Jet Propulsion Laboratory
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Advanced Energy Storage Technologies for Future NASA Planetary Science Mission Concepts

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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

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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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

Overview of Energy Storage Technologies

- **Primary Batteries**
  - One discharge only. Non-rechargeable
  - Examples: Ag-Zn, Li-SO_2, Li-$SOCl_2$
  - Galileo & Cassini Probes

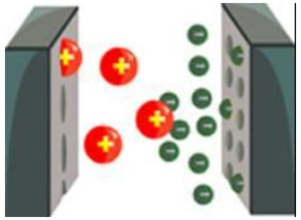
- **Rechargeable Batteries**
  - Can be recharged electrically many times
  - Examples: Ni-Cd, Ni-H_2, Li-Ion
  - MER Rovers, Curiosity Rover, JUNO

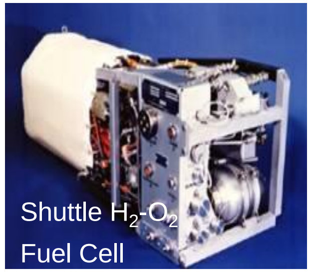
- **Capacitors**
  - Provide high power in short pulses
  - Examples: Film, Double layer, Supercapacitors
  - Galileo & Cassini

- **Fuel Cells (Primary and Secondary)**
  - Energy producing chemicals are stored separately
  - Suitable for very long discharge times
  - Examples: H_2-O_2 (Alkaline, PEM, Regenerative)

MER Li-SO_2 Battery


Odyssey Ni-H_2 Battery


Supercapacitor schematic


Shuttle H_2-O_2 Fuel Cell

Key Performance Characteristics of Energy Storage Technologies

- **Energy Storage Capability**
  - Specific Energy (Wh/kg)
  - Energy Density (Wh/l)
- **Power Capability**
  - Specific Power (W/kg)
- **Efficiency**
  - Charge/Discharge Energy Efficiency (%)
- **Life Performance**
  - Cycle Life (Cycles@ % DOD)
  - Calendar Life (Years)
  - Operational Life (Years)
- **Operational Temperature**
  - Low Temperature Performance (^{o}C)
  - High Temperature Performance (^{o}C)
- **Charge Retention**
  - Capacity Loss (%/month)
- **Radiation Tolerance**

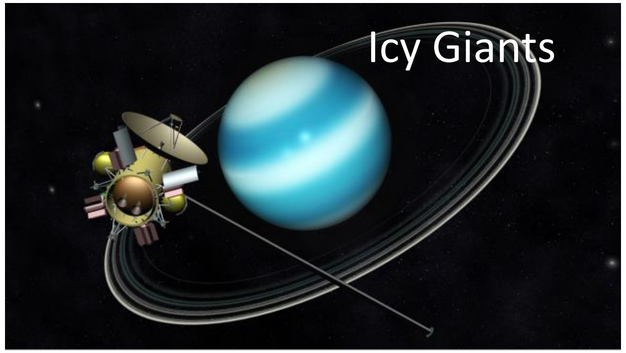
Energy Storage System Needs of Next Decadal Outer Planetary Science Mission Concepts

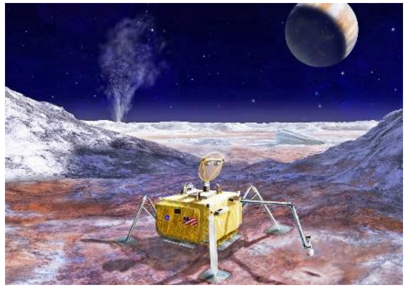
Energy Storage Technology Challenges for Outer Planetary Science Mission Concepts

- Low Temperature Operational Capability (<- 60C for surface missions)
- High Radiation (4 MRad) (Jupiter System Missions)
- Heat/Radiation Sterilization Endurance (Lander missions)
- Low Mass (~ 3X lower than SOP)
- Low Volume (~ 3X lower than SOP)
- Long Operational Life (> 15 years)
- High Reliability

Energy Storage System Needs for Future Outer Planetary Mission Concepts

- Outer Planet orbital/flyby mission concepts require advanced rechargeable batteries with
  - Long calendar life (>15 years),
  - High specific energy (>250 wh/kg),
  - Compliant with planetary protection requirements (certain missions).
- Ocean World landers require advanced primary batteries or primary fuel cells with
  - High specific energy (primary: >500 wh/kg), long calendar life (>15 years),
  - Low self-discharge rate (<0.1%/year),
  - Radiation tolerance, and be
  - Compliant with planetary protection requirements.
- Outer planetary atmospheric probes would benefit significantly with the use of advanced primary batteries with
  - Long calendar life (>15 years),
  - High specific energy (>500 wh/kg),
  - Radiation tolerance (jupiter),
  - Compliant with planetary protection requirements.





Artist's Concepts

Europa Lander

SOP Energy Storage Systems

SOP Energy Storage Systems

Primary Batteries

Sojourner Battery: Li-$SOCl_2$

MER Lander Battery Li-SO_2

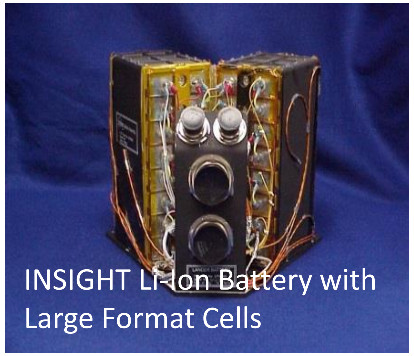
Capacitors

ATC Capacitors for Cassini

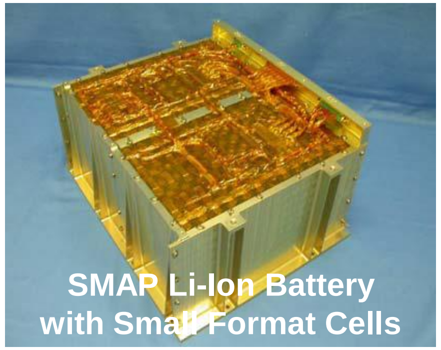
Hybrid Energy Storage System: Battery/Capacitor

Rechargeable Batteries

Odyssey Ni-H_2 Battery

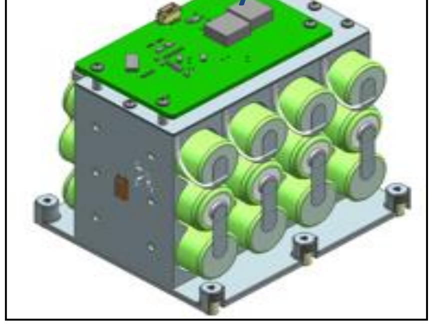


INSIGHT Li-Ion Battery with Large Format Cells



SMAP Li-Ion Battery with Small Format Cells

CubeSat Battery

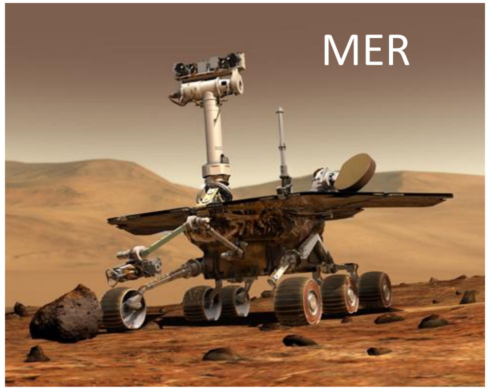


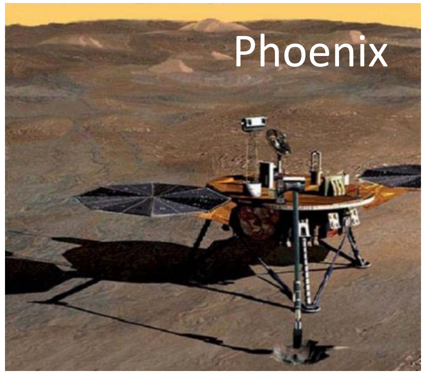
Characteristics Of SOP Primary Batteries Used in PSD Missions

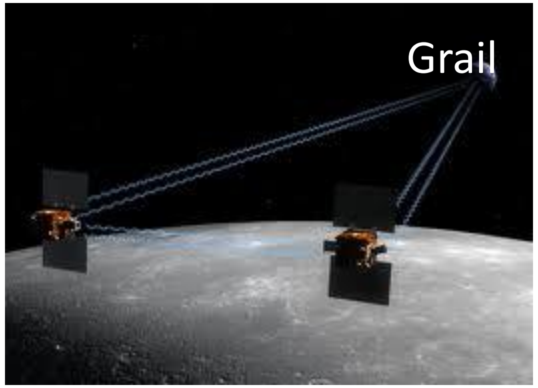
Technology	Mission	Launch Date	Battery Configuration	Manufacturer	Cell Size, or Model	Capacity (Ah)	Operating Voltage Range	Battery Mass (kg)	Specific Energy (Wh/kg)	Operating Temperature Range (^{o}C)	Calendar Life (Years)
$Li\text{-}SO_2$	**Stardust**	2/7/99	4s2p	Saft America, Inc.	LO26SX	14	8V - 12V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

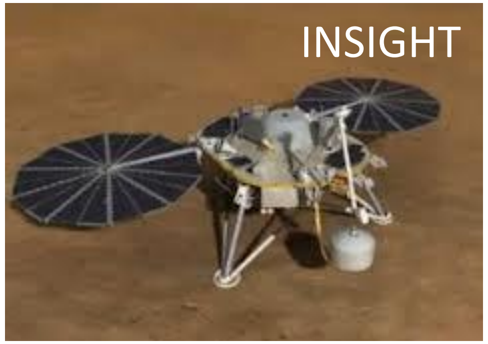
- $Li\text{-}SO_2$ & $Li\text{-}SOCl_2$ batteries continue to be used in various planetary surface missions.
- No major technical advances have happened in these battery technologies over the past decade.
- SAFT America is the only supplier of space-rated $Li\text{-}SO_2$ and $Li\text{-}SOCL_2$ batteries.
- 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)
- Limited cycle and calendar life.

State of the Practice 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 Primary Batteries

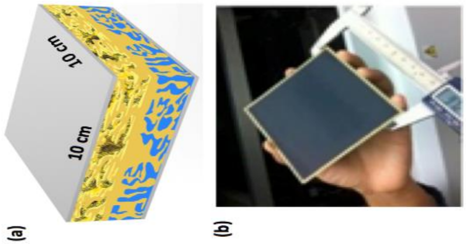
Rayovac Li-CFX D cell

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°C	-30 to +60°C	-40 to +60°C	-20 to +60°C	
TRL	9	4	4	3	

Advanced Rechargeable Batteries



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**

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

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

Key Findings

- Next decadal planetary science mission concepts have unique energy storage system needs
  - Low temperature batteries (primary(<-80°C) and rechargeable (<-60°C) batteries) for planetary probes and Mars surface 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.
- 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

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 to meet its future planetary science mission needs.
- 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 missions.

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.

Acknowledgements

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