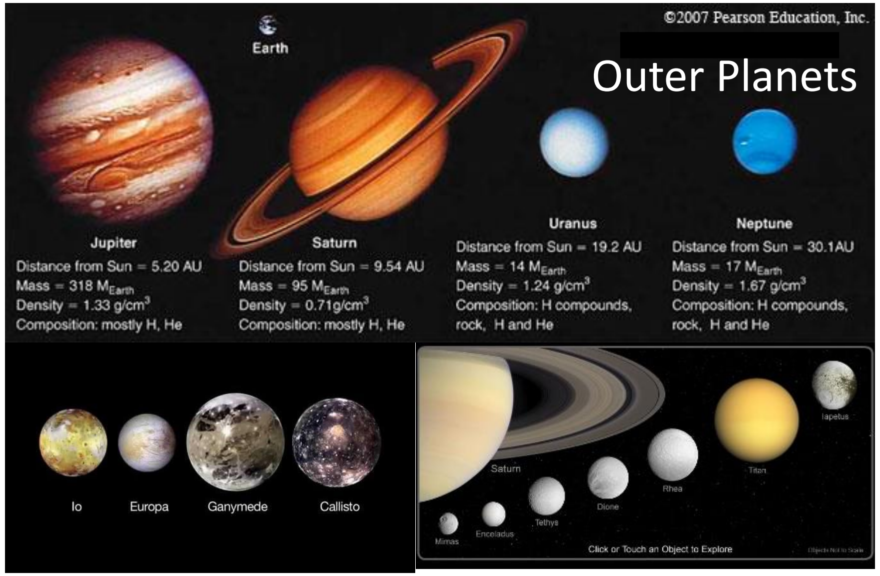
Solar/Rech. Batt
RPS
Primary Battery

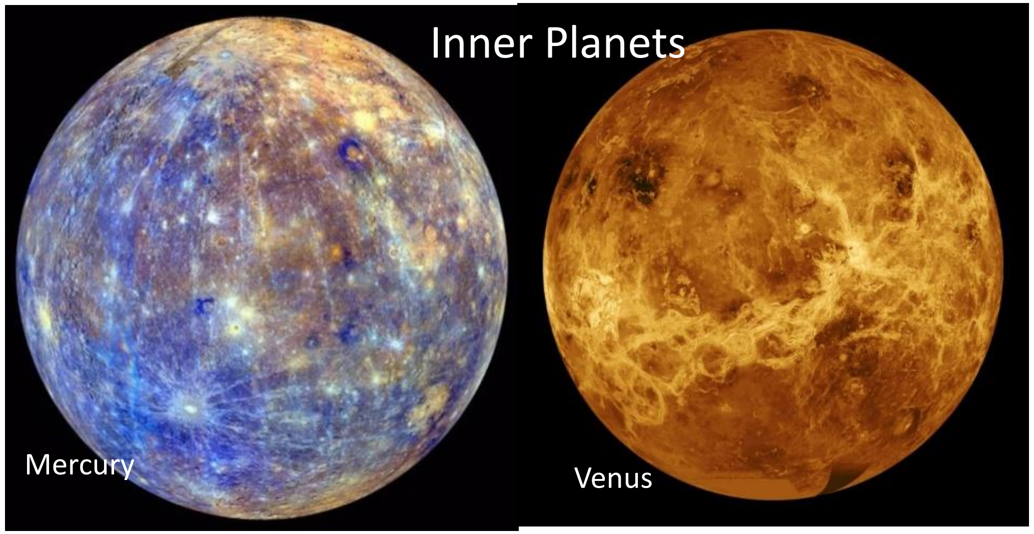
Approximate relative applicability of power technologies to target body missions

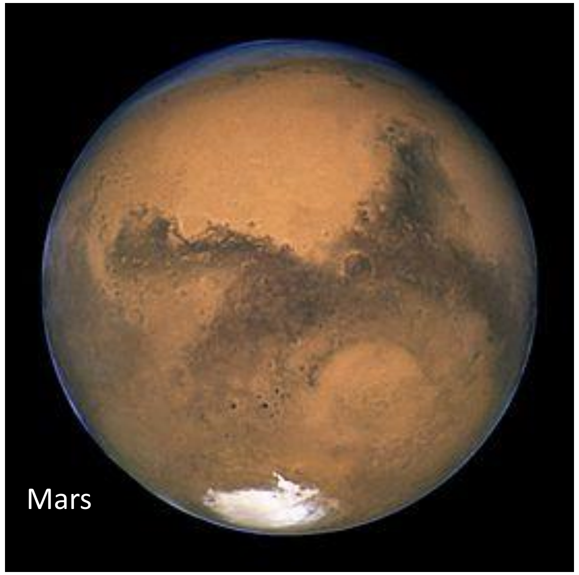
Pre-Decisional Information — For Planning and Discussion Purposes Only

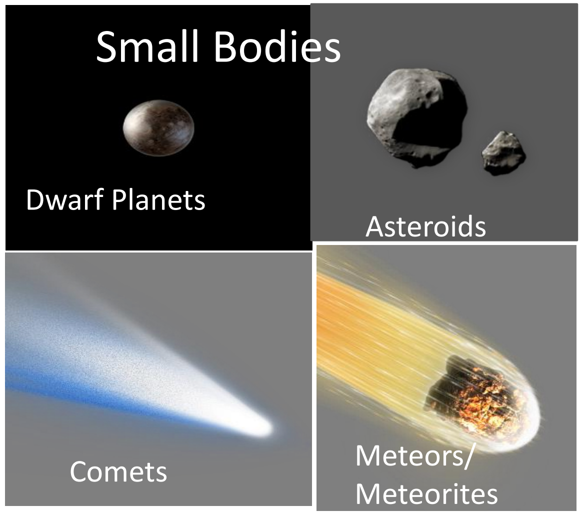
Energy Storage System Needs of Next Decadal Planetary Science Missions

Planetary Science Mission Destinations









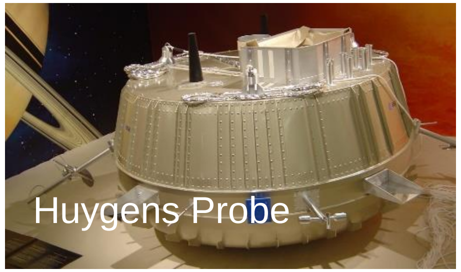
Classification of Planetary Science Missions Based on Mission Type

Flyby (RPS/PV)

Orbiter (RPS/PV & chemical)

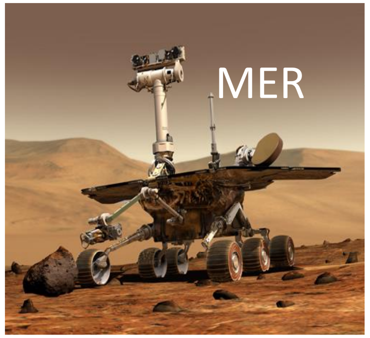
Electric Propulsion
(PV/NEP& Chemical)

Cubesat
(PV & Chemical)



Probes (Chemical)

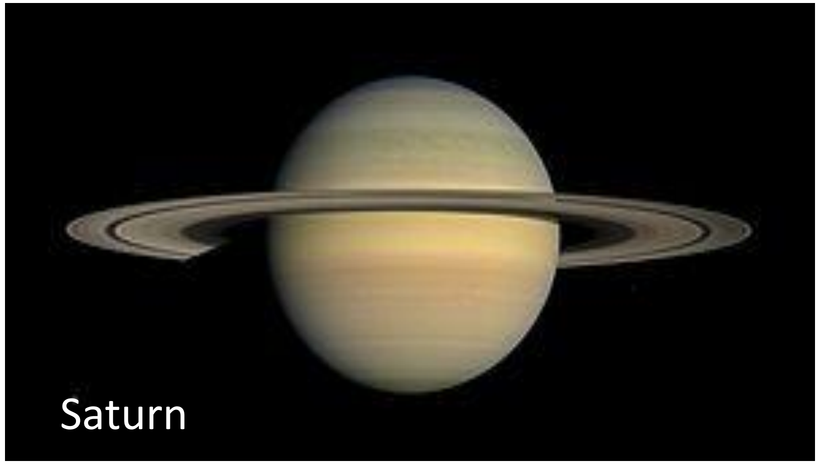
Lander
(PV & Chemical)

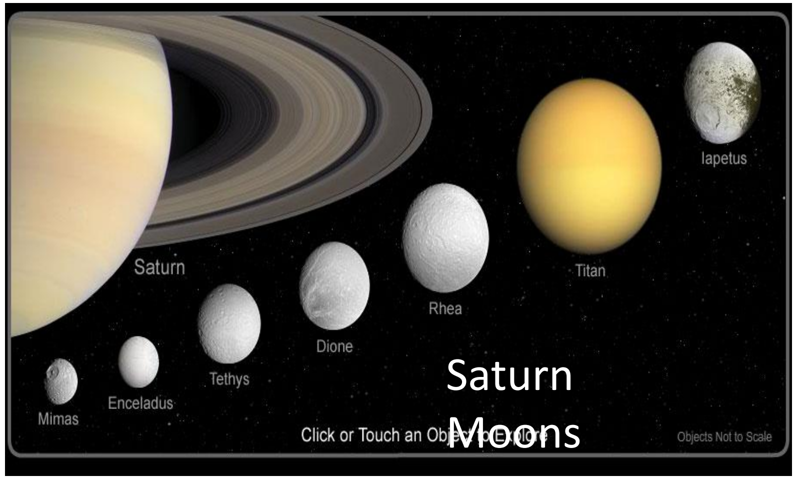


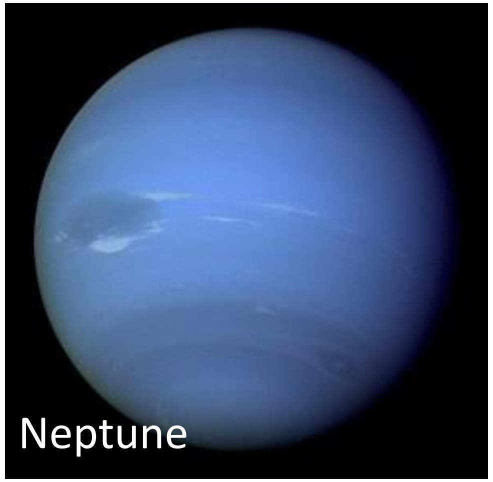
Rover (RPS/PV & Chemical)

Aerial (PV & Chemical)

Outer Planetary Mission Destinations

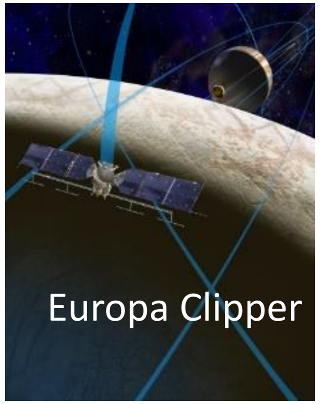


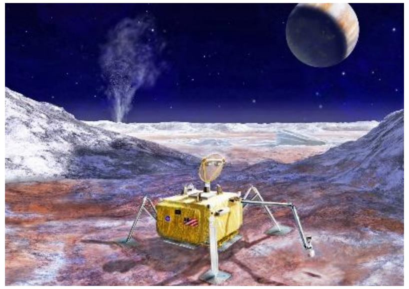




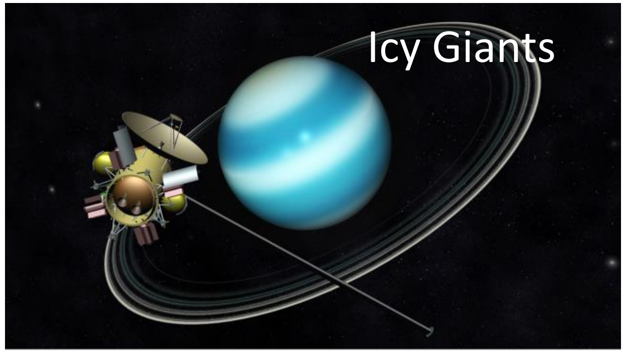
Potential Next Decadal Outer Planet Missions

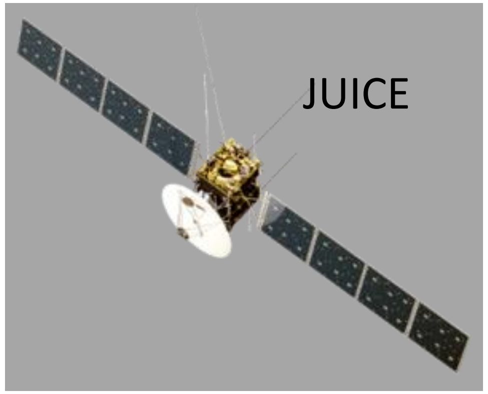
- Ocean Worlds
  - Europa
  - Enceladus
  - Titan
- Icy Giants
  - Uranus
  - Neptune
- Giant Planets
  - Jupiter
  - Saturn





Europa Lander





Artist's Concepts

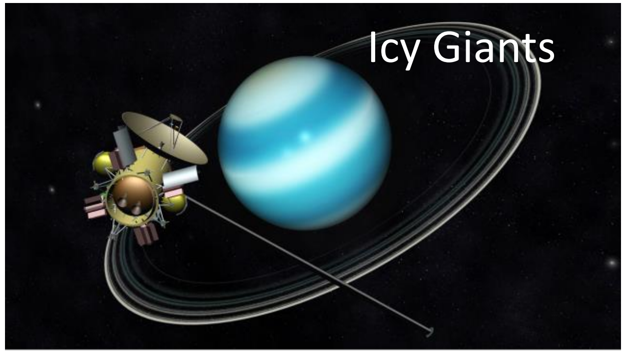
Pre-decisional: for information and discussion purposes only

Energy Storage System Needs for Future Outer Planetary Mission Concepts

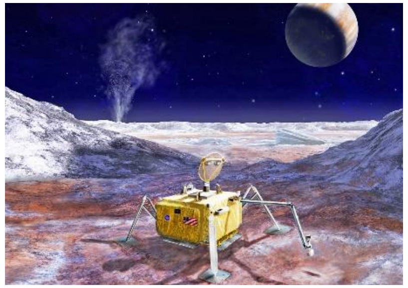
- Primary Batteries/Fuel cells for planetary landers/probes: High Specific Energy (> 500 Wh/kg), Long Life (> 15 years), Radiation Tolerance & Sterilizable by heat or radiation

- Rechargeable Batteries for flyby/orbital missions: High Specific Energy (> 250 Wh/kg), Long Life (> 15 years), Radiation Tolerance & Sterilizable by heat or radiation.

- Low temperature Batteries for Probes and Landers:
  - Low Temperature Primary batteries (< -80C)
  - Low Temperature Rechargeable Batteries (< -60 C)



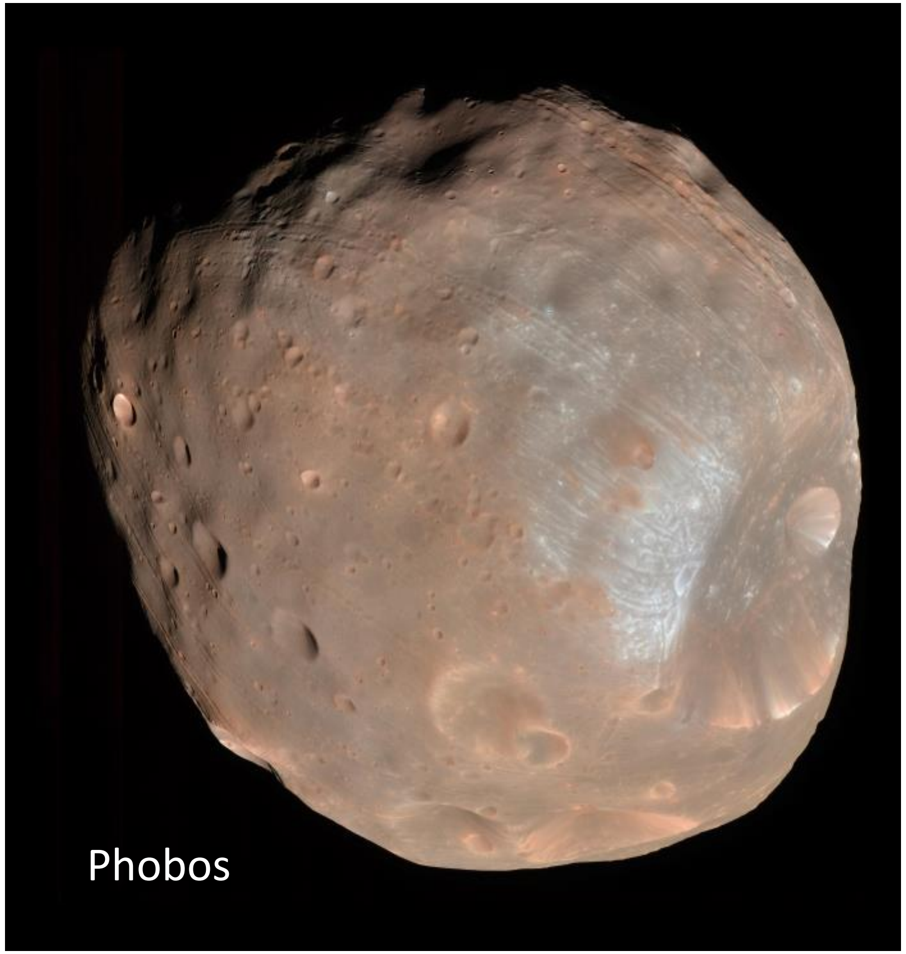
Uranus/Neptune missions



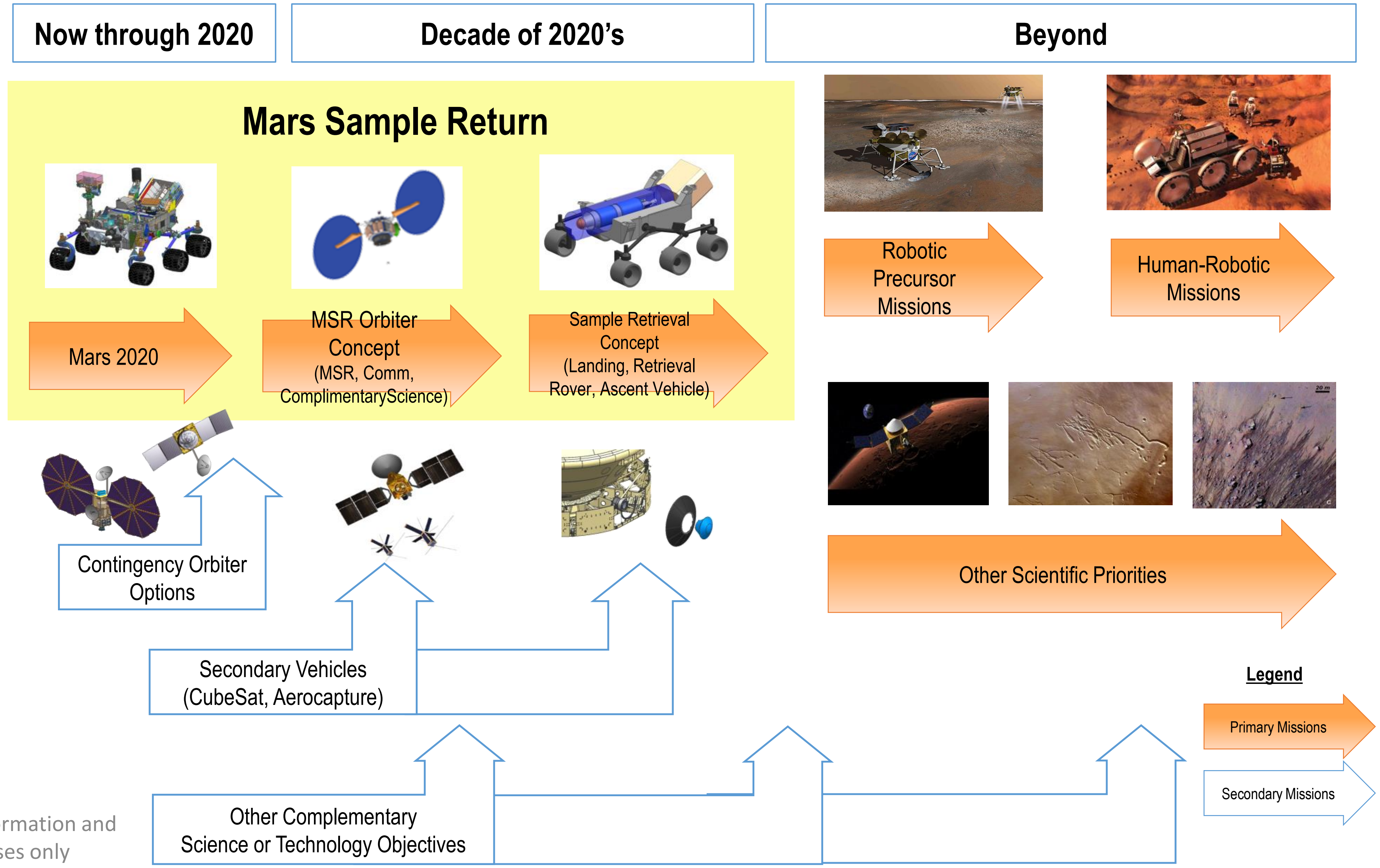
Artist's Concepts

Europa Lander

Mars Mission Destinations

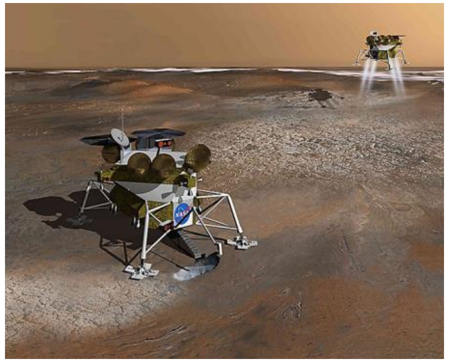


Mars Mission Concepts – 2020s and Beyond

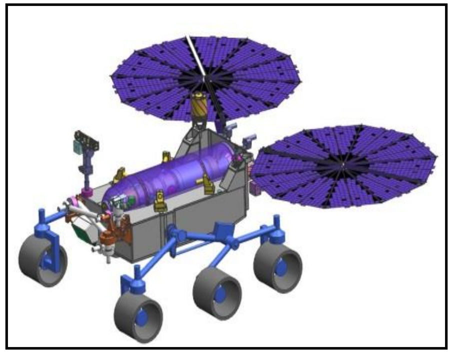


Energy Storage System Needs for Future Mars Mission Concepts

- **Rechargeable Batteries for Orbital Missions:**
  - High Specific Energy (> 250 Wh/kg), Long Life (> 15 years) Long Cycle Life (>50,000 cycles @ 30%DOD),
- **Rechargeable Batteries for Surface Missions:**
  - High Specific Energy (>250 Wh/kg), Low Temperature Operation (-40 C), Long Cycle Life (>3000) , Sterilizable by heat or radiation
- **Rechargeable Batteries for Aerial Missions:**
  - High Specific Energy (>250 Wh/kg), High Power Density (> 3kW/kg), Low Temperature Operation (-40 C)



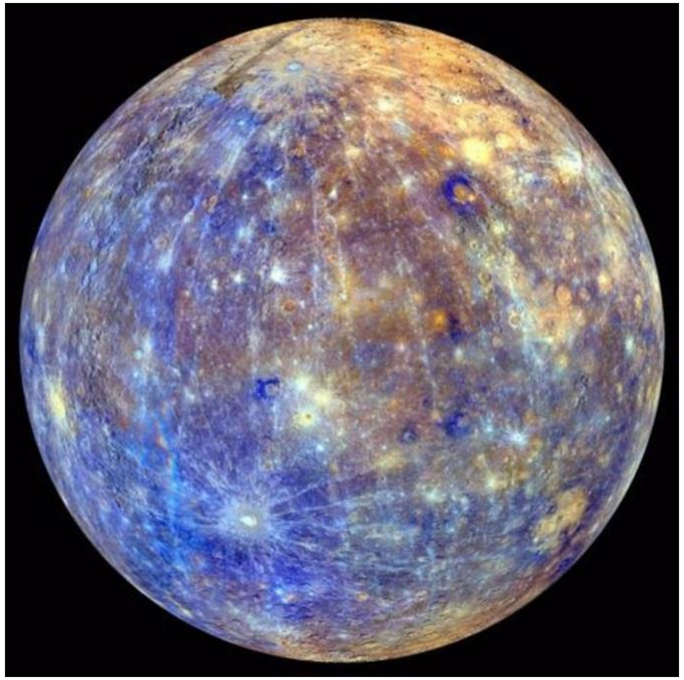
Robotic Precursor Missions



Mars Sample Return Concept

Mars Aerial Vehicle

Inner Planetary Mission Destinations

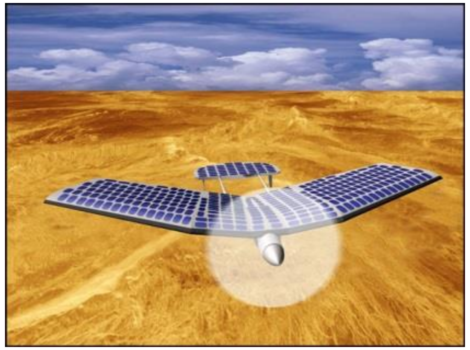


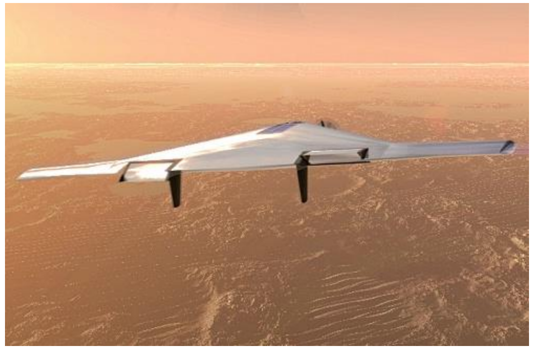
Mercury Solar day 176 Earth days

Venus Solar day 116 Earth days

Potential Venus Mission Concepts

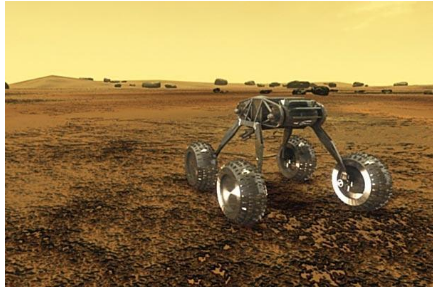
Upper Atmosphere 50 to 70 Km





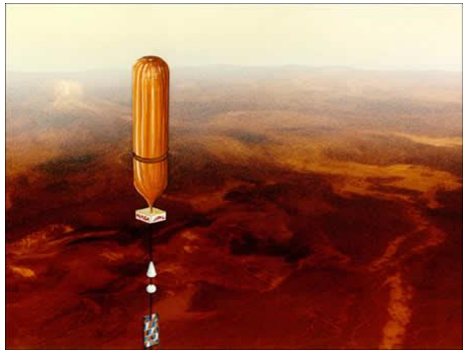
Mid and Lower Atmosphere 50 to 0 Km

Surface

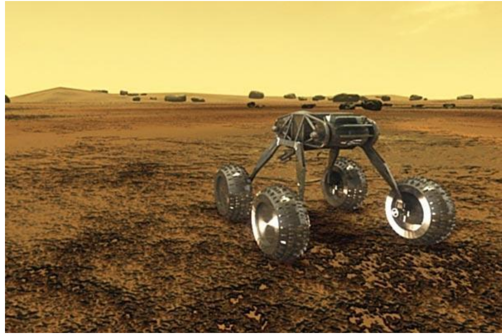


Near Term | Mid Term | Long Term

Energy Storage System Needs for Inner Planetary Mission Concepts

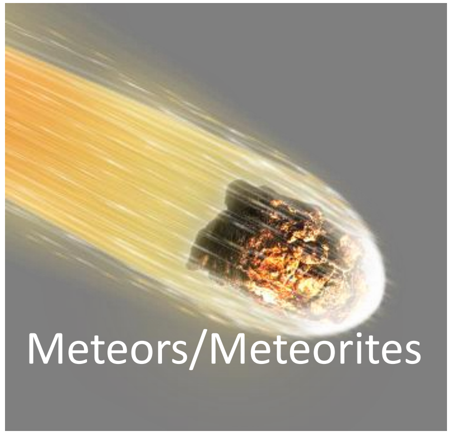


Primary Batteries/Fuel Cells for Surface Probes: High Temperature Operation (> 465C), High Specific Energy (>400 Wh/kg), Operation in Corrosive Environments

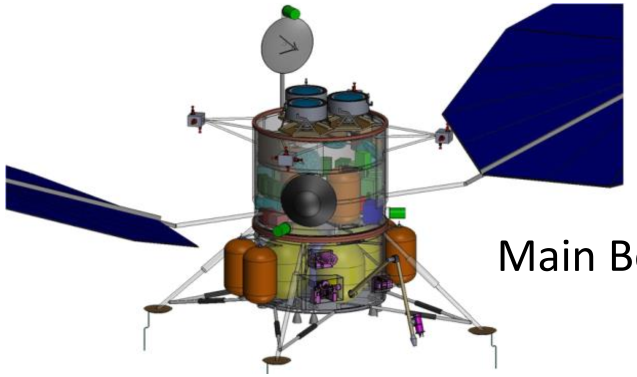
Rechargeable Batteries for Aerial Platforms: High Temperature Operation (300-465C), Operation in Corrosive Environments, Low-Medium Cycle Life, High Specific Energy (>200 Wh/kg), Operation in High Pressures

Small Bodies



Potential Next Decadal Small Body Mission Concepts

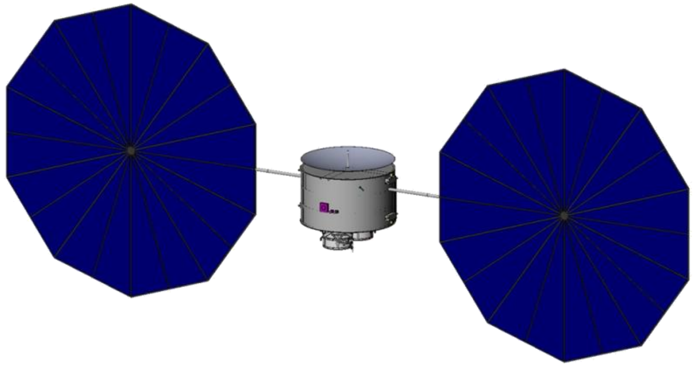
- Flagship Mission:
  - Cryogenic Comet Nucleus Sample Return – explicitly stated in *Vision and Voyages*
- Possible New Frontiers or Discovery
  - Trojan Tour and Rendezvous
  - Follow up to Dawn mission with Ceres **lander**
  - Themis, Hygiea, Pallas of interest after Dawn visiting Vesta and Ceres
  - *Follow-on mission to the Kuiper Belt?*



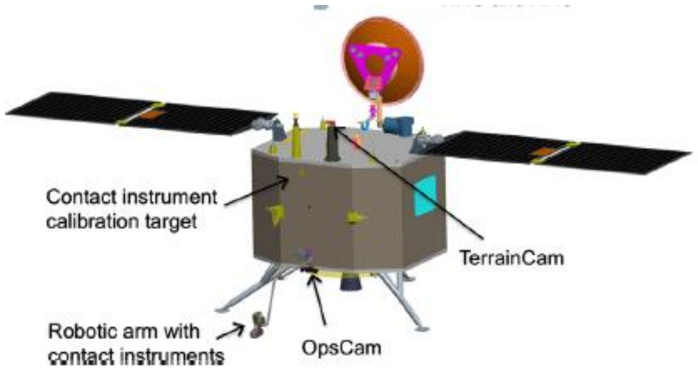
Main Belt Sample Return Mission

Energy Storage System Needs for Future Small Body Mission Concepts

- **Primary Batteries/Fuel cells for Surface Missions**: High Specific Energy (> 500 Wh/kg), Long Life (> 15 years), Radiation Tolerance & Sterilizable by heat or radiation



- **Rechargeable Batteries for Orbital/Flyby Missions:** High Specific Energy (> 250 Wh/kg), Long Life (> 15 years), Long Cycle Life (>50,000 cycles @ 30%DOD),Radiation Tolerance & Sterilizable by heat or radiation



Summary of Energy Storage Technology Needs for Future Planetary Science Missions

- General Needs:
  - Reduced Mass & Volume by >50%
  - Long Life (> 15 years)
  - High reliability
  - Safety
- Mission Specific Needs
  - Outer Planetary Surface Missions: Ultra Low Temperature (< -60^{o}C) Performance, Radiation Survivability, compliance with Planetary Protection Requirements
  - Inner Planetary Aerial/Surface Missions: Survive High Temperature (> 450^{o}C), high pressure, & Corrosive Environments
  - Mars Aerial Missions: Wide Operating Temperature Capability (-60^{o}C to +40^{o}C), High Power Capability, Compliance with Planetary Protection Requirements
  - Orbital Missions: Long Calendar and Cycle Life (>50,000 Cycles)

SOP Energy Storage Systems

SOP Energy Storage Systems

Primary Batteries

Sojourner Battery: Li-$SOCl_2$

MER Lander Battery Li-SO_2

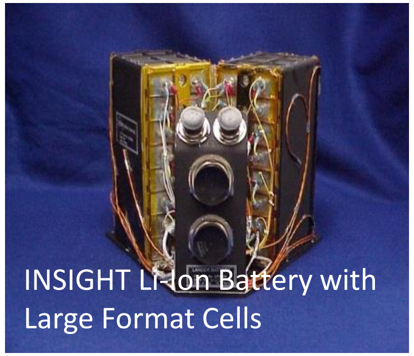
Capacitors

ATC Capacitors for Cassini

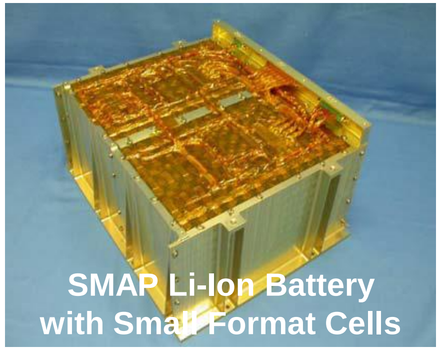
Hybrid Energy Storage System: Battery/Capacitor

Rechargeable Batteries

Odyssey Ni-H_2 Battery

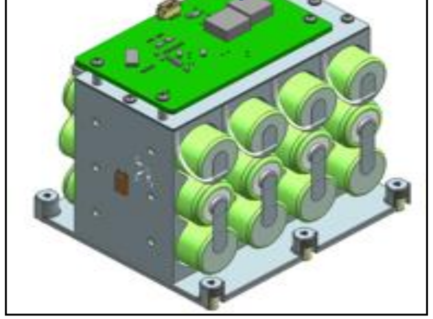


INSIGHT Li-Ion Battery with Large Format Cells

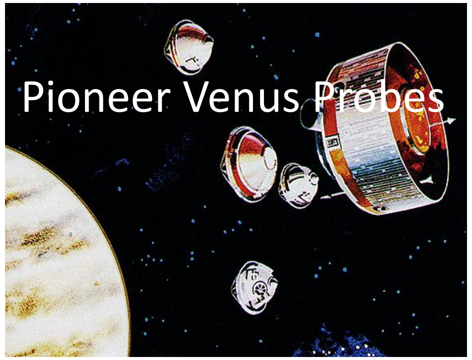


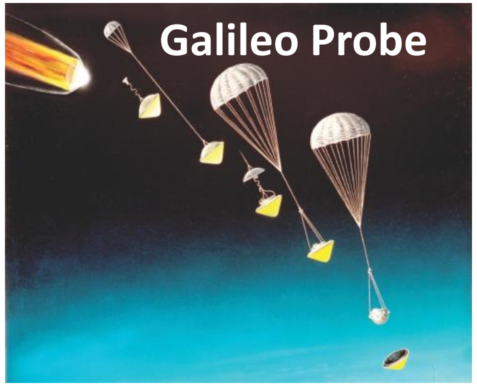
SMAP Li-Ion Battery with Small Format Cells

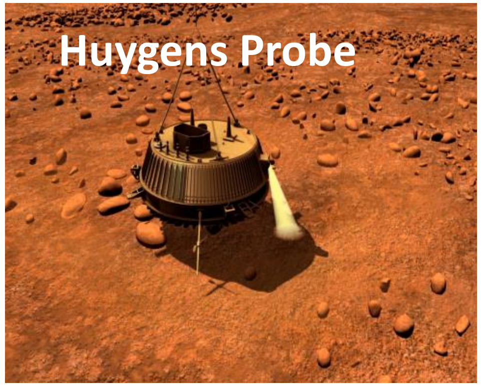
CubeSat Battery

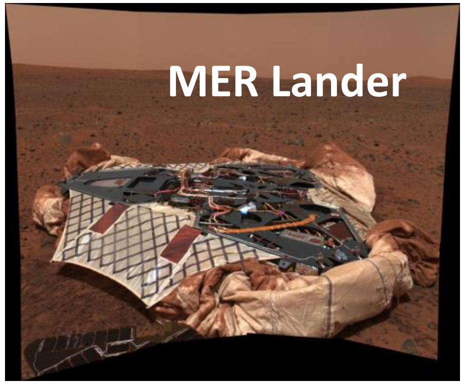


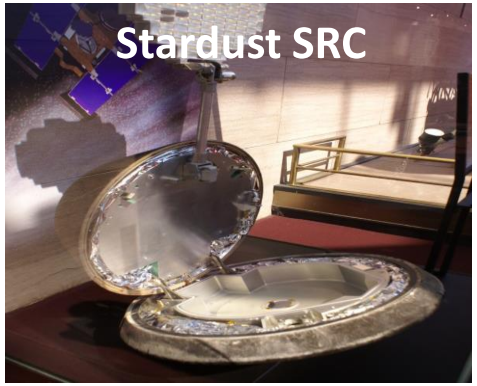
Planetary Missions Powered by Primary Batteries









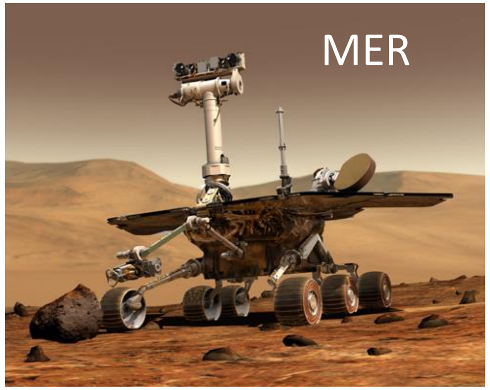


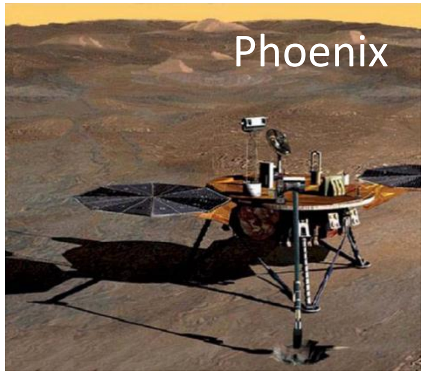
Characteristics Of SOP Primary Batteries Used in Planetary Science Missions

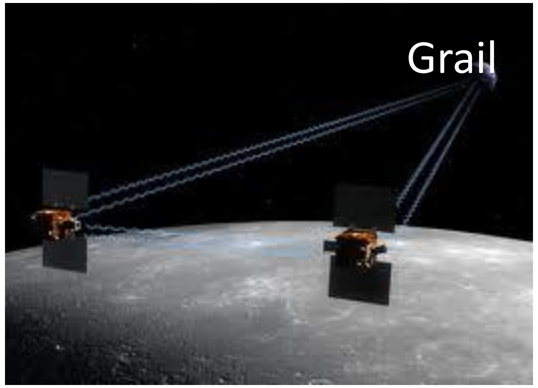
Technology	Mission	Launch Date	Battery Configuration	Manufacturer	Cell Size, or Model	Capacity (Ah)	Operating Voltage Range	Battery Mass (kg)	Specific Energy (Wh/kg)	Operating Temperature Range (^oC)	Calendar Life (Years)
$Li\text{-}SO_2$	**Stardust**	2/7/99	4s2p	Saft America, Inc.	LO26SX	14	8V - 12V	1.2	130	-20^o to 40^oC	9
$Li\text{-}SO_2$	**Genesis**	8/8/01	8s2p	Saft America, Inc.	LO26SX	14	16V - 24V	2.06	150	-20^o to 40^oC	5
$Li\text{-}SO_2$	**MER-Rover**	6/10/03	12s5p	Saft America, Inc.	LO26SX	34	25V - 34V	7.55	155	0^o to 60^oC	3.5
$Li\text{-}SOCl_2$	**Deep Impact**	1/12/05	9s24p	Saft America, Inc.	LSH20	312	24V - 32V	36.6	250	-20^o to 40^oC	4

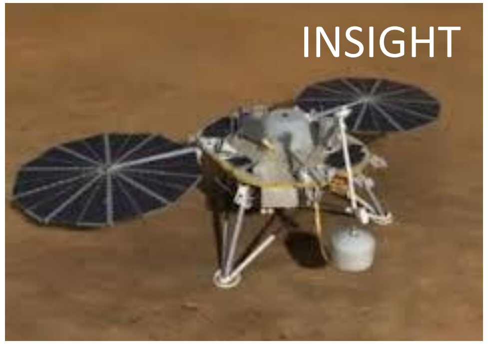
- $Li\text{-}SO_2$ & $Li\text{-}SOCl_2$ batteries continue to be used in various planetary surface missions.
- No major technical advances have happened in these battery technologies over the past decade.
- SAFT America is the only supplier of space-rated $Li\text{-}SO_2$ and $Li\text{-}SOCL_2$ batteries.
- SAFT was acquired by a new French company, (Total Inc.)

PSD Missions Powered by Li-Ion Batteries Based on Large Format Cells









Characteristics Of SOP Li-Ion Rechargeable Batteries

Batteries Based on Large Format Prismatic Cells

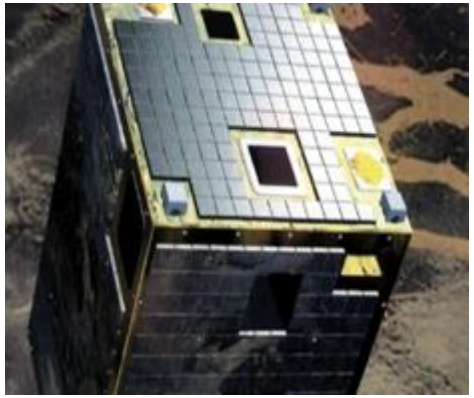
Technology	Mission	Launch Date	Battery Configuration	Manufacturer	Cell Size, or Model	Capacity (Ah) Rated / Actual	Operating Voltage Range	Battery Mass (kg)	Specific Energy (Wh/kg)	Operating Temperature Range (°C)	Calendar Life (Years)	Cycle Life To-Date
Li-Ion	**MER-Rover**	6/10/03	8s2p	Yardney	NCP-8-1	16 / 20	24V - 32.8V	7.1	90	- 20° to 30°C	14	5,000
Li-Ion	**Juno**	8/5/05	8s2p	Yardney	NCP-55-2	110 / 120	24V - 32.8V	34.9	110	15° to 25°C	7	< 50
Li-Ion	**Phoenix**	9/4/07	8s2p	Yardney	NCP-25-1	50 / 62	24V - 32.8V	17.8	105	- 20° to 30°C	4	< 200
Li-Ion	**Grail**	9/10/11	8s1p	Yardney	NCP-25-1	50 / 62	24V - 32.8V	9.3	100	0° to 30°C	3.5	1,500
Li-Ion	**MSL-Rover**	11/26/11	8s2p	Yardney	NCP-43-1	86 / 92	24V - 32.8V	26.5	104	- 20° to 30°C	7	> 1500

Limitations of SOP Li-ion batteries:

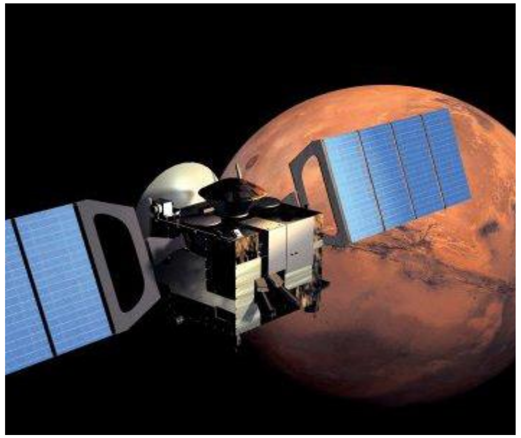
- Heavy and bulky
- Limited operating temperature range (-20°C to 40°C)

PSD Missions Powered by Li-Ion Batteries Based on Small Format Cells

PROBA (2001)

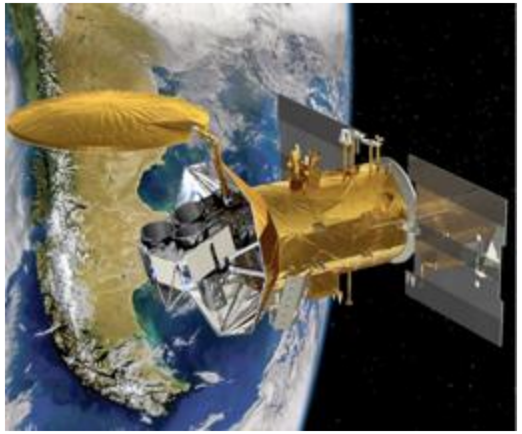


Mars Express (2003)

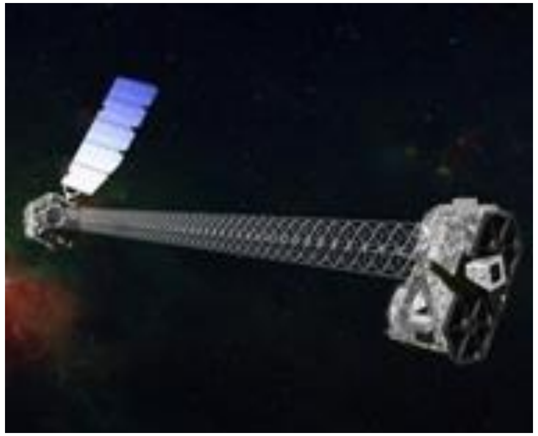


Kepler (2009)

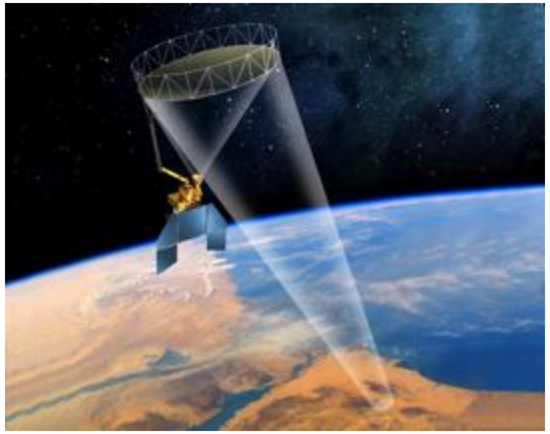
Aquarius (2011)



NuSTAR (2012)



SMAP (2014)



Characteristics Of SOP Li-Ion Rechargeable Batteries

Batteries Based on Small Format Li-ion Cells (18650)

Mission	Launch Date	Battery Configuration	Manufacturer	Cell Size, or Model	Capacity (Ah) Rated / Actual	Operating Voltage Range	Battery Mass (kg)	Specific Energy (Wh/kg)	Operating Temperature Range (°C)	Calendar Life (Years)	Cycle Life To-Date
Kepler	3/6/09	8s16p	ABSL	Sony 18650	24 / 20	25V - 33.4V	6.5	90	- 10° to 45°C	6	< 2,500
Aquarius	6/10/11	4 x 8s20p	ABSL	Sony 18650	30 / 28	24V - 33.6V	4 x 8.5	95	- 10° to 40°C	7.5	~ 6,500
SMAP	1/31/15	8s52p	Enersys/ABSL	Sony 18650	78 / 54	24V - 32.8V	20.40	80	10° to 25°C	4.3	< 1,000
SMAP (LVA)	1/31/15	3 x 8s10p	Enersys/ABSL	Sony 18650	45 / 32	24V - 32.8V	3 x 4.15	75	0° to 35°C	4.3	< 1,000

Limitations of SOP Li-ion batteries:

- Heavy and bulky
- Limited operating temperature range (-20°C to 40°C)
- Limited cycle and calendar life.

SOP Capabilities vs Future PSD Mission Needs

Technology	Capability Required	SOP Technology Capability
Low Temperature Primary Batteries	<-80 C Operation, Radiation Tolerance (~20 M Rads)	> -40 C
High Temperature Primary Batteries	> 450 C Operation,	< 70^{o} C
High Specific Energy Primary Batteries	> 500 Wh/kg, 1000 Wh/l	150-250 Wh/kg, 350 Wh/l
Long Calendar Life Rechargeable Batteries	> 15 years, 250 Wh/kg, Radiation Tolerance	10 years, 100 Wh/kg
Long Cycle Life Rechargeable Batteries	> 50 K cycles @ 30% DOD > 250 Wh/kg at 100% DoD	> 40 K cycles @ 30% DOD > 100 Wh/kg at 100% DoD
Low Temperature Rechargeable Batteries	< -60 C operation,	< -20^{o} C

- Future planetary science missions require energy storage technologies that are mass and volume efficient have long life and operate under extreme environments.
- SOP aerospace batteries are heavy, bulky and have limited operational capabilities at extreme environments

Advanced Energy Storage Technologies

Advanced Energy Storage Technologies Under Development-Overview

- Primary Batteries
  - Li-CFX Batteries
  - Li-CFx/MnO2 Batteries
  - Li-O2 batteries
- Rechargeable Batteries
  - Advanced Li-Ion batteries
  - Li-Solid state Batteries
  - Li-Polymer Batteries
  - Li-Sulfur Batteries
- High Temperature Batteries
  - Li-FeS2 Thermal Batteries
  - Na-S/Na-MCL2 Rechargeable Batteries
- Capacitors
  - Supercapacitors
- Fuel Cells
  - PEM Fuel Cells
  - Solid oxide Fuel Cells
  - Regenerative Fuel Cells

Advanced Primary Batteries

Rayovac Li-CFX D cell

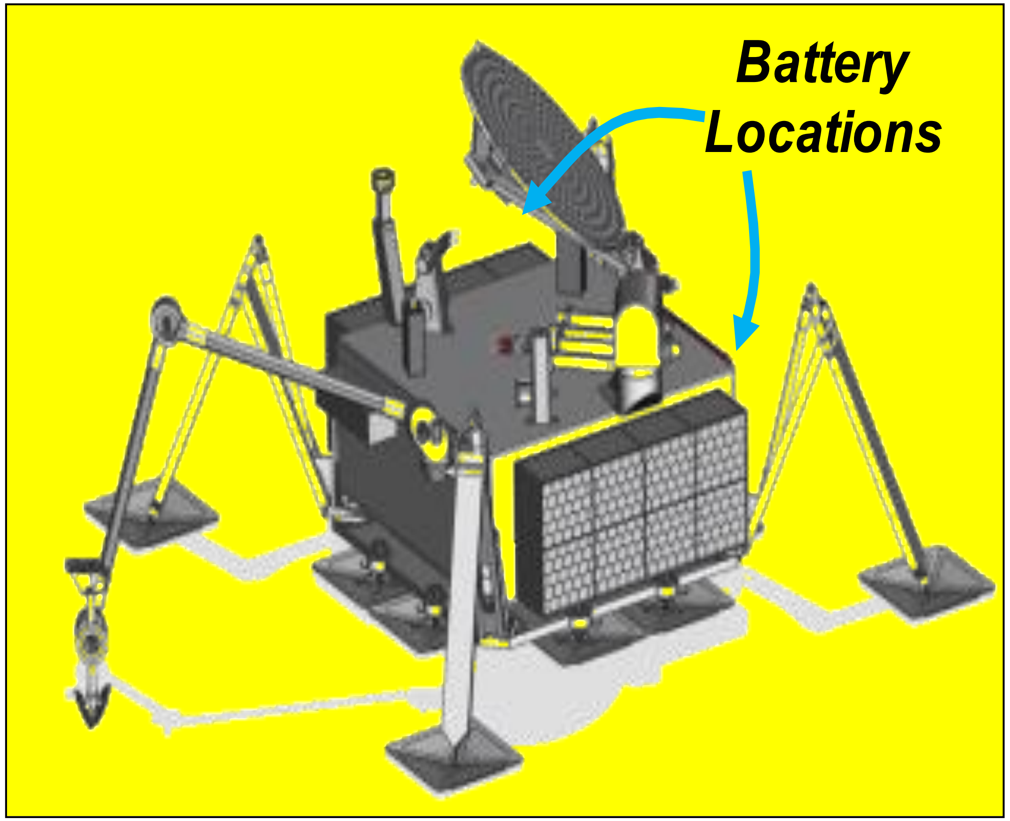
Li-CFx/MnO2 Batteries

Li-O2 batteries

Battery Level	SOP	Adv. Li-CF_x	Adv. Li-CF_xMnO	Adv. Li-O_2	
Specific Energy (Wh/kg)	150-250	400-500	350-450	500-600	
Energy Density (Wh/L)	250-400	600-800	550-600	700-800	
Shelf life (Years)	>10	>10	>10	5	
Operating Temperature	-40 to +60^{o}C	-30 to +60^{o}C	-40 to +60^{o}C	-20 to +60^{o}C	
TRL	9	4	4	3	

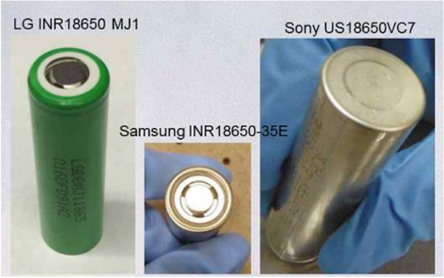
LI-CF$_X$ Batteries

- Li-CFX batteries were found to meet Europa Lander concept mission requirements
  - Battery Configuration: 8S38P
  - DD cells
  - 500 Wh/kg at the battery level
  - 730 Whr/Kg at the cell level
  - Significant battery self heating keeps battery and vault warm
  - Low power: ~50 mA/cell
  - High power: ~600 mA/cell
  - Battery temperature 0 to +60^{o}C
  - 90 kg battery mass allocation

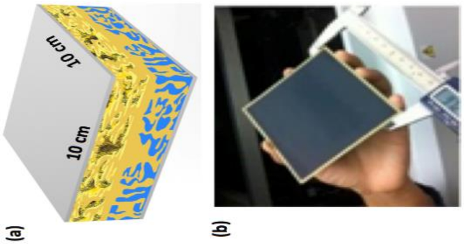


Europa Lander Concept

Advanced Rechargeable Batteries



~260 Wh/kg and >700 Wh/l 18650 cells (some with Si on the anode)

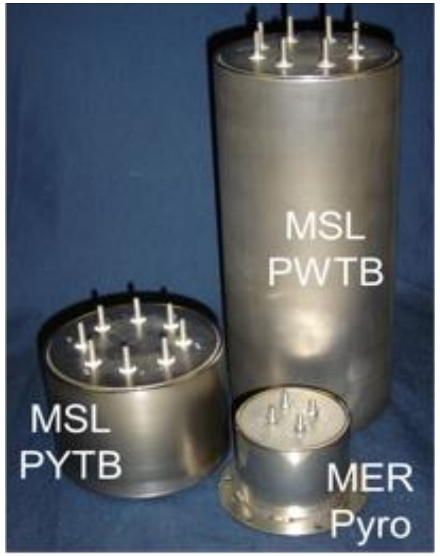


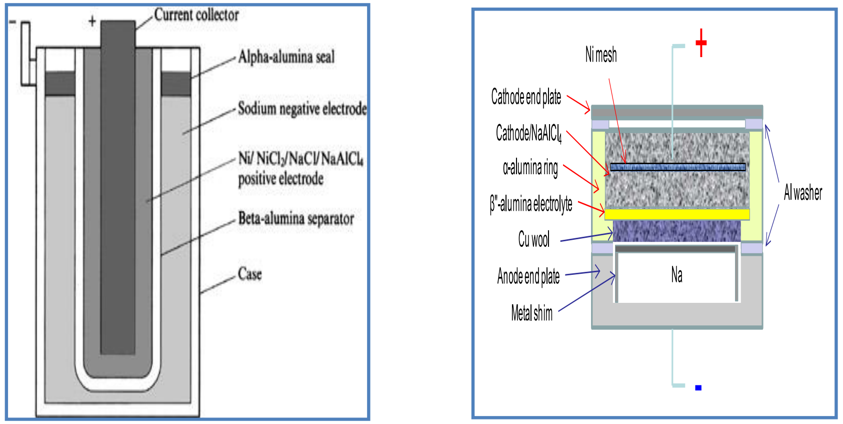
Li-Solid State Cells

Li-S Cells

Battery Level	SOP Li-ion	Adv. Li-Ion	Adv. Solid State	Advanced Li-S
Specific Energy (Wh/kg)	90-110	> 150	250-350	**250-300**
Energy Density (Wh/L)	150	200-300	400-500	**300-350**
Cycle Life (100% DOD)	~2,000	> 50,000	>10,000	**100-500**
Calendar Life (Years)	5-10	>20	>20	**< 5**
Operating Temperature	**-20 to +30°C**	**-10 to +25°C**	**10 to +80°C**	**-30 to +30°C**
TRL		**4**	**2-3**	**3**

High Temperature Batteries





Sodium-Nickel Chloride batteries

Battery Level	SOP Primary	Primary Li-FeS_2
Specific Energy (Wh/kg)	150-250	> 100
Energy Density (Wh/L)	250-350	200
Shelf life (Years)	>10	Reserve Design
Operating Temperature	-40 to +60ºC	350 to +450ºC

Battery Level	SOP	HT Rechargeable
Specific Energy (Wh/kg)	90-110	100
Energy Density (Wh/L)	150	150
Cycle Life	~2000	~1000
Shelf life (Years)	>10	5
Operating Temperature	-40 to +60ºC	250 to +400ºC

Capacitors

Metric	Supercapacitors	Li-Ion Capacitors	Advanced
Voltage	3	3.5	4
Maximum Capacity (F)	>3000	>3000	>3000
ESR (mΩ)	0.28	0.5	0.5
Specific Energy (Wh/kg)	6	14	20
Specific Power (kW/kg)	>15	15	>15
Calendar Life	>10	>10	>10
Cycle Life	10^6	10^6	10^6
Operating Temperature	-40 to +60°C	-20 to +60°C	-100 to +150°C

Fuel Cells:
Proton Exchange Membrane (PEM) Fuel Cells

Technology Status:

- Significant work by NASA and DOD (Navy, Air Force, MDA) to develop hydrogen-oxygen fuel cells. Prototype hardware passed vibration load testing at EUS flight qualification levels*
- Department of Energy (DOE) focus is on the development of hydrogen-air fuel cells (not applicable to NASA SMD).

Advantages:

- High specific energy (>500 Wh/kg at the system level)
- Heat can be used for thermal management
- Options for operating hydrogen from propellants and *in situ* resources
- Potential for compatibility with DHMR planetary protection protocols, and radiation tolerance

Mission Applications

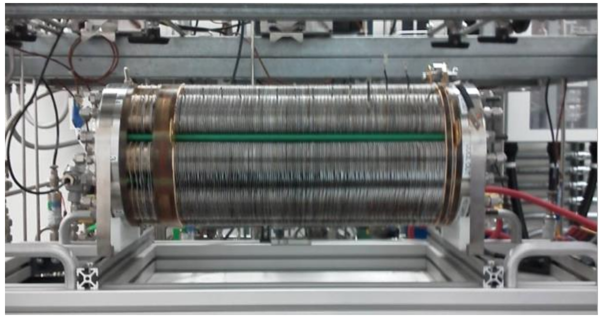
- Long duration (>1 month) outer planets/Ocean Worlds landers

Technical Issues to address

- Reducing balance of plant (mass/power/volume/ complexity)
- Demonstrate long life operation

Active Players

- Infinity, Teledyne, ElectroChem, Giner



Infinity NFT stack

Teledyne stack

Potential Capabilities

Metric	PEM
Stack power density (W/kg)	>100
MEA voltage efficiency (200 mA/cm²)	72%
System Efficiency	65%
Maintenance Free Operating Life (hours)	10,000

AMPS NFT fuel cell power module during field demonstration

* Stack pressurized with inert gas during vibration testing

Fuel Cells
Regenerative Fuel Cell (RFC)

Technology Status

- Aerospace applications include load balancing in hybrid electric aircraft (Boeing) and large airships (Lockheed-Martin)
- Few air-independent systems demonstrated; mainly lab-scale demonstrations
- System designs highly application-specific
- TRL 2-3 at system level (TRL 4-5: Demonstrated at stack level)

Advantages:

- Can be coupled with ISRU and propellant loops (oxygen, hydrogen, water)
- Waste heat can be used for thermal management
- Potential for compatibility with DHMR planetary protection protocols, and radiation tolerance

Mission Applications

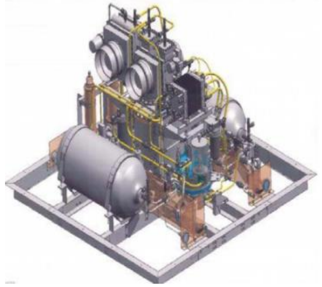
- Human surface power (Lunar, Mars)
- Large mobility systems

Technical Issues to address

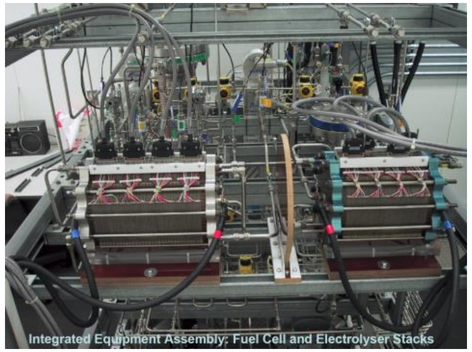
- Reduced balance-of-plant complexity, mass and volume
- Increased round-trip efficiency

Active Players

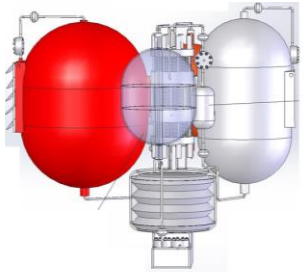
- **Fuel Cells:** Giner, Infinity, Proton, NASA, JAXA
- **Electrolyzers:** Giner, Proton, Sustainable Innovations
- **Systems:** Proton OnSite, JAXA



JAXA RFC used on Boeing demonstration



RFC test bed demonstration at NASA Glenn



Conceptual design of a compact RFC for rover systems

Decoupled RFC demonstration at JPL Mars Yard (fuel cell on ATHLETE + remote hydrogen refueling station)

Modular RFC concept for human surface operations

Advanced Energy Storage Technology
Summary of Findings

- Energy storage technology is continuing to evolve
  - Several advanced primary (Li-CFX, Li-CFx-MnO2) and rechargeable batteries (advanced Li-Ion, Li-solid state, Li-S), fuel cells (PEM) and capacitors (super capacitors) are being developed by DoD, DOE and universities.
  - The major performance drivers are : higher specific energy and higher energy density and low cost.
  - The present major pull for advanced energy storage technologies is consumer electronics and electric vehicles.
- Significant improvement in energy storage performance is envisioned
  - Primary Batteries: Li-CFX (400-450 Wh/kg), Li-CFx-MnO2 (350-450 Wh/kg)
  - Rechargeable Batteries: Li-Ion (125-150 Wh/kg), Li-solid state (250-350 Wh/kg) , Li-S (250-350 Wh/kg)
  - Fuel Cells: PEM Fuel Cells (500 Wh/kg)
  - Capacitors:
- The biggest technology investments are mostly from DoE and DOD
  - Currently there is limited or no NASA funding in this area
- NASA needs to work with DOD and DOE to advance and tailor advanced energy storage technologies for future planetary science missions
  - To improve reliability and life
  - Improve operational capability in extreme environments

Missions Needs & Candidate Advanced Energy Storage Technologies

Driving Mission Concepts	Capabilities Needed	Candidate Technologies
All flyby & orbital Missions	High specific energy (250 Wh/kg) long life & radiation tolerant rechargeable batteries (> 15 years)	Adv. Li-Ion Batteries Li-solid state batteries
Outer Planet Surface Missions	High specific energy Primary batteries and fuel cells	Adv. Li-CFx batteries Adv. Li-CFx/MnO2 batteries PEM fuel cells
Inner planet surface missions	High temperature primary batteries (455 C) with high specific energy (250 Wh/kg)	Li-MS_2 batteries
Mars Surface Missions	Low temperature rechargeable batteries (-60 C)	Low temperature Li-Ion batteries
Outer Planet Aerial and Surface Missions	High temperature rechargeable batteries (475 C) with high specific energy (150 Wh/kg)	Adv. Li-CFx batteries Adv. Li-CFx/MnO2 batteries PEM fuel cells

Summary of Findings & Recommendations

Overall Recommendations

- Make *targeted* investments in specific energy storage technologies that will enable and enhance the capabilities for next generation/decadal planetary science mission concepts.
- Establish and maintain partnerships with HOEMD and STMD and/or other government agencies such as DoE and DoD (AFRL and ARL) to leverage/tailor the development of advanced energy technologies future planetary science mission concepts.
- Upgrade the existing infrastructure and resources for energy storage technology development, testing and qualification at various NASA Centers as needed to support future planetary science mission concepts.

Specific Recommendations

- Even though some of the requirements are common with the DoE and DoD needs, many of them are different due to the unique PSD environments. Therefore, NASA PSD needs to undertake its own technology program, while leveraging the DoE and DoD efforts. Specifically, PSD should advance and/or continue to develop:
  - High specific energy (~250 Wh/kg) and long life (50,000 cycles and 15 years) *rechargeable* batteries required for future orbital mission concepts.
  - High specific energy *rechargeable* batteries (>250 Wh/kg @RT) with low temperature operational capability (150 Wh/kg @<−40°C) required for future planetary surface mission concepts.
  - High specific energy *primary* batteries and/or *primary fuel cells* (>500 Wh/kg) required for outer planetary probes and Ocean World landers.
  - High specific energy *primary* batteries (>500 Wh/kg@RT) with low temperature operational capability (300 Wh/kg @<−60°C) required for future planetary outer planetary probes and Ocean World landers.
  - High temperature (460°C) *primary and rechargeable* batteries required for Venus surface mission concepts.

Key Findings

- Next decadal planetary science mission concepts have unique energy storage system needs
  - Low temperature batteries (primary(<-80^{o}C) and rechargeable (<-60^{o}C) batteries) for planetary probes and Mars surface missions
  - High temperature batteries (> 475^{o}C) for inner planetary missions
  - Long calendar life (>15 years), high specific energy (>250 Wh/kg) & radiation tolerant rechargeable batteries for outer planetary missions
  - High specific energy (>250 Wh/kg) and Long cycle life (>50,000 cycles) rechargeable batteries for Mars and planetary orbital missions
  - High specific energy primary batteries (>600 Wh/kg) for planetary probes
- SOP batteries are not attractive to meet the unique needs of future planetary science missions.
  - Limited life (5-10 years)
  - Limited operating temperature range (-20oC)
  - Radiation tolerance poorly understood
  - Heavy and bulky (100 Wh/kg for rechargeable, 250 Wh/kg for primary batteries)
- Several changes are happening in Li-Ion Battery industry. Implications of these changes on future NASA missions is uncertain
  - Yardney, the supplier of large format Li-Ion cells/batteries was acquired by Eagle Pitcher Industries. It is not known if Eagle Pitcher will continue to offer these products
  - ABSL , the supplier of small formal Li-Ion cells/batteries was acquired by ENERSY and the heritage Sony HC cells have been discontinued.
- Advanced energy storage systems are under development at several companies and universities with support from DOD and DOE funding
  - Primary Batteries: Li-CFX (400-450 Wh/kg), Li-CFx-MnO2 (350-450 Wh/kg)
  - Rechargeable Batteries: Li-Ion (125-150 Wh/kg), Li-solid state (250-350 Wh/kg) , Li-S (250-350 Wh/kg)
  - Fuel Cells: PEM Fuel Cells (500 Wh/kg)
  - Capacitors:

Acknowledgements

This work presented here was carried out at the Jet Propulsion Laboratory, California Institute of Technology under a contract with National Aeronautics and Space Administration.

Backup