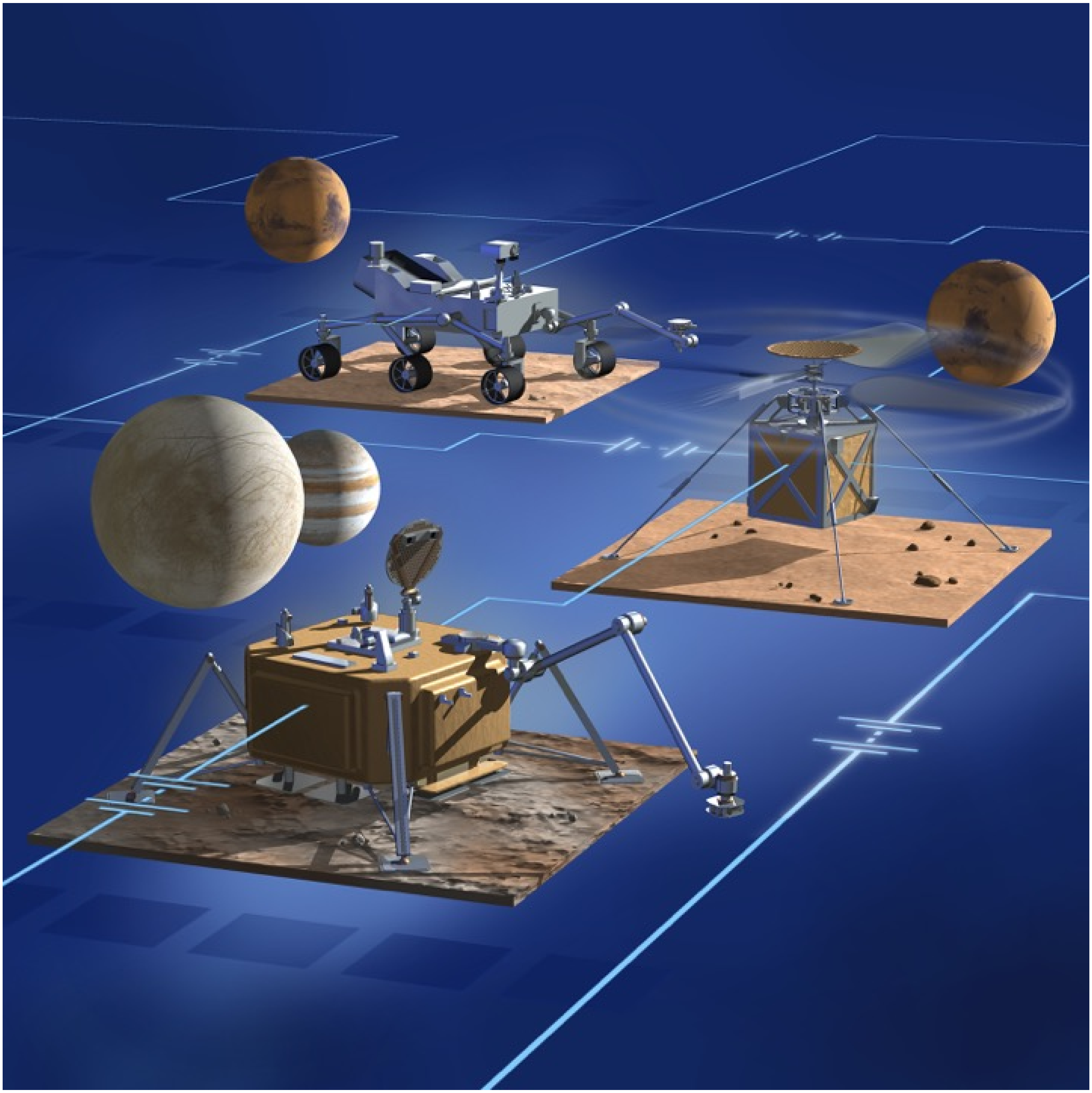

Energy Storage Technologies for Future Planetary Science Missions

December 2017

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
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Pasadena, California

Energy Storage Technologies for Future Planetary Science Missions

Strategic Missions and Advanced Concepts Office
Solar System Exploration Directorate
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for
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Foreword

Future planetary exploration priorities envisioned by the National Research Council's (NRC's) *Vision and Voyages for Planetary Science in the Decade 2013–2022*,[1] developed at the request of the NASA Planetary Science Division (PSD), seek to reach targets of broad scientific interest across the solar system. Power systems are required for all of these mission concepts, but which power system is optimal for a particular potential mission depends on the mission's scientific and operational needs and, in some cases, constraints imposed by NASA. Radioisotope Power Systems (RPS) are extremely important option for many planetary mission types, particularly to the outer reaches of the solar system and beyond. Solar power is used for the majority of planetary spacecraft but *all* missions carry some form of energy storage, be it batteries, capacitors or perhaps, in the future, fuel cells. Thanks, in part, to the Department of Defense (DoD), Department of Energy (DoE), and commercial and aerospace companies that are investing in energy storage for a wide variety of applications, there is a lot of research activity and investment. However, the *extreme* environments of many planetary missions are far more demanding than those on Earth or in near-Earth applications and thus energy storage components and subsystems require considerable evaluation, adaptation and testing for those applications. Currently, many planetary mission concept architectures and designs are constrained by the energy storage systems especially with respect to lifetime, thermal management and, in the case of some landers, mass. Investment by NASA could help alleviate the constraints and lead to lower cost missions. This report is intended to provide a basis for understanding the state of the practice in planetary missions, assess the status and potential capabilities of advanced energy storage systems under development, and to recommend a path forward for NASA PSD.

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[1] National Research Council, "Vision and Voyages for Planetary Science in the Decade 2013-2022," The National Academies Press, Washington, DC (2011). https://solarsystem.nasa.gov/docs/131171.pdf

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Table of Contents

List of Tables

List of Figures

Executive Summary

Background

Since the launch of Explorer in 1958, energy storage devices have been used in all of robotic spacecraft either as a *primary* source of electrical power or for storing electrical energy. The three main devices are primary batteries, rechargeable batteries, and capacitors. In addition, fuel cells are used in human space missions, but so far have not been useful for robotic missions. Primary batteries are typically used in missions that require a single use of electrical power for a period of a few minutes to several hours and in some cases days. Such missions include launch vehicles, planetary probes, and sample return capsules. Rechargeable batteries are used mainly in solar-powered missions to provide electrical power during eclipse periods and for load leveling. Rechargeable batteries are also used in in radioisotope-powered missions for load leveling. Capacitors were used in earlier radioisotope-powered missions and are also used on the Pluto-New Horizons mission for applications that required repeated high-power pulses for short durations (seconds).

The NASA Planetary Science Division (PSD) is considering a number of ambitious missions to a variety of destinations in our solar system, including outer planets, inner planets, Mars, and small bodies, and requested an assessment of the space energy storage systems required to enable/enhance the capabilities of future planetary science missions (>2025).

Study Overview

The specific objectives of this assessment are: a) review the energy storage system needs of future/next decadal planetary science mission concepts, b) assess the capabilities and limitations of state of practice energy storage systems, c) assess the status of advanced energy storage technologies currently under development and their potential capabilities and limitations, and d) identify and recommend candidate energy storage system technologies required for future planetary science missions.

The assessment team consisted of subject matter experts in the areas of mission planning, spacecraft power systems engineering, and space energy storage system technologies. The team members were selected from NASA (HQ, Jet Propulsion Laboratory, Glenn Research Center, Langley Research Center, and Goddard Space Flight Center), Aerospace Corporation, Johns-Hopkins University-Applied Physics Laboratory, DoD, and in industry. The assessment team held four meetings with the energy storage technologists from academia, national laboratories and industry to: a) obtain information about potential next decadal planetary science missions and their energy storage system needs, b) determine the capabilities of state-of-practice (SOP) space energy storage systems, c) assess the status and potential capabilities of advanced energy storage systems under development at various national laboratories, industry, and universities, and d) summarize the findings and compile the recommendations.

Major Findings

Energy Storage System Needs of Future Mission Concepts

The assessment team met with mission formulation study leads and power system engineers from JPL, GSFC, Marshall Space Flight Center (MSFC), and JHU-APL to identify potential planetary science missions that were either identified in the most recent decadal survey, *Vision and Voyages*,[1] and/or could be considered for implementation in the next decade and determine their energy storage system needs. The National Research Council has not yet initiated the next planetary science decadal survey (2023–2032) for NASA, and although some mission concepts will change, the *types* of missions will likely not change significantly. The next decadal planetary science mission concepts are grouped into four categories: a) outer planets, b) inner planets, c) Mars, and d) small bodies. The major findings of the assessment team on the energy storage system needs of these four groups of planetary science mission concepts are described below and summarized in Table 1.

Table 1. Energy storage technology needs for future planetary science mission concepts

Mission Destination	Mission Type	Energy Storage Type		Energy Parameters		Life Parameters		Environmental Parameters			Planetary Protection
		Primary	Rechargeable	High Specific Energy Wh/kg	High Specific Power W/kg	Long Calendar Life (yrs)	Long Cycle Life	High Temp. °C	Low Temp. °C	Radiation*	
Outer Planets	Orbital		X	>250		>15	1,000			Jup	OW
	Surface	X		>500		>15	NA		−180	Jup	OW
	Probes	X		>500		>15	NA		−180	Jup	OW
Inner Planets/ Venus	Orbital		X	>250		>10	>50,000				
	Aerial		X	>100		>4	>500	25–350			
	Surface	X		>200		0.5–1	NA	~460			
Mars	Orbital		X	>250		>15	>50,000				
	Aerial		X	>250	3000	>5	>1000		−40		X
	Surface		X	>250		>5	>1000		−40		X
	Sample Return Missions		X	>250		>10			−40		X
	Human Precursor Missions		X	>250		>15	>1000				X
Small Bodies	Orbital		X	>250		>15	>50,000				
	Surface		X	>250		>5	>1000		−40 to 40		
	Sample Return	X		>500		>15	NA		−40 to 40		

X: required; JUP: Jupiter system; OW: Ocean Worlds

Outer Planetary Mission Concepts: There are two categories of outer planetary missions being considered for the next decade: a) missions to Ocean Worlds and b) missions to the Ice Giants. Potential Ocean World mission destinations include: Enceladus, Europa, Titan, Ganymede, and Callisto, while the Ice Giant destinations are Neptune and Uranus. Outer planet missions pose several technical challenges for energy storage systems, which include: a) long life capability, b) radiation tolerance (Jupiter system missions), c) heat/radiation sterilization endurance and d) high reliability. The type of mission (flyby/orbital/landers/probes) is also critically important in deriving the energy storage system requirements for these long missions.

The team found that energy storage systems requirements for future outer planetary mission concepts are:

1. Outer planetary orbital/flyby missions likely require advanced rechargeable batteries with long calendar life (>15 years), high specific energy (>250 Wh/kg) and high energy density (>500 Wh/l) and should be compliant with planetary protection requirements.
2. Ocean World landers would require advanced primary batteries or primary fuel cells with high specific energy (>500 Wh/kg), long calendar life (>15 years), and radiation tolerance and should be compliant with planetary protection requirements.

3. Outer planet atmospheric probes would benefit significantly from the use of advanced primary batteries with long calendar life (>15 years), high specific energy (>500 Wh/kg), and radiation tolerance (Jupiter and moons).

Inner Planet Mission Concepts: Inner planet mission destinations include Venus and Mercury. No missions to Mercury are presently under consideration for the next decade unless proposed as a Discovery mission. The Venus exploration mission concepts being considered for the next decade include: a) orbital missions, b) variable-altitude aerial platforms, and c) long-duration surface probes and landers. Energy storage system needs for Venus missions once again depend on the type of mission (orbital/surface/aerial). Venus surface missions pose challenges for energy storage systems where the temperature and pressure are 460°C and 92 bars. However, at an altitude of ~55 km where the winds are strong enough to enable aerial missions there are benign conditions of 0°C and 1 bar. If aerial missions are contemplated lower in the atmosphere then batteries may need to operate at higher temperatures up to 350°C corresponding to an altitude of 15 km.

The team found that the requirements on the energy storage systems for next decadal Venus mission concepts are:

1. Orbital missions can be implemented with SOP rechargeable batteries, but would be benefitted by the advanced rechargeable batteries with high specfic energy (>250 Wh/kg), high energy density (>500 Wh/l), and long cycle life capability (>25,000 cycles).
2. Aerial missions would require advances in rechargeable battery technologies with high specific energy (>1000 Wh/kg) and a wide (high) temperature operational capability (25°C–350°C) over the altitude range of 55–15 km, while near-surface aerial systems would require rechargeable batteries that can operate at higher temperatures (up to 460°C) if exposed to ambient conditions.
3. Surface missions would require advances in primary battery technologies or fuel cells that have high specific energy (>200 Wh/kg) and enable operation for many hours or days at high temperature (up to 460°C), high pressure, and in a corrosive environment, without any insulation or shielding.

Mars Mission Concepts: The Mars robotic missions being considered for the next decade include: a) Mars orbiters, b) potential Mars sample return missions (includes Mars ascent vehicles, landers, and sample-fetching rovers), c) Mars helicopters and other forms of proposed aerial vehicles, and d) human Mars precursor missions (large landers, rovers, In-Situ Resource Utilization [ISRU] demonstration missions, etc.).

Mars surface missions pose several challenges for energy storage systems: a) low-temperature operational capability (<−40°C), b) long-life capability, and c) compliance with planetary protection requirements. Other desirable features include high specific energy (to reduce mass) and high energy density (to reduce volume). Major technical challenges of the energy storage systems required for Mars aerial missions are: a) *very high* power capability (>3000 W/kg), b) low-temperature operational capability (<−40°C), and c) compliance with planetary protection requirements. Mass and volume are also at a very high premium for these missions.

The energy storage systems required for future Mars mission concepts are:

1. Orbital missions would benefit significantly from the use of advanced rechargeable batteries with high specific energy (>250 Wh/kg), long cycle life (>50,000 cycles), and long calendar life (>15 years).

2. Aerial missions would require advanced rechargeable battery technologies with high specific power (3000 W/kg), high specific energy (250 Wh/kg), low temperature (<−40°C) operational capability, and should be in compliance with planetary protection requirements.
3. Surface missions would benefit significantly with the use of advanced rechargeable batteries with high specific energy (>250 Wh/kg,) long cycle life (>1000 cycles), long calendar life (>5 years), wide operating temperature range (−40°C to 40°C), and compliance with planetary protection requirements.

Small Body Mission Concepts: Small bodies in our solar system include asteroids, comets, and dwarf planets. Most of the potential missions to these bodies are achievable throughout the competitive Discovery or New Frontiers missions, but science priorities and missions provided through the Small Body Assessment Group (SBAG) are illustrative. They are: a) Near-Earth Objects: Mega-multi–flyby, Multi-rendezvous, and Sample return, b) Main belt asteroids and Jupiter Trojans: Main belt sample return, Multi-asteroid rendezvous, and Jupiter Trojan rendezvous, c) Comets: Comet Surface Sample Return and Comet Nucleus Sample Return, d) Phobos and Deimos Sample Return, e) Dwarf Planets: Haumea flyby (rendezvous preferred), and f) Centaurs and Trans-Neptunian Objects: Flyby (rendezvous preferred). As with other mission types, the energy storage system needs of the small body mission concepts depend significantly on the type of spacecraft (flyby/orbital/surface/sample return).

The major technical challenges of the energy storage systems required for small body missions are: a) low-temperature operational capability (landers and probes), b) low mass and low volume (~3× lower than SOP), and c) long operational life (>5 years).

The energy storage systems required for future small body mission concepts are:

1. Flyby/orbital missions would benefit significantly with the use of advanced rechargeable batteries with high specific energy (>250 Wh/kg), long cycle life (>50,000 cycles), and long calendar life (>15 years).
2. Surface (landers/rovers) would benefit significantly with the use of advanced rechargeable batteries with high specific energy (>250 Wh/kg), long cycle life (>1000 cycles), long calendar life (>5 Years), wide operating temperature range (−40°C to 40°C).
3. Sample return capsules would benefit significantly with the use of advanced primary batteries with high specific energy (>500 Wh/kg), long calendar life (>5 years), high specific power (1,000 W/kg), wide operating temperature range (−40°C to 40°C).

Capabilities and Limitations of SOP Space Energy Storage Systems

The assessment team met with engineers and technologists from U.S. battery manufacturers (EaglePicher/Yardney Technical Products, Amprius, Inc., SAFT Batteries), aerospace organizations, (LMA, Boeing, Aerospace) and NASA mission centers (NASA JPL, NASA GSFC) to obtain information on the SOP batteries capabilities and their limitations.

The major findings of the team on the capabilities and limitations on SOP space energy storage systems are:

Primary Batteries: Primary batteries are typically used for power generation in missions that require a single use of electrical power for a period of a few minutes to several hours or even a few days. Primary batteries that are currently being used in planetary space missions are: silver-zinc (Ag-Zn), lithium-sulfur dioxide ($Li-SO_2$), and lithium-thionyl chloride ($Li-SOCl_2$). They have been used in planetary probes (Galileo, Deep Impact, and Huygens), and sample return capsules (Stardust and Genesis).

In recent years, lithium-based primary batteries have been the technology of choice for most planetary science missions due to their higher specific energy and superior shelf life compared to aqueous-based systems. SOP Li-SO_2 and Li-$SOCl_2$ batteries have moderate specific energy (150–250 Wh/kg) and operate over a temperature range of −40°C to 60°C. These batteries have a proven lifetime of up to 10 years. But SOP Li-SO_2 and Li-$SOCl_2$ batteries are heavy and bulky and not attractive for Ocean World *lander* mission concepts as they likely would require several weeks of operation on battery power. They also have limited low temperature operational capabilities and are not attractive for missions that require operation below −40°C.

Rechargeable Batteries: Rechargeable batteries are being used mostly in solar-powered missions to provide electrical power during eclipse periods and for load-leveling. They have also been used in some RTG-powered missions, such as Mars Curiosity (Li-ion). They have also been used in orbital missions (Mars Global Surveyor and Mars Reconnaissance Observer), Mars landers (Phoenix), and Mars rovers (Spirit, Opportunity, and Curiosity). Rechargeable batteries that are presently in use in planetary missions include: Nickel-hydrogen (Ni-H_2) and Lithium-ion (Li-ion) batteries. *It should be noted that manufacturing of Ni-H_2 batteries is being phased out and they may not be available for future space missions*. Fortunately, we are transitioning to Li-ion batteries in the U.S. for the majority of our missions.

Li-ion batteries offer significant mass and volume advantages (three- to four-fold) compared to SOP Ni-H_2 batteries. Two types of Li-ion batteries are currently in use: a) batteries made with large-capacity prismatic or cylindrical Li-ion cells, and b) batteries made with small capacity cylindrical Li-ion cells. Batteries made with large-capacity prismatic Li-ion cells played an enabling role on the MER missions. This battery has successfully supported the MER mission for over 13 years on Mars, far exceeding the design requirement of 90 days. JPL has used such batteries (manufactured by Yardney) with large-capacity Li-ion cells on a number of planetary missions, including Juno (2005), Phoenix (2007), Grail (2011), and MSL (2011). Likewise, a number of SMD applications have also utilized batteries (manufactured by ABSL/Enersys) with small cylindrical Li-ion cells (Sony), e.g., Kepler (2009), Aquarius (2011), NuStar, and SMAP (2015). Similar batteries with E-One Moli 18650 cells are planned for use on Europa Clipper.

The SOP Li-ion batteries have low-specific energies (<100 Wh/kg) and low-energy densities (<200 Wh/l). Other shortcomings of SOP Li-ion batteries are: a) limited resilience to high temperature exposure (>60°C), b) limited low temperature operational capability (<−30°C), c) poor abuse tolerance (during inadvertent over charge/over discharge and short circuit), and d) incompatibility with standard planetary protection methods.

Capacitors: Capacitors are typically used on spacecraft to meet peak power demands. Tantalum capacitors (solid and electrolytic designs) were used in the Galileo and Cassini deep space missions. The most important advantage of capacitors is the capability to supply high pulses over short durations repeatedly for hundreds of thousands of cycles. The major limitations of SOP capacitors are their low-specific energy and low-energy density.

Advanced Energy Storage Technologies Under Development

The assessment team met with energy storage system scientists and technologists from universities, battery industry, NASA, DoD, and aerospace industry to obtain information on advanced energy storage technologies currently under development. The major findings of this assessment team on the status of advanced energy storage technologies are given below.

Primary Batteries: Advanced lithium-primary systems currently under development include Li-CF_x, Li/CF_x-MnO_2 and Li-O_2. These advanced primary battery technologies offer several advantages, such as higher specific energy, long shelf-life, and the potential for improved performance at low temperatures. The projected specific energy of these advanced primary batteries are: Li-CF_x (350–400 Wh/kg), and Li-CF_x-MnO_2 (300–350 Wh/kg). These batteries are being developed for DoD applications and are also for use by the oil and gas industry. The Europa Lander mission is currently funding the development of Li-CF_x batteries that can provide 350 Wh/kg (at the battery level) and that can operate in high-radiation environments.

Rechargeable Batteries: Advanced rechargeable battery systems are under development at DoE laboratories, industry, and academia, and include: advanced Li-ion, lithium solid state batteries, lithium-sulfur, and lithium metal-based batteries. These advanced Li batteries are projected to offer one or more of the following advantages: a) higher specific energy and energy density (2–3× compared to SOP Li-ion batteries, b) long cycle life and calendar life, and c) improved low-temperature performance.

The projected specific energies of these advanced rechargeable batteries are: advanced Li-ion (150–200 Wh/kg), Li-solid state (250–350 Wh/kg) and lithium-sulfur (250–350 Wh/kg). Among these battery technologies, the advanced Li-ion batteries have the highest potential to meet the needs of near- to mid-term space science missions in view of their high level of technical maturity, potential to offer improved cycle life, and low temperature performance capabilities. In the longer term, Li solid state batteries may provide mass and volume advantages over Li-ion batteries with liquid electrolytes. However, these technologies are currently less mature. Li-S batteries are also promising for high specific energy but are at a low TRL. DoE and DoD are leading the development of these advanced battery technologies. Currently there is limited or no NASA funding in this area.

High-Temperature Batteries: High-temperature battery systems that are attractive for potential near-term Venus surface mission applications are: a) LiAl-FeS_2 (lithium-aluminum/iron disulfide) and b) Na-Metal Chloride. These systems were brought to fairly advanced stages of development (TRL 3–4) for Electric Vehicle (EV) and grid scale applications. NASA-PSD is currently funding the development of high-temperature batteries required for future Venus missions.

Capacitors: Advanced capacitor technologies such as ultracapacitors or supercapacitors are currently under development for non-space applications. These advanced capacitors have 2–3× higher specific energy compared to the SOP double-layer capacitors. They can deliver high power densities over thousands of cycles with minimal degradation in performance, and are attractive for applications that require repeated short high discharge pulses. Supercapacitors are currently baselined for several small probe applications, including CubeSat power supplies, small Mars probes with milliwatt power supplies (MASER), and ice transceivers used with melt probes.

Fuel Cells: Advanced fuel cell systems under development include: polymer electrolyte membrane (PEM) fuel cells, solid oxide fuel cells, and regenerative fuel cells. Among these systems, H_2-O_2 PEM fuel cells and regenerative fuel cells are the most promising systems in view of their performance advantages and advanced stage of development. H_2-O_2 PEM fuel cells are attractive for some applications such as Ocean World landers as they are projected to provide higher specific energy compared to primary batteries. However, fuel cells do not readily scale to small sizes. Nevertheless, small PEM fuel cells may become attractive for space science missions that require power levels of 100 watts or greater for time periods of 20–30 hours or more.

Infrastructure: The team has determined that there are two major inadequacies present in the infrastructure that are of concern for the successful development of energy storage technologies required for future Planetary Science missions. The first concern involves the trend of vanishing domestic manufacturing capabilities, and the second involves the lack of adequate performance testing capabilities.

The team recommends that NASA partner with DoD in sponsoring domestic technology maturation and manufacturing technology programs to produce space quality energy storage systems for NASA and DoD. These actions are essential to preserve and maintain U.S. manufacturing capabilities in the area of energy storage technologies.

NASA must have available resources to maintain a healthy testing infrastructure for energy storage systems at GRC, JPL, GSFC/Naval Surface Warfare Center Crane, and other institutions. The testing infrastructure is essential to assure the quality of flight hardware and reduce mission risk. It is essential that the capability of this infrastructure be maintained and upgraded to verify performance in the extreme environments expected of future planetary science missions.

Summary and Recommendations of the Assessment Team

The assessment team has formulated the following overall and specific recommendations to NASA-PSD. These recommendations were formulated after reviewing the energy storage system needs of next decadal planetary science missions and after examining the capabilities and limitations of SOP energy storage systems and the status of the advanced energy storage technologies currently under development.

Overall Recommendations

NASA PSD should:

- 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 for advanced energy storage technology development, testing and qualification at various NASA Centers required to support future planetary science mission concepts.

Specific Technical Recommendations

Even though some of the requirements are common with the DoE and DoD needs, many of them are different because of the unique PSD environments. Therefore, the NASA PSD needs to undertake its own technology program, while leveraging the DoE and DoD efforts. Specifically, the PSD should advance 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 missions 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.

DoD, DoE, commercial and aerospace companies are investing in energy storage for a wide variety of reasons, but planetary missions, because of their extreme environmental conditions, are far more demanding than terrestrial or near-Earth conditions and thus components and subsystems require considerable evaluation, adaptation and testing. Many planetary mission concept architectures and designs are constrained by the energy storage systems especially with respect to lifetime, thermal management and in the case of some landers, mass. Investment by PSD will help alleviate the constraints and lead to lower cost missions.

1 Study Overview

1.1 Introduction

The NASA Planetary Science Division (PSD) requested that JPL, in conjunction with other NASA Centers, assess the energy storage systems that will enable/enhance the capabilities of future planetary science mission concepts (>2025). This is an update to the study from an earlier (2004) report entitled Energy Storage Technology for Space Science Missions (https://solarsystem.nasa.gov/docs/D-30268).

Since the launch of Explorer in 1958, energy storage systems have been used in Earth orbital and planetary spacecraft to supply primary electrical power or store electrical energy generated by on-board solar or radioisotope power systems. Energy storage systems are used on spacecraft for various functions to a) provide power to the spacecraft subsystems during launch before deployment of the solar panels, b) fire rocket motors for mid-course correction, c) to meet temporary power needs during eclipse periods, d) provide power for spacecraft and payload instruments, e) meet peak power demands such as data transmission and communication, f) fire pyros for landing/deployment operations, and g) meet peak power demands during surface mobility.

The energy storage technologies that have been used in planetary science missions are primary batteries, rechargeable batteries, and capacitors. Primary batteries (single discharge only) are typically used in missions, such as planetary probes, that require electrical power for a period of a few minutes to several hours. Rechargeable batteries (also referred to as secondary batteries) are used mostly in solar-powered spacecraft to provide electrical power during eclipse periods and for load leveling. Capacitors are used for applications that require high power short duration (seconds) pulses. Primary fuel cells are used in missions that require large amounts of electrical power for periods of many hours to many days, such as human space missions, but they have not been used so far on planetary science missions.

1.2 Objectives

The purpose of this study is to identify candidate advanced energy storage technologies that will enable or significantly enhance the capabilities of future Planetary Science mission concepts. The specific objectives of this study are:

- Review the energy storage system needs of future planetary science mission concepts.
- Assess the capabilities and limitations of SOP energy storage systems to meet the needs of future planetary science mission concepts.
- Assess the status of advanced energy storage technologies currently under development at NASA, DoD, DoE, and in industry and assess their potential capabilities and limitations to meet the needs of future planetary science mission concepts.
- Identify and recommend candidate advanced energy storage technology programs that will enable and/or enhance the capabilities of future planetary science mission concepts.

1.3 Study Approach

A technical assessment team was assembled to support this study. The team consists of subject matter experts in the areas of mission planning, spacecraft power systems engineering, and space energy storage systems. The team members were selected from NASA (HQ, JPL, GRC, LaRC, and GSFC), Aerospace Corporation, APL, and DoD. Three multi-day meetings were held to: a) obtain information about potential next decadal planetary science mission concepts and their power system needs, b) determine the capabilities of SOP energy storage systems, and c) assess the status and potential capabilities of advanced energy storage systems under development at various national labs, in industry, and universities.

To make the study manageable, the technology needs of a large number of potential future missions were classified into four generic mission types: a) Outer planet missions, b) Inner planet missions,

c) Mars missions, and d) Small Body missions. For each generic mission type, we have analyzed energy storage system capabilities needed, assessed the capabilities of SOP systems, and identified the gaps between current capabilities and mission needs. The team also reviewed the advanced energy storage technologies currently under development at various national laboratories, industry, and universities. The assessment team examined each energy storage technology to try to answer the following questions:

- How does the technology function?
- What is the present status of the technology?
- What is the future potential of the technology in terms of performance parameters such as specific energy, energy density, power density, and life under various conditions?
- What would be its impact on future missions?
- What technical challenges remain to be resolved?

The assessment team evaluated the information presented at the meetings and identified the most promising advanced energy storage technologies that will enable and/or enhance capabilities of the future planetary science missions. Their recommendations are documented in this report.

1.4 Schedule

The assessment team conducted three meetings between March and September of 2016. The first meeting was held at JPL, the second was held at NASA GSFC, and the third was held at NASA GRC. The fourth meeting was held at JPL in October 2016 to compile the results and formulate the findings. The draft report was prepared in May 2017 for review by the assessment team, and was revised to the final format in October 2017.

1.5 Review Team

The names of the Energy Storage Technology Assessment Team are listed on the first page of this report.

1.6 Study Participants

This study required detailed technical information on: a) next decadal planetary science missions and their energy storage system needs, b) SOP energy storage systems currently being used in various planetary space science missions and their capabilities, and c) advanced energy storage technologies currently under development and their potential capabilities. This information was obtained from various NASA Centers, aerospace companies, companies involved in the development and manufacturing of energy storage systems, and National Laboratories. The names of the organizations that supported this study are:

Batteries/Manufacturers

1. EnerSys
2. EaglePicher/Yardney Technical Products
3. Amprius, Inc.
4. Lockheed Martin Astronautics (LMA)
5. Boeing Defense, Space, and Security
6. SAFT Batteries
7. University of Maryland
8. SKC Power Technologies

Fuel Cells/Manufacturers

1. Giner, Inc.
2. Infinity
3. Teledyne Technologies, Inc.
4. Proton

NASA Centers

1. Glenn Research Center (GRC)
2. Jet Propulsion Laboratory-California Institute of Technology (JPL-Caltech)
3. Langley Research Center (LaRC)
4. Goddard Space Flight Center (GSFC)

DoD & National Laboratories

1. Army Research Laboratory
2. Aerospace Corporation
3. Applied Physics Laboratory (APL)
4. Argonne National Laboratories (DoE)

2 Energy Storage Needs of Future Planetary Missions

2.1 Introduction

The Planetary Science Division is considering a number of ambitious mission concepts to a variety of destinations in solar system including outer planets, inner planets, Mars, and small bodies. Energy storage system requirements vary based on the mission destination and mission type. The objective of this section is to identify the energy storage system needs of future/next decadal planetary science missions. As missions become more complex and focus on environments that are extremely challenging, the requirements placed on the technologies become more taxing. There are many ways that flight systems can deal with the challenges, but the least expensive ways are often those where the technologies are able to work directly in the environment. This is not always possible, as in the case of low temperature batteries, but the closer the technology can come to minimizing the thermal requirements or the radiation shielding, etc., the more streamlined and simpler the flight design can become thereby saving mass, volume, and ultimately lowering the cost of the mission. We invited the mission formulation study leads and power system engineers from JPL-Caltech, GSFC, MSFC, and JHU-APL to provide information on future planetary science missions and energy storage system needs, and this section summarizes those needs.

2.2 Outer Planet Mission Concepts

The outer planet destinations consist of four planets: Jupiter, Saturn, Uranus, Neptune, and their satellites (Figure 2-1). All past and present outer planet missions (prior to Juno) have been powered by Radioisotope Thermoelectric Generators (RTGs). Capacitors were used to meet the peak power demands in most of these missions. However, the NASA Cassini mission included the Huygens probe provided by European Space Agency (ESA) and this probe was powered by a primary battery. Juno is the first outer planetary solar-powered mission and required the use of rechargeable batteries to manage the electrical loads.

The current planetary decadal survey (2013–2022), *Vision and Voyages*,[1] recommends the following outer planet mission concepts for development: a) Europa multiple flyby mission (now Europa Clipper), b) Uranus orbiter, c) Enceladus obiter, d) Saturn probe, and e) Io observer. Among these, a Europa mission (Europa Clipper) was selected for development and is scheduled for launch no

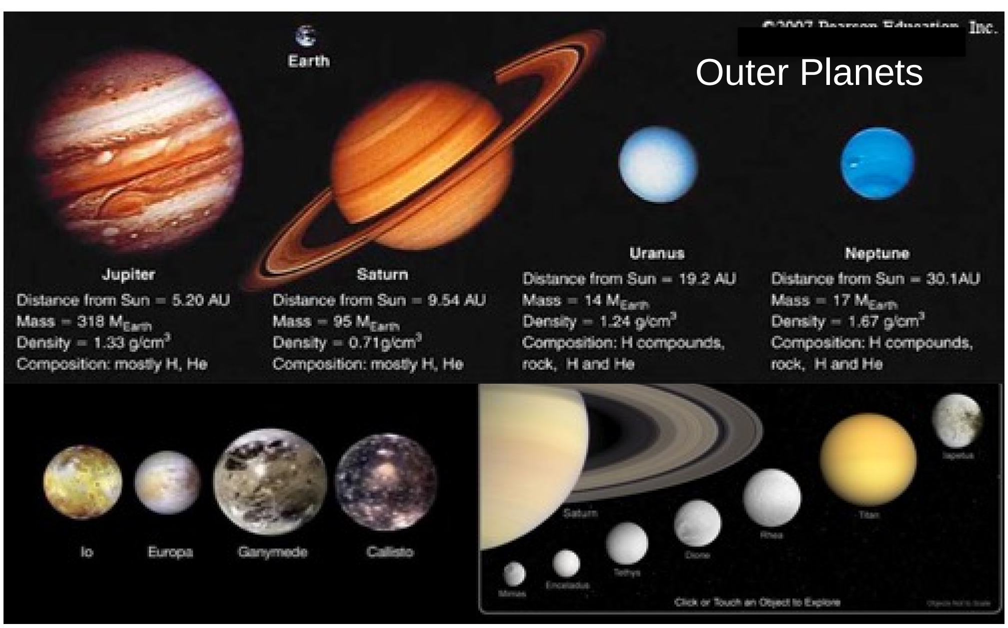


Figure 2-1. Outer planet mission destinations

earlier than 2022. The Europa Clipper will be the second solar-powered outer planet mission to use rechargeable batteries. In addition, several New Frontiers (NF) outer planet mission concepts, currently in the proposal development stage, are also considering using solar power systems with rechargeable batteries for load management. ESA is also developing a solar-powered orbiter (JUICE) for the exploration of Jupiter's Icy Moons and is considering the use of rechargeable batteries.

The outer planet mission concepts recommended in the past decadal survey were not all funded, but may be considered for development in the next decade. Scientists are presently advocating two groups of outer planet mission concepts for future flagship development: a) missions to Ocean Worlds (http://www.lpi.usra.edu/opag/ROW/) and b) missions to the Ice Giants (http://www.lpi.usra.edu/icegiants/). However, under NF, there are also an Io Observer and a Saturn Probe mission that figure prominently in outer planet mission priorities. Saturn Probe was included in NF4, while it is expected that for NF5, Io Observer will be included.

Potential Ocean Worlds mission destinations include Enceladus, Europa, Titan, Ganymede, and Callisto, which likely have subsurface oceans as determined from measurements by the Galileo and Cassini instruments but Triton, Pluto, and Ceres are also considered as possible Ocean Worlds. The overarching goals are to: a) identify Ocean Worlds in the solar system, b) characterize the ocean c) assess the habitability, and d) understand how life might exist at each Ocean World and search for life. It is expected that many of the next decadal Ocean Worlds destination missions will be orbital missions with landers/probes for surface/atmospheric exploration.

The Ice Giants destinations are Neptune and Uranus. Uranus particularly figured prominently in *Vision and Voyages*[1] with the subpanel of the decadal survey ranking Ice Giants as their first priority and recommending a Uranus mission concept for development. However, this mission was not selected for development during 2012–2023 and could be one of the higher priority outer planet missions for the next decade. A Neptune System Orbiter with a probe could be another option for the next decade. PSD has completed an Ice Giants Study (http://www.lpi.usra.edu/icegiants/) to assess science priorities and affordable mission concepts and options in preparation for the next decadal survey (2023–2032). These Ice Giants destination mission concepts are planned to be orbital missions with probes for atmospheric exploration.

Both RTG and solar-powered flyby/orbital missions of the outer planet require energy storage systems, e.g., rechargeable batteries or capacitors to meet peak power demands and load management. These missions pose several challenges for energy storage systems. These challenges include: a) long life capability, b) radiation tolerance for Jovian missions, c) heat/radiation sterilization endurance for OW lander missions, and d) high reliability. Other desirable features include low mass and volume. Energy storage system needs of the outer planet missions depend significantly on the destination and type of spacecraft (flyby/orbital/aerial/probe/lander). For example, Titan landers and aerial platforms and Europa landers may encounter temperatures as low as −200°C or lower depending on the target region. No battery or fuel cell can function at such temperatures. Therefore, the batteries must be enclosed in a thermal protection container. However, by lowering the operating temperature of the battery, the complexity of the thermal management system can be reduced and the s/c design simplified, leading to lower costs.

Long duration (> tens of hours) outer planet atmospheric probes require high specific energy storage technologies such as primary batteries or fuel cells that can operate effectively at low temperatures and capable of withstanding high acceleration loads. They also need a long life to withstand the cruise to their destinations. Advances in primary batteries/fuel cells would enable long-duration probes with larger science payloads and increased data return. Energy storage system needs of the future outer planet missions are summarized in Table 2-1.

Table 2-1. Energy storage system needs of future outer planet mission concepts

Mission Type	Destination/ Spacecraft Type	Energy Storage System Type	Needs
Orbiters/flyby (Radioisotope/ solar)	• Jupiter/Saturn Orbiters • Europa/Titan/ Enceladus Orbiters • Neptune/Pluto Flyby/ Orbiters • Io Observer	Rechargeable Batteries	• High Specific Energy (>250 Wh/kg) • Long Calendar Life (>15 Years) • Cycle Life ~1000 cycles • Radiation Tolerance • Sterilizable by heat or radiation (Europa)
Surface Missions (Non-Radioisotope)	• Europa Lander • Titan Lander • Titan Lake Probes	Primary	• High Specific Energy (>500 Wh/kg @ RT) • Long Calendar Life (>15 Years) • Low Self Discharge (<0.1%/year) • Low Temperature Performance (<−60°C) • Sterilizable by heat or radiation (Europa)
Surface Missions (Radioisotope)	• Titan Lander • Titan Aerial • Titan Lake Probes	Rechargeable	• High Specific Energy (>250 Wh/kg @ RT) or 350 Wh/kg for primary • Long Calendar Life (>15 Years) • Radiation Tolerance
Atmospheric Probes (Non-Radioisotope)	• Titan/Enceladus/ Titan Probes • Uranus Probes • Neptune Probes • Saturn Probes	Primary Batteries	• High Specific Energy (>500 Wh/kg) • Long Calendar Life (>15 Years) • Low Self Discharge (<0.1%/year) • Low Temperature Performance (<−60°C)

2.3 Inner Planet Mission Concepts

The inner planets, Mercury, Venus, Earth, and Mars, are closer to the Sun and are much more closely spaced to each other than their outer Solar System counterparts. In NASA's nomenclature, only Mercury and Venus are classified as inner planetary destinations (Figure 2-2). Earth and Mars missions are considered separately. An interesting distinction of these destinations is that Mercury and Venus have no moons unlike Earth, Mars, and the outer planets.

Past U.S. missions that explored Mercury are: Mariner-10 and Messenger. Messenger was the first spacecraft to orbit Mercury. Both Mariner-10 and Messenger were solar-powered spacecraft with rechargeable batteries for electrical load management. BepiColombo is an ESA orbital mission to Mercury that will launch in 2018 and will use lithium-ion batteries. However, there are no Mercury missions currently planned or under development for the next decade.

Past U.S. missions to Venus are: Mariner-2, Mariner-5, Mariner-10 (which flew by Venus on its way to Mercury), and Magellan. The Soviet Union sent several space missions to explore Venus including orbiters, atmospheric probes, landers and balloons. More recently, ESA operated the Venus Express orbiter from launch in November 2005 until it ceased operating in December 2014. The only Venus mission currently in operation is a Japanese spacecraft, Akatsuki. It is a solar-powered orbiter with rechargeable batteries. Currently there are no U.S. or Russian inner planetary space missions in operation.

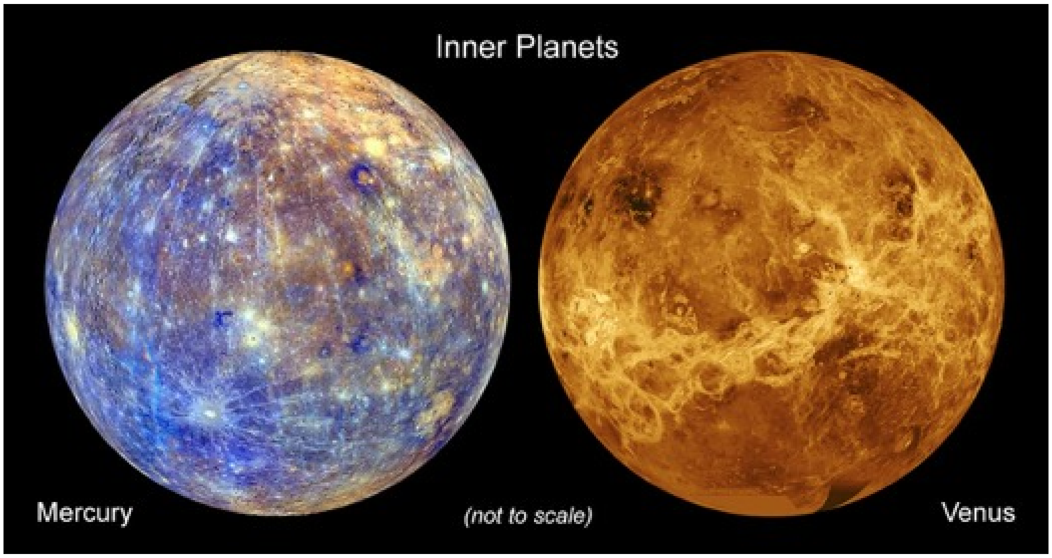


Figure 2-2. Inner planet mission destinations

The past planetary decadal survey (2013–2022) recommended a Venus In-Situ Explorer (VISE) for development during 2013–2023. Several proposals are currently being developed in response to the New Frontiers (NF-4) mission call, with Step 2 selections expected late in 2017. The inner planet mission concept recommended in the past decadal survey by NRC may be considered for development in the next decade. The highest priority science objectives (as defined by the Venus Exploration Analysis Group [VEXAG]) for the next decadal Venus exploration mission concepts are: 1) understand atmospheric formation, evolution, and climate history on Venus, 2) determine the evolution of the surface and interior of Venus, and 3) understand the nature of interior–surface–atmosphere interactions over time, including whether liquid water was ever present. The Venus exploration missions under consideration include: a) orbital missions, b) variable altitude aerial platforms, c) long duration surface missions, and d) Venus sample return missions.

Venus *orbital* missions do not pose significant technical challenges for energy storage systems. However, Venus *aerial and surface* exploration missions pose significant challenges for energy storage systems. The temperature and pressure on Venus range from 460°C and 92 bars at the surface, to 0°C and 1 bar at an altitude of 55 km (Figure 2-3). Venus aerial and surface missions under consideration for the next decade are given in Figure 2-4. Types of Venus mission examined include: orbiters, short and medium duration aerial platforms, atmospheric probes, and short and medium duration landers/probes.

Venus Orbiters require energy storage systems such as rechargeable batteries with low mass and volume and with long cycle life capability similar to Mars and Earth orbiters.

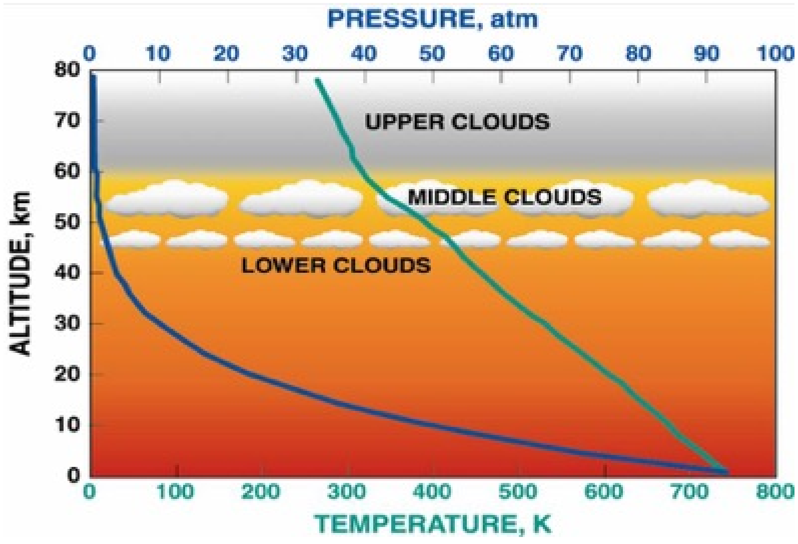


Figure 2-3. Venus environment

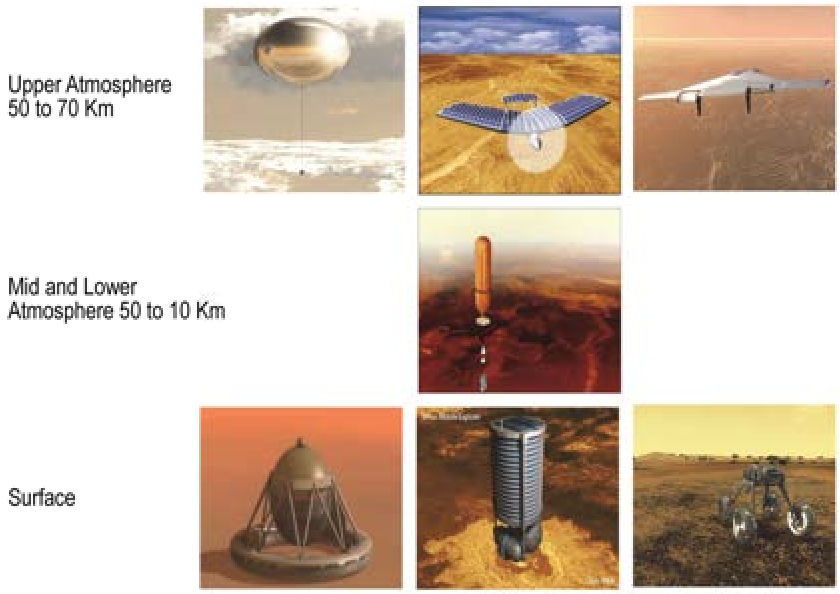


Figure 2-4. Potential Venus aerial and surface missions under consideration

Venus aerial systems in the upper atmosphere will benefit from rechargeable batteries with low mass and volume and provide power for extended periods of solar occultation. Lower atmosphere aerial systems require rechargeable batteries that can operate over a range of temperatures from 200°C to 460°C.

Venus Landers/Probes require energy storage systems such as primary batteries or fuel cells with high specific energy that can operate at high temperature, high pressure, and in corrosive environments. Increases in the specific energy of primary batteries or fuel cells would enable a reduction in volume and mass required for lander, thereby increasing the space for science instruments. Alternatively, if energy storage systems could operate at 460°C and in a corrosive environment, the energy storage subsystem could be entirely housed outside the containment vessel.

Energy storage system needs of the future inner planetary missions are summarized in Table 2-2.

Table 2-2. Energy storage system needs of future inner planet mission concepts

Mission Type	Destination/ Spacecraft Type	Energy Storage System Type	Needs
Orbital	Venus and Mercury Orbiters	Rechargeable Batteries	• High Specific Energy (>250 Wh/kg) • Low- Medium Temperature Operation (0–60°C) • Long Cycle Life (>25,000 Cycles)
Aerial	Venus Aerial Platforms	Rechargeable Batteries	• Medium-High Temperature Operation (0–400°C) • High Specific Energy (>100 Wh/kg) • Medium Cycle Life (> 500 Cycles) • Operation in Corrosive Environments
Surface (short-medium duration missions)	Venus Landers/Probes	Primary Batteries/ Fuel Cells	• High Temperature Operation (>460°C) • Operation in Corrosive Environments • High Specific Energy (>200 Wh/kg) • Operation for tens of hours in High Pressures • Medium-High Specific Power

2.4 Mars Mission Concepts

NASA has sent numerous robotic space missions to Mars to understand whether it was, is, or could be, a habitable world. The major goals of the Mars Exploration Program are: 1) determine if Mars ever supported life, 2) understand the processes and history of climate on Mars, 3) understand the origin and evolution of Mars as a geological system, and 4) prepare for human exploration missions.

Several types of spacecraft have been used for the exploration of Mars. These include flybys spacecraft, orbiters, landers, and rovers.

Flyby Missions: Flyby missions were the first missions used to explore Mars and they simply flew by Mars, taking as many pictures as possible on their way. Flyby missions include: Mariner–4, Mariner–6, and Mariner–7. Solar power systems with rechargeable batteries were used to power these flyby spacecraft.

Orbital Missions: The past and present Mars orbital missions include: Mariner–9, Viking 1–2, Mars Observer, Mars Global Surveyor, Mars Climate Orbiter, 2001 Mars Odyssey, Mars Express, Mars Reconnaissance Orbiter, Mars Atmosphere, and Volatile Evolution (MAVEN) and ESA's ExoMars Trace Gas Orbiter. Solar power systems with rechargeable batteries were used to power all the Mars orbital missions.

Landers and Rovers: The past and present lander and rover missions include: Viking-1 and -2 landers, Pathfinder lander, Sojourner Rover, Spirit and Opportunity Rovers, Phoenix lander, and Curiosity Rover. Most of these missions are solar powered except for Viking-1 and 2 landers, and the Curiosity Rover, which used RTG power systems. The lander and rover missions presently under development include: InSight lander, ESA's ExoMars Rover, and the Mars-2020 Rover. Insight lander and ExoMars Rover are solar powered. Radioisotope power systems will be used for Mars-2020 Rover. Rechargeable batteries are used in these missions for the management of electrical loads. Further, a Mars Helicopter, which will be deployed on Mars-2020 as a technology demonstration, will be powered by a high power-density rechargeable lithium-ion battery based on small cylindrical cells (recharged with an onboard solar array).

The Mars mission concepts under consideration for the next decade include: a) Multi-functional next-generation Mars Orbiters, b) potential Mars Sample Return missions (includes Mars ascent vehicle, Orbiter, and sample-fetching rovers), c) Phobos Lander Mission, d) Mars Helicopters and other forms of Aerial Vehicles, e) Subsurface explorers and f) Human Mars Precursor missions (large landers, rovers, ISRU demonstration missions, etc.). Some of the potential missions are shown in Figure 2-5.

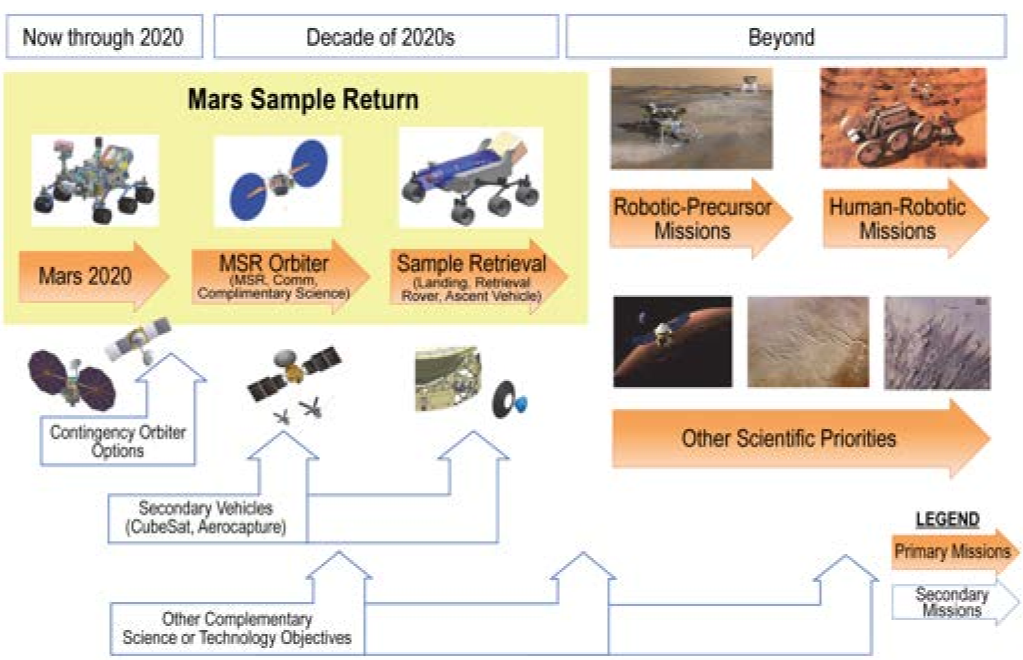


Figure 2-5. Notional future Mars missions: forward planning — 2020s and beyond

A Mars Orbiter, utilizing Solar Electric Propulsion (SEP) and advanced telecommunication is also being considered in low Mars orbit. The Mars science community, via *Vision and Voyages*[1] is advocating Mars Sample Return (MSR) to bring samples of martian rocks, soils, and atmosphere back to Earth to study samples extensively in laboratories. Future Mars subsurface mission concepts are also under consideration. Mars aerovehicles could enable the study of Mars from a perspective that was never achieved before. Such missions will provide aerial views from the martian sky where the spatial resolution is much better than can be achieved from orbit and the range of observation is much greater than is possible from the mastcam on the rover. NASA is also considering Human Mars missions to launch in mid or late-2030s and several robotic precursor missions to Mars are being considered to take place before the first human mission, with a mixture of both scientific and human mission preparation objectives.

Mars surface exploration missions pose several challenges for energy storage systems. These challenges include: a) low temperature operational capability (<−40°C), b) long life capability, c) heat/radiation sterilization endurance, and d) high reliability. Other desirable features include low mass and volume. Energy storage system needs of future Mars missions depend on the type of spacecraft (orbital/aerial/probe/lander), as described below.

Aerial Missions include short duration airplane or glider missions with lifetimes measured in minutes for gliders, and possibly hours for other aero-vehicles if there is sufficient power available. Such missions require rechargeable batteries with high specific energy, high energy density, high power capability and low temperature operational capability.

Mars Surface Missions require advanced rechargeable batteries with high specific energy, energy density, cycle life capability and low-temperature operational capability. These missions also require energy storage systems that can be sterilized to comply with Planetary Protection policies.

Table 2-3. Energy storage system needs of future Mars mission concepts

Mission Type	Mission	Energy Storage System Type	Needs
Orbital Missions	Mars Com Orbiter Mars Science Orbiter	Rechargeable Batteries	• High Specific Energy (>250 Wh/kg @ RT and 100% DOD) • Long Cycle Life (>50,000 cycles @ 30% DOD) • Long Calendar Life (>15 Years) • Low-Medium Specific Power
Aerial Missions	Helicopter	Rechargeable Batteries	• High Specific Energy (>250 Wh/kg) • Long Cycle Life (>1000 Cycles @>70% DOD) • Long Calendar Life (>5 Years) • High Specific Power (3000 W/kg) • Low Temperature Operation (<−40°C) • Sterilizable
Surface Missions	Robotic Landers Human Precursor Landers Robotic Rovers	Rechargeable Batteries	• High Specific Energy (>250 Wh/kg) • Long Cycle Life (>1000 Cycles @>70% DOD) • Long Calendar Life (>5 Years) • Low-Medium Specific Power • Low Temperature Operation (<−40°C) • Sterilizable
Sample Return Missions	Mars Ascent Vehicle	Primary Batteries	• High Specific Energy (>500 Wh/kg) • Long Calendar Life (>5 Years) • High Specific Power (1000 W/kg) • Low Temperature Operation (<−40°C) • Sterilizable
Human Precursor Missions	Landers / Rovers	Regenerative Fuel Cells	• High Specific Energy (>500 Wh/kg) • Long Calendar Life (>5 Years) • Long Cycle Life (> 1000 Cycles) • High Specific Power (500 W/kg) • Sterilizable

A notional Mars Sample Return Mission architecture consists of landers, rovers, ascent vehicles and orbiters. These missions are highly sensitive to mass and volume and their capabilities would benefit greatly from *higher specific energy* rechargeable batteries.

Human Mars Precursor Missions (e.g., large landers and rovers) require energy storage systems such as rechargeable batteries and regenerative fuel cells with high specific energy and energy density, and long cycle and calendar life.

Specific performance needs for these different Mars missions are listed in Table 2-3.

2.5 Small Body Mission Concepts

Small bodies in our solar system include asteroids, comets, and dwarf planets. Asteroids and comets are considered remnants from the giant cloud of gas and dust that condensed to create the Sun, planets, and moons some 4.5 billion years ago and are a few feet to several miles in diameter. Today, most asteroids orbit the Sun in a tightly packed belt located between Mars and Jupiter (Figure 2-6). Comets are made up of primarily ice and rocks and shed ice and dust particles as they approach the Sun in the course of their highly elliptical orbits. Dwarf planets, e.g., Ceres, Pluto, Eris, Haumea, and Makemake are celestial bodies resembling small planets but lack certain technical criteria to be classed as planets. They share their orbits around the Sun with other objects such as asteroids or comets.

Past missions to small bodies are New Millennium Deep Space 1 (NM-DS-1), Stardust, WISE, and Deep Impact. NM-DS-1 was a solar electric propulsion mission that passed by the near-Earth asteroid 9669 and comet Braille. NASA's Wide-field Infrared Survey Explorer ([WISE] an Explorer mission) was an unmanned solar powered spacecraft with an infrared-sensitive telescope. WISE studied asteroids, the coolest and dimmest stars and the most luminous galaxies. Stardust was a solar powered spacecraft that collected interstellar dust from the nucleus of comet Wild-2 during its closest encounter and returned them back to Earth for analysis. All these missions used rechargeable batteries for the management of electrical loads of the flyby/orbiting spacecraft. Stardust contained a sample return capsule that was powered by a Li-SO_2 primary battery. The Deep Impact deployed a "smart impactor" that struck the comet at 10.3 km/sec and observed the resulting cratering event from a safe distance. High energy Li-$SOCl_2$ primary batteries were used to power the impactor.

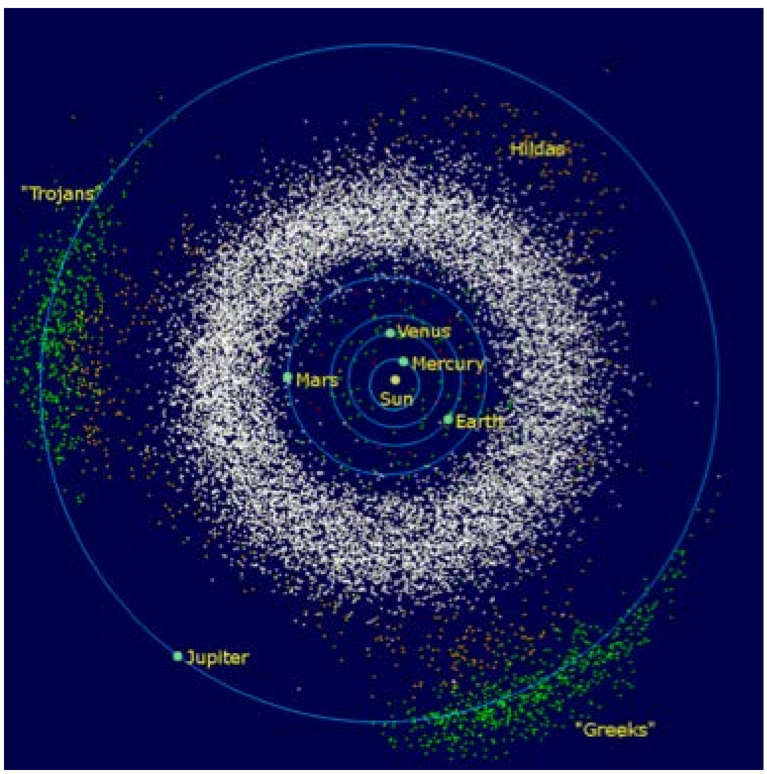


Figure 2-6. Asteroids orbit the Sun in a tightly packed belt located between Mars and Jupiter

Recent/ongoing comet and asteroid missions include: Rosetta, OSIRIS-REx, and Dawn. The ESA Rosetta spacecraft, launched in 2004, was the first to orbit a comet (67P/Churyumov-Gerasimenko) in 2014 and carried a lander module (Philae) developed by the German Space Agency (DLR) that was the first to land on the surface of the comet in November 2014. The Philae power system comprised solar arrays and Li-ion rechargeable batteries.

Dawn is a NASA solar-powered spacecraft, which uses solar electric propulsion that requires large solar arrays, visited the giant asteroid Vesta and now orbits the dwarf planet Ceres. Dawn entered Vesta orbit on July 16, 2011, and completed a 14-month survey mission before leaving for Ceres in late 2012. Its power system contains nickel-hydrogen rechargeable batteries for the management of electrical loads. OSIRIS-REx, a mission to a near-Earth asteroid, Bennu, is also a solar powered mission but uses chemical propulsion and manages electrical loads by lithium-ion batteries. It will orbit the asteroid in August 2018, collect a sample that will return to Earth in September 2023.

NASA-SMD has recently approved two new solar-powered Discovery missions (Psyche and Lucy) to explore a metal asteroid and the Jupiter Trojans in early 2020s. The power systems of both these missions will contain rechargeable batteries for the management of electrical loads.

Since many of the small body missions are selected competitively, we have taken the science priorities and mission recommendations provided through community white papers and the Small Body Assessment Group (SBAG). These are:

a) Near-Earth Objects: Mega-multi-flyby, Multi-rendezvous, Sample return from various types of objects
b) Main belt asteroids and Jupiter Trojans: Main belt sample return, Multi-asteroid rendezvous
c) Comets: Comet Surface Sample Return and Comet Nucleus Sample Return
d) Small Satellites: Phobos and Deimos Sample Return,
e) Dwarf Planets: Haumea flyby (rendezvous preferred),
f) Centaurs and Trans-Neptunian Objects: Flyby (rendezvous preferred).

The major technical challenges of the energy storage systems required for small body mission concepts are: a) low temperatures operational capability (landers and probes), b) low mass and low volume (~3× lower than state-of-the-practice [SoP]), and c) long operational life (>5 years). Energy storage system needs of the small body missions depend significantly on the type of spacecraft (flyby/orbital/surface/sample return), as described below:

- **Small Body Flyby/Orbital Missions** require rechargeable batteries with high specific energy, energy density, long cycle and calendar life.
- **Small Body Surface Missions** would also benefit from the advanced rechargeable batteries with high specific energy, high energy density and low-temperature performance capability.
- **Small Body Sample Return missions** require primary batteries for the ascent phase of the mission. These missions are highly sensitive to mass and volume and require primary batteries with high specific energy, high energy density and low temperature operational capability.

Specific performance needs for these various Small Body mission concepts are shown in Table 2-4.

Table 2-4. Energy storage system needs of future small body mission concepts

Mission Type	Spacecraft Type	Energy Storage System Type	Needs
Flyby/Orbital Missions	Small Body Flyby/Orbiters	Rechargeable Batteries	• High Specific Energy (>250 Wh/kg @ RT and 100% depth of discharge • Long Cycle Life (>50,000 cycles @ 30% DOD) • Long Calendar Life (>15 Years) • Low-Medium Specific Power
Surface Missions	Robotic Landers/ Probes	Rechargeable Batteries	• High Specific Energy (>250 Wh/kg) • Long Cycle Life (>1000 Cycles @ >70% DOD) • Long Calendar Life (>5 Years) • Low Temperature Operation (<−40°C)
Sample Return Missions	Ascent Vehicles	Primary Batteries	• High Specific Energy (>500 Wh/kg) • Long Calendar Life (>5 Years) • High Specific Power (1000 W/kg) • Low Temperature Operation (<−40°C)

2.6 Summary

NASA is considering a number of exciting planetary science mission concepts for the next decade. The energy storage systems required for the outer planet, inner planet, Mars, and small body missions are given below:

General Needs:

- Reduce Mass & Volume by >50%
- Increase lifetime to >15 years
- Enable high reliability
- Ensure safety of all types of energy storage devices

Mission Specific Needs

- Outer Planet Orbital Missions: Rechargeable batteries with long calendar and cycle life and compliance with planetary protection requirements for Ocean Worlds.
- Outer Planet Surface Missions: Primary batteries with low temperature (<−60°C) performance, radiation survivability, compliance with planetary protection requirements (OW).
- Venus Aerial Missions: Rechargeable batteries that can survive high temperature (25°C–350°C), high pressure, and corrosive environments
- Venus Surface missions: Rechargeable batteries that can survive high temperature (>460°C), high pressure, and corrosive environments
- Mars Orbital Missions: Rechargeable batteries with long calendar and cycle life
- Mars Aerial Missions: Rechargeable batteries with wide operating temperature capability (−40°C to 40°C), high power capability, and compliance with planetary protection requirements
- Mars Surface Missions: Rechargeable batteries wide operating temperature capability (−40°C to 40°C), compliance with planetary protection requirements
- Small Body Orbital Missions: Rechargeable batteries with long calendar and cycle life
- Small Body Surface missions: Rechargeable batteries wide operating temperature capability (−40°C to 40°C)

3 State-of-Practice Energy Storage Systems

This section provides an overview of the state-of-practice (SOP) energy storage devices used in space missions. The term SOP refers to reliable devices that *have been* widely used or *are* currently used on planetary missions.

3.1 Introduction

Space missions impose several critical performance requirements on energy storage devices. They must be custom-made and tested to ensure reliability and to meet a broad range of requirements to:

- Operate in vacuum or dense atmosphere (Venus, Titan)
- Withstand vibration, shock, and acceleration environments
- Have long calendar life and cycle life and over a range of mission scenarios
- Withstand Temperature and/or Pressure extremes
- Survive radiation
- Fit into a specific size/footprint
- Be safe throughout the mission

Energy storage devices used in planetary science missions include primary (non-rechargeable) batteries, secondary (rechargeable) batteries, and capacitors. Fuel cells have been used in human space missions but not in planetary science missions. A list of the first use of energy storage devices on all space missions is given in Table 2-1-1 of an earlier (2004) report entitled “Energy Storage Technologies for Future Space Science Missions” (https://solarsystem.nasa.gov/docs/D-30268).

Primary batteries (single discharge only) are typically used in missions that require a single use of electrical power for a period of a few minutes to several hours. Such missions include planetary probes (Galileo, Deep Impact, and Huygens), sample return capsules (Stardust and Genesis), Mars Landers (MER), and Mars Rovers (Sojourner). Primary batteries that are presently in use in space missions are: silver-zinc (Ag-Zn), lithium-sulfur dioxide (Li-SO_2), and lithium-thionyl chloride (Li-$SOCl_2$).

Rechargeable batteries (also referred to as secondary batteries) have been used primarily in solar powered missions to provide electrical power during eclipse periods and for load leveling. They have been used in orbital missions (TOPEX, Mars Global Surveyor, and Mars Reconnaissance Observer), Mars landers (Viking and Phoenix), and Mars rovers (Spirit, Opportunity, and Curiosity). Rechargeable batteries used in space missions include: silver-zinc (Ag-Zn), nickel-cadmium (Ni-Cd), nickel-hydrogen (Ni-H_2), and more recently, lithium-ion (Li-ion).

Primary fuel cells have been used in missions that required large amounts of electrical power for periods of many hours to many days, such as human space missions (Gemini, Apollo, and the Space Shuttle), but they have not been used on planetary science missions.

Capacitors have been used for applications that required repeated high power and short duration pulses (seconds). The Galileo and Cassini missions used capacitors for firing pyros and stepping motorized instrument platforms. New Horizons, with the primary mission to perform a flyby study of the Pluto system and now a Kuiper Belt object, used a capacitor bank in conjunction with a radioisotope thermoelectric generator (RTG).

3.2 Primary Batteries

3.2.1 *Overview of Primary Battery Technologies*

Primary batteries are electrochemical devices that convert chemical energy into electrical energy. Primary batteries are intended for single-use or "one shot" applications. They are used in spacecraft to supply:

- power during launch and post launch operations prior to deployment of solar panels.
- power for very short one-time needs such as firing a pyro or firing a rocket motor for mid-course correction.
- power for short encounters in which no rechargeable battery is employed or no energy source is available for recharging a rechargeable battery.
- very low power for extended periods (years) for clocks and computer memory.

The primary battery technologies that have been used in various space missions include: (a) silver-zinc (Ag-Zn), (b) lithium-sulfur dioxide (Li-SO_2), and (c) lithium-thionyl chloride (Li-$SOCl_2$).

Primary batteries used in early spacecraft were largely of the aqueous alkaline type, such as silver-zinc (Ag-Zn) technology. Aqueous-based systems generally exhibit high specific power, relatively low voltage, limited life, moderate specific energy, and energy density, and are limited in operating temperature range. In recent times, these aqueous alkaline batteries have been largely replaced by more energetic lithium-based primary battery systems, e.g., Li-SO_2 and Li-$SOCl_2$, which have much higher voltage, specific energy, and energy density. In addition, the lithium systems exhibit much longer storage life capabilities than the aqueous systems. The limitations of SOP lithium systems include lower specific power compared to aqueous batteries, safety issues under inadvertent abuse conditions, and voltage delay anomalies. The operational temperature range of lithium-based technologies is much wider than that displayed by aqueous batteries, but is still inadequate to meet many future mission needs.

As illustrated in Table 3-1, Li-SO_2 batteries have been used on a number of planetary exploration spacecraft, including Stardust (1999), Genesis (2001), and the MER–Rovers (2003). In some cases, such as the Deep Impact mission (2005), Li-$SOCl_2$ batteries were preferred due to the ability to provide even higher specific energy, given the moderate power requirements. Future missions may be required to operate for 20 days or more on primary battery power alone, unlike previous missions, which only required several hours of power. This requires significant enhancements in flight-qualified primary batteries, relative to state of practice options.

Table 3-1. State of practice (SOP) lithium-based primary batteries used in NASA missions

Tech-nology	Mission	Launch Date	Battery Config.	Battery Vendor	Cell Size, or Model	Capacity (Ah) Rated/ Actual	Operating Voltage Range	Battery Mass (kg)	Specific Energy (Wh/kg)	Operating Temperature Range (°C)	Design Life (Years)
Li-O_2	Stardust	2/7/1999	4s2p	Saft America	LO26SX	14	8V–12V	1.2	130	−20° to 40°	5
Li-SO_2	Genesis	8/8/2001	8s2p	Saft America	LO26SX	14	16V–24V	2.06	150	−20° to 40°	6
Li-SO_2	MER-Rover	6/10/2003	12s5p	Saft America	LO26SX	27.5/34	25V–34V	7.55	155	0° to 60°	3.5
Li-$SOCl_2$	Deep Impact	1/12/2005	9s24p	Saft America	LSH20	312	24V–32V	36.6	250	−20° to 40°	6

3.2.2 *Li-SO_2 Batteries*

NASA has used Li-SO_2 cells and batteries in planetary probes (Galileo and Cassini), sample return capsules (Genesis and Stardust) and the Mars Exploration Rover (MER) Lander.

In these batteries, Li is used as the anode material and SO_2 is the active cathode reactant. The electrolyte is comprised of sulfur dioxide (SO_2) dissolved in an organic solvent, such as acetonitrile, containing lithium bromide (LiBr). The electrode pack is comprised of a lithium anode and carbon coated-cathode on a metallic substrate (cathode current collector) separated by a polymeric polypropylene membrane. The electrode pack is spirally wound to fit into a cylindrical case. Only one U.S. manufacturer, SAFT America, currently produces Li-SO_2 cells for space applications.

Li-SO_2 cells exhibit an open circuit voltage of 3.0 V and a high specific energy of >225 Wh/kg) and high energy density of ~375 Wh/l. The specific energy and energy density at the battery level depend strongly upon the battery design and construction, and typically varies from 50–80% of the specific energy of the cells. The Li-SO_2 cell has the highest rate capability (specific power) of SOP lithium primary cells, and can operate with little loss of performance between −40°C and 60°C. When the load is first initiated, this cell exhibits a short delay in reaching the nominal voltage, due to the presence of a passivation layer on the lithium electrode which is broken down with operation. The application of a conditioning discharge prior to use, typically performed using a de-passivation circuit, minimizes this problem. The other limitations of this battery system for space science missions are reduced capacity at low temperatures (<−40°C), moderate specific power, unknown radiation tolerance, and uncertain life capabilities beyond ten years. These batteries can be still be considered for future space applications that require operation between −40°C and 60°C with moderate specific energy. There is little to be gained by attempting to improve these batteries and efforts would be better spent on battery technologies with more potential capabilities.

3.2.3 *Li-$SOCl_2$ Batteries*

Li-$SOCl_2$ batteries have been used in the past on the Mars Pathfinder Rover–Sojourner (1996), New Millennium Deep Space–2 (1998), with astronaut equipment, and the Centaur launch vehicles (Air Force). More recently, they have been used on the Deep Impact mission (2005) (see Table 3-1).

Lithium metal is the anode material in these batteries, and the cathode material is liquid thionyl chloride ($SOCl_2$). The electrolyte consists of tetrachloroaluminate ($LiAlCl_4$) dissolved in $SOCl_2$. Li-$SOCl_2$ cells, like Li-SO_2 cells, are available in a cylindrical configuration. Each cell is comprised of a spirally wrapped Li anode, a carbon cathode current collector, and a polymeric separator.

A few variants of this basic chemistry have been used. In some cells (Li-BCX), bromine chloride (BrCl) is added to the electrolyte to improve safety. BrCl also functions as a liquid cathode and provides higher open circuit voltage. In some developmental cells, addition of an electrolyte salt, lithium tetrachlorogallate ($LiGaCl_4$), allowed cell operation down to −80°C. Li-$SOCl_2$ cells are available from SAFT and Li-BCX cells are available from Wilson Greatbatch, Ltd.

Li-$SOCl_2$ and Li-BCX cells have higher specific energy (390–410 Wh/kg) and energy density (875–925 Wh/l) than Li-SO_2 cells. Deliverable battery outputs have varied from 30–60% of cell values in actual applications, depending on design and construction. The major limitations of these batteries are low specific power (<100 W/kg), limited performance capability at low temperatures (<−40°C), and significant voltage delay especially after storage due to Li electrode passivation. The use of a conditioning discharge regime prior to use minimizes the voltage delay associated with this system.

The Li-$SOCl_2$ system has the potential for improvements in the delivered rate capability, operation at low temperature, and reduced voltage delay. Several modifications are needed to accomplish these improvements, e.g., use of alternative liquid cathodes and salts.

3.3 Rechargeable Batteries

3.3.1 *Overview of Rechargeable Battery Technologies*

Rechargeable batteries are electrochemical devices that convert chemical energy into electrical energy during discharge, and electrical energy into chemical energy during charge and can be charged and discharged (cycled) numerous times. For planetary applications, rechargeable batteries are used in solar-powered orbital missions and Mars surface missions as well as on the asteroids, e.g., Rosetta Philae lander, where there is a source of recharge energy. Rechargeable batteries are used in spacecraft to supply:

- power to the spacecraft during launch before deployment of the solar panels.
- power during cruise anomalies where stored energy may be needed for events requiring power.
- power to the spacecraft, its equipment, and instrumentation during Sun eclipse periods.
- peak power for operations such as data transmission and communication.
- peak power for surface mobility.
- power for interim power outage.

Rechargeable batteries that have been used in space missions include: silver-zinc (Ag-Zn), nickel-cadmium (Ni-Cd), nickel-hydrogen (Ni-H_2), and lithium-ion (Li-ion). Currently, Li-ion rechargeable batteries are the technology of choice for the majority of aerospace applications. There are several variations of this technology. Table 3-2 lists the cathodes and anodes that are used in Li-ion and lithium rechargeable cells.

Table 3-2. Cathode and anode materials in lithium rechargeable cells

Cathode		Anode	
Composition	Designation	Composition	Designation
Lithium cobalt oxide, $LiCoO_2$	LCO	Meso-carbon micro-bead	MCMB
Lithium iron phosphate, $LiFePO_4$	LFP	Graphite	Gr
Lithium nickel cobalt oxide, $LiNi_{0.8}Co_{0.2}O_2$	NCO	Hard carbon	HC
Lithium nickel cobalt aluminum oxide, $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	NCA	Silicon (with graphite)	Si
Lithium nickel manganese cobalt oxide	NMC	Lithium metal	Li
Lithium manganese oxide (spinel)	LMO		

For long life applications (>5 years) in spacecraft that have suitable thermal management, nickel-hydrogen batteries have typically been the technology of choice in the past, since they have been proven to provide over 60,000 partial depth-of-discharge cycles (20–40%) and over 15 years of operation. However, due to the low specific energy, high cost, and limited operating temperature range of Ni-H_2 batteries, lithium-ion batteries have replaced them even for orbital missions. It should be noted that there are a number of permutations of lithium-ion batteries, since they can be effectively designed for the particular application by choosing the desired electrode couple and/or modifying the cell design to provide high specific energy, long life, or high power. The SMD missions that have utilized rechargeable batteries since 2000 are summarized in Table 3-3.

Table 3-3. SOP lithium-ion rechargeable batteries used in NASA missions (where NCO refers to $LiNiCoO_2$-based systems and LCO refers to $LiCoO_2$-based systems)

Mission	Launch Date	Destination	Battery System
2001 Mars Odyssey	April 2001	Mars	$Ni\text{-}H_2$
COUNTOUR	July 2002	Comet	Ni-Cd
MER-Spirit	June 2003	Mars	Li-ion (NCO)
MER-Opportunity	July 2003	Mars	Li-ion (NCO)
Messenger	August 2004	Mercury	$Ni\text{-}H_2$
Deep Impact	January 2005	Comet	$Ni\text{-}H_2$
Mars Reconnaissance Orbiter	August 2005	Mars	$Ni\text{-}H_2$
New Horizons	January 2006	Pluto	*No Battery*
Phoenix	August 2007	Mars	Li-ion (NCO)
Dawn	September 2007	Vesta & Ceres	$Ni\text{-}H_2$
Kepler	March 2009	Earth Orbit	Li-ion (LCO)
Lunar Reconnaissance Orbiter	June 2009	Moon	Li-ion (LCO)
LCROSS	June 2009	Moon	Li-ion (LCO)
Juno	August 2011	Jupiter	Li-ion (NCO)
GRAIL	September 2011	Moon	Li-ion (NCO)
Mars Science Laboratory	November 2011	Mars	Li-ion (NCO)
LADEE	September 2013	Moon	Li-ion (LCO)
MAVEN	November 2013	Mars	Li-ion (NCO)
OSIRIS-REx	September 2016	Asteroid	Li-ion
InSight	May 2018	Mars	Li-ion (NCA)
Mars 2020	Summer 2020	Mars	Li-ion (NCA)
Deep Space Climate Observatory (DSCOVR)	February 2015	L-1	Li-ion (LCO)
Magnetospheric Multiscale Satellites (MMS)	March 2015	Various Orbits	Li-ion (LCO)
Transiting Exoplanet Survey Satellite (TESS)	December 2017	HEO Orbit	Li-ion (NCO)
James Webb Space Telescope (JWST)	2018	L-2	Li-ion (LCO)
JPSS2	2021	LEO	Li-ion (LCO

3.3.2 *SOP Li-ion Rechargeable Battery Technologies*

The original Li-ion cells introduced by Sony employed coke-type carbon as the anode material and lithium cobalt oxide (LCO) as the cathode material and an organic electrolyte containing 1.0 M $LiPF_6$ in propylene carbonate and diethyl carbonate. Since then, Li-ion cells have undergone several changes with respect to electrode materials and electrolytes and cell designs. Most Li-ion cells used for aerospace applications employ graphitic type carbons as anode materials and mixed metal oxides, such as $LiCoO_2$ (LCO), $LiNiCoO_2$ (NCO), or $LiNiCoAlO_2$ (NCA), as cathode materials and electrolytes based on mixtures of linear and cyclic carbonates. It should be noted that Li-ion cell technology has evolved with improved cathode, anode, and electrolyte materials currently under development. The cathode materials well developed include, lithium cobalt oxide, lithium nickel cobalt oxide with and without Al, $Li(Ni,Co,Mn)O_2$ and $LiFePO_4$. The anode materials under investigation include alternate carbon materials and silicon-based carbon composites.

Aerospace Li-ion batteries can generally be divided into two different categories: a) batteries based upon large capacity prismatic or cylindrical cells, or b) batteries based upon small 18650-size Li-ion cells typically connected in parallel strings. The use of large capacity prismatic cells has typically been in conjunction with battery management systems, so the individual cells can be monitored, controlled, and balanced with respect to one another. This type of Li-ion battery system has found wide use in long life applications and/or missions that require a wide temperature range of operation. The U.S. manufacturers of large capacity Li-ion cells include Yardney, SAFT, Quallion, and EaglePicher. EaglePicher Technologies, LLC, acquired Yardney in 2016 and is in the process of relocating the plant from the east coast to midwest. The overseas manufacturers of large capacity aerospace Li-ion cells include SAFT (France) and GS Yuasa (Japan). Batteries that utilize small 18650-size Li-ion cells, which are arranged in a series-parallel configuration, have become more widely used in recent years. There are a number of key attractive features of these batteries, including the fact that a) they do not require any cell-balancing electronics, b) the individual cells possess built-in safety devices, and c) the multi-string architecture provides modularity and improved redundancy. ABSL/Enersys is the primary manufacturer of aerospace batteries using this approach. The majority of the batteries that have been fabricated by ABSL/Enersys utilize Sony Hard Carbon (HC) or Hard Carbon Mandrel (HCM) 18650-size Li-ion cells. However, recent high-energy 18650 cells, with ~2× improvement in the specific energy, have started being the baseline in the upcoming SMD missions.

SOP Li-ion cells have a specific energy of 100–150 Wh/kg and energy density of 250–350 Wh/L (depending on cell size and chemistry/vendor) but at the battery level these values are 20–50% lower. SOP Li-ion cells can provide over 1000 cycles at 100% DOD and can operate over the temperature range of −20°C to 40°C. In the past, JPL has developed a low temperature Li-ion battery technology for Mars surface missions and advanced this technology to a flight product level (TRL 6) in collaboration with Yardney Technical Products, AFRL, and NASA GRC. JPL successfully used these batteries for the first time on a NASA mission in 2003 to power the Mars Rovers (Spirit and Opportunity). The MER Rover Battery Assembly Unit (RBAU) consisted of two parallel 8-cell batteries. Each battery was designed for operation at 28 V and the nominal capacity of the battery is 10 Ah, at room temperature. It was designed for operation (both charge and discharge) at temperatures as low as −20°C. To date, the battery has successfully supported the mission over 13 years on the surface of Mars, far exceeding the design requirement of 90 days. Based on this success, this same cell chemistry has been used on a number of other missions, using different cell sizes, as shown in Table 3-4. It should be noted that proper battery design is critical to achieving extended lifetimes, including the desired thermal and charge management. For example, the batteries used on MER benefited from the use of radioisotope heater units (RHUs), thermal switches, and an on-board battery management system (BMS) that effectively provided individual cell monitoring and balancing. The latter is essential for batteries with large-format cells.

For planetary applications, the use of large capacity Li-ion batteries has involved utilizing the “heritage” MCMB-$LiNiCoO_2$ chemistry used for the MER program and manufactured by Yardney Technical Products. As illustrated in Table 3-4, this heritage cell chemistry has been utilized on missions, including Juno (2005), Phoenix (2007), Grail (2011), and MSL (2011).

Table 3-4. SOP large cell Li-ion batteries used in NASA missions

Tech-nology	Mission	Launch Date	Battery Config	Battery Vendor	Cell Size or Model	Capacity (Ah) Voltage Range	Operating Voltage Range	Battery Mass (kg)	Specific Energy (Wh/kg)	Operating Temp-erature Range (°C)	Cycle Life To Date
NCO Li-Ion	MER–Rover	6/10/2003	8s2p	Yardney	NCP–8-1	16/20	24–32.8V	7.12	90	−20° to 30°	>4,500
NCO Li-Ion	Juno	8/5/2005	8s2p	Yardney	NCP–55–2	110/120	24–32.8V	34.90	110	15° to 25°	<50
NCO Li-Ion	Phoenix	9/4/2007	8s2p	Yardney	NCP 25–1	50/62	24–32.8V	17.80	105	−20° to 30°	<200
NCO Li-Ion	Grail	9/10/2011	8sp1	Yardney	NCP 25–1	50/62	24–32.8V	9.25	100	0° to 30°	1,500
NCO Li-Ion	MSL Curiosity	11/26/2011	8s2p	Yardney	NCP 43–1	86/92	24–32.8V	26.50	104	−20° to 30°	>1,500

A number of planetary applications have also used the small cell battery approach, involving the use of Sony $LiCoO_2$-based 18650-size Li-ion cells, in large capacity batteries manufactured by ABSL/Enersys. As displayed in Table 3-5, these NASA missions include Kepler (2009), Aquarius (2011), and SMAP (2015). The European Space Agency (ESA) has also used batteries manufactured by ABSL/Enersys, including the Mars Express (2003) mission which represents the first Li-ion battery to orbit Mars.

Despite their outstanding energy performance, the current generation of Li-ion batteries displays some shortcomings. These include, moderate long cycle and operational life beyond 12 years and a limited operating temperature range (−20°C to 40°C). In addition, Li-ion cells require electronic controls for charge and discharge to achieve long life and ensure safe operation at high rates. Li-ion cells are less tolerant to electrical and thermal abuse than aqueous Ni-based cells.

It should be mentioned that many changes are occurring in the aerospace battery industry, and the implications of this upon future NASA missions are uncertain. With regard to Ni-H_2 batteries, their production is being phased out and will no longer be available for future planetary missions. The availability of heritage large-format Li-ion batteries is also uncertain, due to the recent acquisition of Yardney Technical Products by EaglePicher Technologies, LLC. It is currently not known if EaglePicher will continue to offer these heritage products. Regarding small cell format batteries provided by ABSL/Enersys, the production of the heritage Sony HC cells has been discontinued so alternates will have to be identified and qualified for aerospace use.

Table 3-5. SOP small cell Li-ion batteries used in NASA missions

Tech-nology	Mission	Launch Date	Battery Config	Battery Vendor	Cell Size or Model	Capacity (Ah) Rated/ Actual	Operating Voltage Range	Battery Mass (kg)	Specific Energy (Wh/kg)	Operating Temp-erature Range (°C)	Cycle Life To Date
LCO Li-Ion	Kepler	3/6/2009	8s2p	ABSL	Sony 18650	24/20	24V–33.4V	6.5	90	−10° to 45°	<2,500
LCO Li-Ion	Aquarius	6/10/2011	8s2p	ABSL	Sony 18650	30/28	24V–33.6V	4×8.5	95	−10° to 40°	~6,500
LCO Li-Ion	SMAP	1/31/2015	8s52p	Enersys/ ABSL	Sony 18650	78/54	24V–32.8V	20.4	80	10° to 25°	<1,000
LCO Li-Ion	SMAP (LVA)	1/31/2015	3×8sp1	Enersys/ ABSL	Sony 18650	45/32	24V–32.8V	3×4.5	75	0° to 35°	<1,000

3.4 Capacitors

Traditional capacitors are made by rolling up thin sheets of metal separated by a dielectric film. Capacitors store small amounts of energy per kg compared to batteries, but they can deliver this energy in short high-power pulses. Batteries have a much higher specific energy, but cannot release this energy in short bursts like capacitors.

Capacitors store energy in the form of separated electrical charge. The greater the area for storing charge, and the closer the separated charges, the greater is the capacitance. A conventional capacitor derives its area from plates of a flat, conductive material. To achieve high capacitance, this material can be wound in great lengths, and can sometimes have a texture imprinted on it to increase its surface area. A conventional capacitor has charged plates separated by a dielectric material such as a plastic or paper film, or a ceramic. These dielectrics can be made only as thin as the available films or applied materials.

Tantalum capacitors (solid and electrolytic designs) were used in the Galileo, Cassini, and New Horizons deep space missions. They were used for filtering applications requiring high capacitance values at low frequencies. These capacitors were in the regular manufacturer product line but had been specially qualified for space use. They provide high volumetric efficiency and good temperature stability. However, they have low gravimetric efficiency; tantalum has 50% higher density than lead. Tantalum wet-slug capacitors are often used as input and output filter capacitors of dc–dc converters in spacecraft power management and distribution systems (PMAD). Capacitor banks were used in the Galileo and Cassini missions for power "keep-alive" and high pulse power support during radar operations. The devices used in these missions were rated at 1200 microfarads and were capable of providing 20 amps in one millisecond.

Electrochemical capacitors were first demonstrated in the 1950s, but became widely commercially available in the late 1970s. Recent electrochemical capacitors employ high surface area electrodes (usually activated carbon) and an electrolyte and are often referred to as double-layer capacitors or supercapacitors, and sometimes as ultracapacitors. Due to the high equivalent series resistance (ESR) of these cells, their main use was in backup power applications. Manufacturing advances in the 1990s led to the development of the first low ESR parts. Cells are available in the <1 F to >3000 F range, typically at 2.7 V to 3 V, with a specific energy of 5 Wh/kg and specific power exceeding 1 kW/kg. The capacitors can provide power for extended discharge periods up to a few minutes as opposed to fractions of a second. As such, the energy and power capabilities of supercapacitors are intermediate between conventional capacitors and batteries. These are presently being developed for commercial and military use, and are often used in a hybrid configuration with Li-ion batteries. By supporting high power pulses, they can extend the life of a Li-ion battery. Finally, since charge storage occurs through non-Faradaic (vs. Faradaic) processes, wide temperature operation is possible. Cells can operate at temperature <−40°C, and up to 150°C through the use of appropriate cell designs and electrolytes.

3.5 Summary of SOP Energy Storage Devices

3.5.1 *Primary Batteries*

- Primary batteries presently in use in space missions include: Li-SO_2 and Li-$SOCl_2$
- Li-SO_2 batteries have the highest rate capability (specific power) of SOP lithium primary cells, and can operate with little loss of performance between −40°C and 60°C. Li-SO_2 cells and batteries have been used in planetary probes (Galileo and Cassini), sample return capsules (Genesis and Stardust) and the MER Lander.
- Li-$SOCl_2$ batteries have higher specific energy (250 Wh/kg) and energy density than Li-SO_2 batteries (150 Wh/kg), but they display poor rate capability, poor low temperature performance, and have significant voltage delay. Li-$SOCl_2$ batteries have been used on the Mars Pathfinder Rover-Sojourner (1996), New Millennium Deep Space-2 (1998), astronaut equipment, and Deep Impact mission (2005).
- Major limitations of the SOP primary batteries are: a) low specific energy b) limited resilience to high temperature exposure (>60°C), c) limited low temperature operational capability (<−40°C), d) poor abuse tolerance (over discharge and short circuit).

3.5.2 *Rechargeable Batteries*

- Rechargeable batteries that are presently in use in space missions include: nickel-hydrogen (Ni-H_2) and lithium-Ion (Li-ion).
- Ni-H_2 batteries have low specific energy (~30 Wh/kg) and low energy density (30 Wh/l). However, they have excellent cycle life capability (>50,000 cycles at 30% depth of discharge).
- Ni-H_2 batteries will no longer be available for the next decadal planetary missions, since their production is being phased out.
- The state of practice Li-ion batteries have high specific energy (~100 Wh/kg), high energy density (>200 Wh/l), and operate over a temperature range of −20°C to 40°C. Li-ion batteries offer significant mass and volume advantages (three- to four-fold) compared to SOP Ni-H_2 batteries. Two types of Li-ion batteries are currently in use:

a) batteries made with large-capacity prismatic or cylindrical Li-ion cells and b) batteries made with small capacity cylindrical Li-ion cells (18650).

- Major limitations of the SOP Li-ion batteries are: a) low specific energy, b) limited resilience to high temperature exposure (>60°C), c) limited low temperature operational capability (<−20°C), d) poor abuse tolerance (inadvertent over-charge/over-discharge and short circuit), and e) incompatibility to the standard planetary protection methods. Availability of heritage large-format Li-ion batteries is uncertain for future missions.
- EaglePicher Technologies, LLC, acquired Yardney, the primary supplier of large format aerospace Li-ion cells/batteries. It is not known if EaglePicher will continue to offer these products.

3.5.3 *Capacitors*

- For PSD applications, capacitors have only been used for a few applications. Tantalum capacitors (solid and wet slug designs) were used in the Galileo, Cassini, and New Horizons deep space missions. They were used for filtering applications requiring high capacitance values at low frequencies.

4 Advanced Energy Storage Technologies

This section describes the status of advanced energy storage technologies that have the potential to meet the needs of future space science missions. In this report, advanced technologies are referred to as those technologies that have not been used in space missions to this point and are still currently under development. The advanced technologies presented in this section are in the areas of primary batteries, rechargeable batteries, fuel cells, capacitors, and fly wheels. The chapter is organized such that each technology is described in six sections: Potential Benefits and Applications, Chemistry, Status, Key Issues, Technical Directions and Potential Capabilities. The Technical Direction reflects the recommended direction that industry and agencies, including NASA-PSD, need to embark upon to enable or significantly enhance future missions by providing the Potential Capabilities.

4.1 Advanced Primary Batteries

To circumvent the limitations of the SOP primary batteries, several advanced lithium-primary systems are under development, which include: low temperature Li-$SOCl_2$, Li-CF_x, and Li/CF_x-MnO_2. These advanced systems are projected to offer one or more of the following advantages: a) significantly higher specific energy and energy density, b) minimal voltage delay, c) longer life, and d) improved low temperature performance compared to the SOP Li-SO_2 and Li-$SOCl_2$ batteries. Among these advanced systems, Li-CF_x batteries (with and without MnO_2 blends) are projected to be the most attractive candidates for the near-term future space science missions because of their improved energy densities and the high level of technological maturity. Li-air primary battery system is projected to be a very long-term option with further expected gains both in specific energy and energy density and is not discussed here. Below is a brief description of these advanced primary battery systems.

4.1.1 *Low-Temperature Lithium – Thionyl Chloride (Li-$SOCl_2$) Cells*

Potential Benefits and Applications: Among the various primary batteries, this system possesses the highest potential for good performance at ultra-low temperatures (−100°C). This is because of the lower freezing point of the electrolyte/liquid cathode (~ −85°C), which can be lowered further with suitable thiohalide co-solvents, as demonstrated recently at JPL. In addition, these systems have good stability at warm temperatures, although the voltage delay needs to be contended with, especially if the batteries are stored at warm temperatures prior to discharge. Further, these batteries have moderate to high specific energy and energy density coupled with demonstrated long life capability. These characteristics make these batteries attractive for future space science missions that require operation at very low temperatures.

Chemistry: A detailed description of the Li-$SOCl_2$ system and its capabilities are given in earlier section and not repeated here. The state of practice Li-$SOCl_2$ can operate down to −60°C, though at low discharge rates. The improved low temperature Li-$SOCl_2$ cell chemistries can operate down to −100°C, with suitable modifications to the electrolyte/liquid cathode composition (with co-solvents and salts that improve conductivity at low temperatures), and cathode designs(with electro-catalysts to improve the kinetics of $SOCl_2$ reduction).

Status: Under the New Millennium Deep Space-2 program in the late 1990s, JPL developed a unique battery that required operation at temperatures as low as −60°C for a Mars microprobe mission. JPL (in collaboration with Yardney) modified the Li-$SOCl_2$ chemistry by using an alternate electrolyte salt ($LiGaCl_4$) and optimizing the salt concentration (reduced to 0.5 M). Small cylindrical cells of 2 Ah were designed and developed under this program to withstand impact shock levels as high as 80,000 g. These modified cells showed improved power and energy density at −60°C compared to SOP Li-$SOCl_2$ cells, and were observed to deliver 25% of their room temperature capacity at −80°C. There was a problem of increased voltage delay at low temperatures, which is inherent with this chemistry. In subsequent R&D work, JPL demonstrated that with a $LiGaCl_4$ salt dissolved in sulfuryl chloride fluoride and chloro-difluoromethane, it is possible to lower the operating temperatures below −100°C. There is no ongoing work, however, either in NASA, industry, or DoD laboratories to resolve the issues of low temperature performance and voltage delay.

Key Issues: The SOP Li-$SOCl_2$ batteries exhibit moderately high specific energy (>250 Wh/kg) and energy density (>350 Wh/l), at the battery level. The major limitations of SOP Li-$SOCl_2$ batteries are poor rate capability and low energy delivery capabilities at temperatures lower than −60°C, as well as, severe voltage delay after extended periods of storage. Voltage delay is particularly severe at low temperatures and at high discharge rates, especially after prolonged storage at warm temperatures. The limited power and energy performance of these batteries at temperatures lower than −60°C is generally due to three factors: a) low electrolyte conductivity, b) poor ionic conductivity of the surface film, lithium chloride on Li anode, and c) and poor reduction kinetics of $SOCl_2$.

Technical Directions: In order to improve the low temperature performance of these batteries, alternate electrolytes and improved cell designs are needed. Addition of suitable solvents/co-solvents, use of alternate electrolyte salts, and controlling the purity of the electrolyte are anticipated to minimize voltage delay and improve the low temperature performance.

4.1.2 *Improved Lithium-Carbon Monofluoride (LiCF_x) Cells*

Potential Benefits and Applications: Potential payoffs of LiCF_x batteries are: a) 2–3× mass and volume savings relative to SOP Li-SO_2 and Li-$SOCl_2$ batteries, b) wider operating temperature range (−40°C to 60°C), c) minimal voltage delay, and d) improved shelf life characteristics. This system is attractive for planetary probes and surface missions that require high energy density primary batteries and also with operational capability at low temperatures.

Chemistry: The chemistry involves a Li anode and a carbon monofluoride cathode in an electrolyte containing propylene carbonate (PC), dimethoxyethane (DME) and tetrahydrofuran (THF) (in some cases), and with $LiBF_4$ salt. The reactions at the CF_x cathode and Li anode are described below (Figure 4-1).

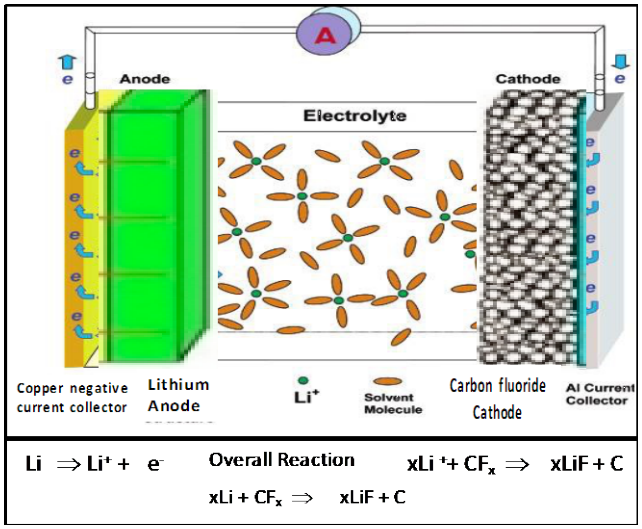


Figure 4-1. Chemistry of Li-CFx primary cell

Status: Existing Li-CF_x batteries have impressive specific energy and energy density, but only at low discharge rates of ≤C/20 at room temperature, and display poor performance at low temperatures. Currently, there are no major research and development efforts reported by the industry in this area. However, at two DoD laboratories (NRO and Army-CECOM) there are some efforts, which are focused on improving the specific energy, rate capability, and low temperature performance of this system. A few companies, including EaglePicher, Ultra-life, Rayovac, and Quallion, have been actively improving this system for DoD applications. The recent improvements with aluminum cans have resulted in impressive performance characteristics: capacity of >19 Ah in a D-size cell, i.e., specific energy of over 700 Wh/kg and energy density of 1000 Wh/l (Figure 4-2). Safety characteristics have improved as well with built-in positive temperature coefficient (PTC) current limiting devices.

Key Issues: The poor discharge rate capability of Li-CF_x cells, especially at low temperatures is due to three factors: a) low electronic conductivity of the cathode material, CF_x a significant contributor, especially in thick electrodes that are needed for high-energy designs, b) low ionic conductivity of the electrolyte at low temperatures, and c) slow reduction kinetics of CF_x cathode. The rate capability at low temperatures can be improved by the use of alternate solvent-electrolytes that include low-viscosity solvents, such as linear and cyclic ethers in conjunction with suitable salts and electrolyte additives. The radiation tolerance of the Li-CF_x cells, and the individual components contained within, is still unknown and currently is being assessed at JPL, but this has the possibility of improving by the use of alternate cathode binder materials, separators and seal designs. Likewise, the shock sensitivity of the cells, if needed, can be enhanced through modifications in electrode/cell design. The current versions are not compatible with the NASA standard planetary protection method of Dry Heat Microbial Reduction (DHMR) to make the batteries pristine biologically to allow them to be used in planetary missions seeking the presence of extra-terrestrial life. The DHMR results in a substantial performance loss instantaneously and also in unknown effects on their subsequent ability to be stored. Currently, irradiation to high levels of gamma radiation appears to be a viable approach for achieving the bio-sterility required as part of planetary protection.

a) 

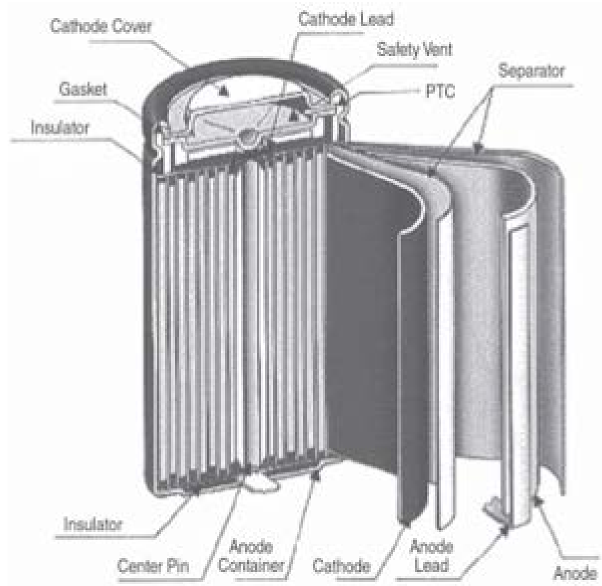
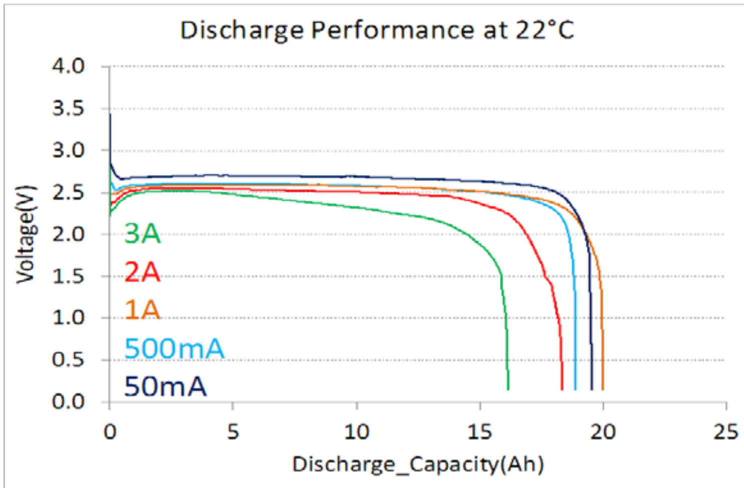
b) 

Figure 4-2. a) Typical D-cell aluminum can b) Interior of a D-cell and c) Performance of Li-CFx D cell at different discharge currents. High specific energies are realizable at moderate rates of <2 A (or ~10 h discharge rate) at 22°C.

c) 

Technical Directions: In order to provide planetary missions with Li/CF_x primary batteries that have high specific energy >700 Wh/kg), moderate power densities (>200 W/kg), long life (10–15 years), and the ability to operate in low temperature environments (to −80°C), the research and development efforts should focus on the following areas:

- New electrolytes with suitable electrolyte, salts, and additives that enhance the ionic conduction and reduce the passivation effects of cathode to improve the rate capability and low temperature performance.
- Modified electrode designs with dense electrodes, thin current collectors and lightweight cell cans for enhanced specific energy and energy density.
- Evaluation of alternate cathode and binder materials and seals to improve the radiation tolerance.
- Development of robust cell designs to withstand high shock levels.
- Understanding the effects of radiation or high-temperature exposure to develop methods for planetary protection.

Potential Capabilities: Advanced Li-CF_x batteries have the potential to offer: a) specific energy of 400–500 Wh/kg, b) energy density of 600–700 Wh/l, c) shelf-life of >10 years, and d) a wide operating temperature range of −30°C to 60°C.

4.1.3 *Improved Lithium-Carbon Monofluoride Hybrid (Li/CF_x-MnO_2) Cells*

Potential Benefits and Applications: Potential payoffs of (Li/CF_x-MnO_2) batteries are: a) 2× the mass and volume savings relative to SOP Li-SO_2 and Li-$SOCl_2$ batteries, b) wider operating temperature range (−40°C–60°C), c) minimal voltage delay, and d) improved shelf life characteristics. This cell system is very attractive for planetary probes and surface missions that require high energy density primary batteries, moderate power densities and low temperature operations.

Chemistry: The chemistry involves a Li anode and a hybrid cathode comprising carbon monofluoride and manganese dioxide (or silver vanadium oxide) in an electrolyte containing propylene carbonate (PC), dimethoxyethane (DME), tetrahydrofuran (THF) (in some cases), and with $LiBF_4$ or $LiClO_4$ salt. The chemistry of the (Li/CF_x-MnO_2) cell involves two different cathode reactions, i.e., reduction of MnO_2 followed by the reduction of CF_x as shown below:

$$\begin{array}{lcl} xLi + CF_x & \Rightarrow & xLiCF_x \\ xLiCF_x & \Rightarrow & xLiF + C \\ \hline xLi + CF_x & \Rightarrow & xLiF + C \end{array}$$

$$\begin{array}{llcl} \text{Positive reaction:} & MnO_2 + Li^+ + e^- & \rightarrow & MnOOLi \\ \text{Negative reaction:} & Li & \rightarrow & Li^+ + e^- \\ \text{Total reaction:} & MnO_2 + Li & \rightarrow & MnOOLi \end{array}$$

The hybrid chemistry addresses some of the challenges of the Li-CF_x chemistry, i.e., it displays: a) reduced heat dissipation at moderate to high rates, b) reduced voltage delay at low temperatures and high rate, and c) reduced cost. The hybrid chemistry provides improved discharge rate capability, especially at low temperatures, as well as enhanced safety characteristics. The higher the percentage of MnO_2, the lower the heat generation observed. The hybrid cathode cells show 25–50% less heat generation compared with the cells containing l-CF_x cathode.

Status: SOA Li/CF_x-MnO_2 batteries have impressive specific energy and energy densities, slightly lower than the Li-CF_x cells, but have improved rate capability and safety. Interestingly, the ratio of MnO_2 to CF_x can be tailored to the needs of the applications. There are significant efforts ongoing at the DoD laboratories (Army-CECOM) for the replacement of BA5590 Li-SO_2 batteries. These efforts are focused on improving the rate capability and low temperature capability of this system. A few companies, including EaglePicher, Ultra-life, Rayovac, and Quallion, have been actively improving this system for the DoD application. This system is of great interest to future outer planetary missions, because of its higher energy density and longer shelf life. Recent improvements observed with lightweight aluminum cans have resulted in impressive performance characteristics: capacity of >16 Ah in a D-size cell, corresponding to a specific energy of over 600 Wh/kg and an energy density of 900 Wh/l (Figure 4-3).

Key Issues: As with the Li-CF_x cells, the poor rate capability of Li-CF_x-MnO_2 cells, especially at low temperatures is due to three factors: a) low conductivity of the cathode material, CF_x, which is a dominant component, b) low conductivity of the electrolyte at low temperatures, and c) low surface area of thick electrodes utilized in existing cells. The rate capability at low temperatures can be improved by the use of alternate electrolytes that include linear and cyclic ether co-solvents and suitable salts and electrolyte additives. Alternate cathode binder materials and improved seal designs are promising approaches to increasing the radiation tolerance. The shock sensitivity of the cells can be greatly enhanced through modifications in electrode/cell design. As with other SOP primary battery chemistries, the current Li/CF_x-MnO_2 versions are not compatible with the

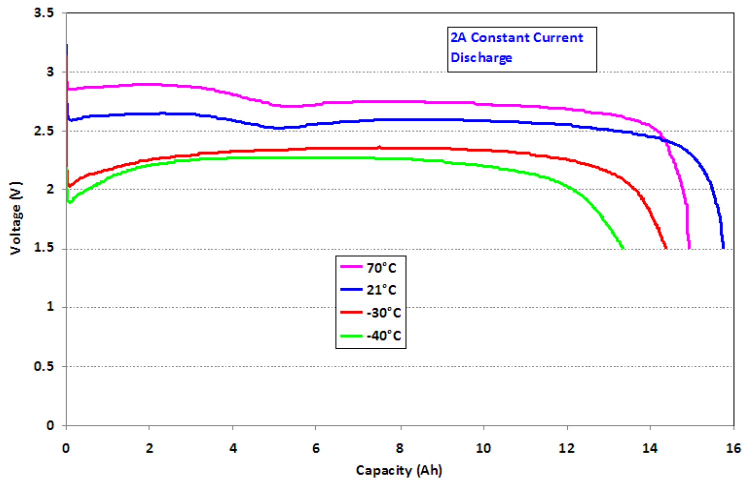


Figure 4-3. Performance of Li/CF_x-MnO_2 D cell at different temperatures. The CF_x-MnO_2 hybrid cathode allows operations over a wide range of −40°C to 70°C.

standard planetary protection method of Dry Heat Microbial Reduction (DHMR) to make the batteries pristine biologically and allow them to be used in planetary missions seeking the presence of extra-terrestrial life. Again, this results in a substantial loss of performance instantaneously and also in unknown effects on their subsequent storage ability. Currently, irradiation to high levels of gamma radiation appears to be a viable approach for achieving bio-sterility required by planetary protection.

Technical Directions: In order to provide PSD with Li-CF_x-MnO_2 hybrid primary batteries that have high specific energy (>600 Wh/kg), moderate power densities (>200 W/kg), long life (10–15 years), and the ability to operate in harsh temperature environments (to −60°C), developments should focus on the following areas:

- New electrolytes and salts that enhance the ionic conduction and reduce passivation effects of the cathode to improve rate capability and low temperature performance.
- Modified electrode designs with dense electrodes, thin current collectors, and lightweight cell cans for enhanced specific energy and energy density.
- Optimization of CF_x to MnO_2 ratio in the cathode.
- Evaluation of alternate cathode and binder materials, as well as seals, to improve the radiation tolerance.
- Development of robust cell designs to withstand high shock levels.
- Enhancing the understanding of the effects of radiation or high-temperature exposure to develop methods for planetary protection.

Potential Capabilities: Advanced Li/CF_x-MnO_2 batteries have the potential to offer: a) specific energy of 350–450 Wh/kg, b) energy density of 550–600 Wh/l, c) shelf-life of >10 years, d) a wide operating temperature range of −40°C to 60°C, e) moderate power densities of 200 W/kg, and f) improved safety.

4.2 Advanced Rechargeable Batteries

The state of practice Li-ion batteries have low specific energies (<150 Wh/kg) and energy densities (<400 Wh/l) at the cell level, especially with respect to large format aerospace cells. The heritage commercial 18650-size cells (Sony Hard carbon) have even lower specific energy density. However, some of the recent commercial 18650-size cells (Panasonic, LG, Sony, and Samsung) have higher specific energy (250 Wh/kg) and energy density (600 Wh/l), but they are yet to be qualified for aerospace use. As a result of the low specific energy and energy density, the SOP Li-ion batteries are heavy and bulky. In order to circumvent the limitations from the SOP rechargeable batteries, several advanced systems are under development, which include: a) Long-life Li-ion batteries, b) Low temperature Li-ion batteries, c) Lithium solid state inorganic electrolyte batteries, d) High specific energy Li-ion batteries, e) Lithium-sulfur batteries, f) Li rechargeable batteries with alternate anodes, and g) high temperature batteries. Below is a brief description of each of these systems.

4.2.1 *Long-Life Li-ion Batteries*

Potential Benefits and Applications: Lithium-ion batteries are very attractive for planetary orbiters, due to the advantages in specific energy, energy density coulombic and energy efficiency and self-discharge compared to the aqueous systems. Extending the life of the SOP Li-ion batteries (including both cycle life and calendar life) is one area where there is considerable interest by all the aerospace organizations, whether to extend the life of a planetary mission, a satellite, or to reduce the replacement costs, e.g., International Space Station (ISS).

Chemistry: The chemistry of advanced long-life systems is similar to the state of practice Li-ion batteries, with a carbonaceous anode and either a metal oxide or phosphate cathode in an electrolyte comprised of carbonate-based solvents (Ethylene Carbonate, Propylene Carbonate, Diethyl Carbonate, Demethyl Carbonate), $LiPF_6$ salt, and selected additives (Vinylene Carbonate, Vinyl Ethylene Carbonate, etc.).

Status: SOP Li-ion batteries, especially with large format cells, provide good cycle life of > 30,000 cycles at 30% depth of discharge and a calendar life of ~10 years. However, these life characteristics are only possible at *shallow depths of discharge* of <30% and also at benign temperatures of ≤25°C. Higher depths of discharge, or temperatures, will lead to faster capacity fade. Heritage 18650-size cells (Sony hard carbon) display comparable life characteristics, but the recent high energy versions have limited life characteristics. There is *no* developmental work ongoing in the NASA laboratories, but there are considerable efforts in industry and in the DoE laboratories to improve life characteristics, especially for vehicular applications (for surface applications on Earth).

Key Issues: The causes for the limited cycle/calendar life are commonly attributed to one or more of the following processes: a) electrolyte degradation by electrochemical reactions at the electrodes, b) loss of reversible lithium due to electrode passivation (solid electrolyte interface film formation) processes, c) structural degradation of the cathode, and d) increased interfacial impedance at the electrodes due to the passivation processes. Beyond this nominal capacity fade, there may be rapid failures resulting from lithium plating and dendrite formation, internal shorts, and internal pressure build-up due to the formation of gaseous products from electrolyte reactions. Another difficulty in effectively developing long-life Li-ion batteries is that real-time storage tests take unreasonably long times and acceleration methods are uncertain about their predictability.

Technical Directions: To improve the cycle life capability of these batteries, industry is focusing its efforts in the following areas: a) establishment of stringent process controls, b) optimization of operational regimes (depth of discharge, charge voltage selection and temperature of operation), and c) minor modifications in cell chemistry in terms of electrolytes and electrode additives. In addition to electrolyte, the electrode materials (cathode and anode) play a strong role in determining the cycle life characteristics. Among the various cathode materials investigated, the cycle life decreases in the following order: $LiFePO_4$ > Lithium Nickel Manganese Cobalt oxide > Lithium nickel cobalt aluminum oxide > Lithium Manganese spinel oxide>Lithium cobalt oxide > Lithium nickel cobalt oxide) Among the anodes, the cycle life decreases with the following trend: Lithium Titanium Oxide (LTO) > hard carbon > graphite. However, some of these materials that provide long-life (such as $LiFePO_4$ and LTO) provide low specific energies. The approaches currently being adopted include developing new surface-modified and high-capacity cathodes (Ni-rich NMC cathode) with new electrolytes (additives/co-solvents), which also provide higher specific energies compared to SOP batteries.

Potential Capabilities: Upon successful completion of these efforts**,** advanced long-life Li-ion batteries are projected to have following characteristics: a) specific energy of 150–200 Wh/kg, b) energy density of 300–400 Wh/l, c) cycle life of >100,000 at 30% depth of discharge, d) calendar life of >20 years, and e) an operating temperature range of −10°C to 25°C.

4.2.2 *Low-Temperature Li-ion Batteries*

Potential Benefits and Applications: Li-ion batteries with improved low temperature performance are desired for near-term and mid-term solar-powered planetary surface missions. They are particularly beneficial for future missions to Ocean Worlds and Icy Moons. Small rovers and probes do not have elaborate thermal management for the batteries. Batteries with inherent ability to operate at low temperatures of −60°C to −80°C would be desired for such surface missions.

Chemistry: The chemistry is similar to the SOP Li-ion batteries, with a carbonaceous anode and either a metal oxide or phosphate cathode, used in conjunction with a low temperature electrolyte comprised of carbonate-based solvents (EC, PC, DEC, DMC), ester co-solvents (i.e., methyl butyrate, methyl propionate, ethyl propionate, etc.), $LiPF_6$ salt, and selected additives (VC, FEC, LiBOB, etc.).

Status: JPL has developed several generations of low-temperature electrolytes with co-solvents and additives and demonstrated improved operation to −60°C. The first generation electrolyte (a ternary all-carbonate blend) was used in the earlier Mars missions. The upcoming Mars InSight will use a lower temperature (−40°C) electrolyte with an ester-blended solvent. The early versions of 18650-size cells did not have appreciable performance at low temperature. In some of the recent versions, however, various low temperature electrolytes are being incorporated. Use of good low temperature electrolytes with the high-energy cell deigns will result in cells that have both these beneficial attributes. JPL has recently demonstrated specific energies of ~150 Wh/kg at −40°C and over 100 Wh/kg at −60°C to −70°C, at low discharge rates in commercial 18650-size cells with the JPL electrolytes. These cells can also be charged at ≥ −40°C without Li plating. There is some ongoing work at JPL to develop low temperature Li-ion cells. Considerable effort is being made in the industry and the DoE laboratories to enable operation to −30°C in the context of electric vehicles.

Key Issues: Significant improvements have taken place over the last several years to improve the performance of Li-ion cells from −20°C to −40°C. However, the power and energy capabilities of SOA Li-ion cells are poor at −40°C, and require further improvement for future planetary surface applications. Even though electrode materials determine the low temperature kinetics, the electrolyte has probably the most dramatic impact on low temperature performance not only for ionic mobility but for interfacial stability as well. Another factor limiting performance is poor lithium diffusivity within the bulk of the electrode material.

Technical Directions: The approach being adopted by the industry and DoE laboratories, to improve the low temperature performance involves developing low temperature electrolytes that are ionically conducting at low temperatures and form stable and kinetically-favorable surface films on the electrodes at low temperatures. Low-viscosity and low-melting point solvents, aliphatic esters and their fluorinated analogues, would be beneficial as co-solvents. Likewise, certain additives can modify the SEI properties favorably for good stability and kinetics at low temperatures. Additionally, new electrode materials with enhanced kinetics for lithium intercalation and for Li^+ diffusion will also contribute to improved low temperature performance.

Potential Capabilities: Upon successful completion of the above efforts, the advanced long-life Li-ion batteries will have the following characteristics: a) specific energy of 150–200 Wh/kg, b) energy density of 300–400 Wh/l, c) cycle life of >500 at 100% depth of discharge, d) calendar life of ~5 years, and e) an operating temperature range of −60°C to 30°C.

4.2.3 *Lithium Solid-State Inorganic Electrolyte Batteries*

Potential Benefits and Applications: All solid-state lithium batteries have the potential to satisfy the long calendar life and radiation tolerance requirements of outer planetary missions with calendar life of more than 15 years and tolerance to radiation levels of >20 MRad. They will also be useful in micro/nano-spacecraft by virtue of their fabrication and co-location with devices and sensors on silicon chips possible by the compatible fabrication techniques of integrated circuits. This co-location could yield highly integrated, miniaturized micro-systems enabling several “niche” applications, such as autonomous micro-sensors, self-powered memory chips, micro-spacecraft, and “systems-on-a-chip”-based devices. Upon scaling up to reasonable cell sizes, the solid-state lithium cells could be attractive options for deep space missions requiring long calendar/operating life.

Chemistry: Solid-state inorganic lithium rechargeable batteries are similar to the Li-based solid polymer electrolyte rechargeable batteries. The difference is in the electrolyte layer, which is an inorganic amorphous or glassy compound with good permeability for lithium ions at ambient temperature. In solid-state inorganic lithium rechargeable batteries, lithium metal is typically used as the anode material, transition metal oxides/chalocogenides are used as the cathodes, and inorganic solid materials (garnet oxides, phosphates, lithium phosphorus oxynitride [LiPON; developed at a DoE lab]) are employed as electrolytes. The electrode materials used in these batteries are usually the same as those employed in liquid electrolyte-based Li-ion batteries. The total cell thickness used in these systems is usually on the order of 20–100 microns.

Status: Solid-state inorganic lithium rechargeable batteries are projected to deliver high specific energy and energy density over a wide operational temperature range (0°C to 80°C), while providing tens of thousands of cycles. These solid-state batteries offer enhanced safety compared to other Li-ion batteries with liquid electrolyte or with gel polymer electrolyte. New solid electrolytes have emerged recently with decent ionic conductivity and (some) stability toward Li. These include garnet oxides (e.g., lithium lanthanum zirconium oxide, LLZO), LATP (Lithium Aluminum Titanium Phosphate), and LiPON. Good performance is shown in small coin cells with these electrolytes. With LiPON, good cycle life of over 80,000 deep discharge cycles and a calendar life of about 10 years were demonstrated. Considerable efforts are ongoing in the DoE laboratories, universities, and in industry to mature these technologies but there are no ongoing efforts within NASA although JPL has developed these micro-batteries in the past under a System on a Chip (SOAC) effort.

Key Issues: The technologies are in very early stages of development and still need development of a suitable packaging process. The state-of-the-art cells have extremely low capacity (a few micro-mAh) and the power densities are at least an order magnitude lower than desired for many applications. Significant advances are needed at the materials level before this technology can be considered for future space applications. One major deficiency of today’s lithium thin-film battery technology is the low area-specific capacity, which is due to the inability to use thicker electrodes, because of delamination issues or conductivity problems.

Future Directions for Lithium Solid Inorganic Electrolyte Battery Development: New inorganic solid-state electrolytes are needed with high conductivity (10^{-4} S/cm), stability and manufacturability to fabricate thin (10 µm) membranes. Additionally, there is a need to develop thicker composite cathodes with improved electronic and ionic conductivity for enhancing the area-specific capacity and hence power densities and develop:

- fabrication methods to construct high capacity cells and batteries.
- methods for cell sealing or enclosure.

Potential Capabilities: Advanced solid-state Li batteries will have the following characteristics: a) specific energy of 250–350 Wh/kg, b) energy density of 300–400 Wh/l, c) cycle life of >10,000 at 100% depth of discharge, d) calendar life of >20 years, and e) an operating temperature range of 10°C to 80°C.

4.2.4 *High Energy Li-ion Batteries*

Potential Benefits and Applications: Lithium-ion batteries with high specific energy and energy density are very attractive for planetary rovers, landers, and probes. They are also beneficial in miscellaneous applications, such Extra-Vehicular Activities (EVA), CubeSats, etc., where lightweight and compact batteries are desirable.

Chemistry: The chemistry is similar to the SOP Li-ion batteries, but with active materials that have higher specific capacities and/or higher voltages. The anode is a Si alloy anode, which provides >3× specific capacity compared to carbonaceous anodes and cathodes with higher voltages and or higher specific capacities, including the nickel manganese cobalt (NMC) cathodes with gradient composition (Ni in the core and Mn on the shell) with suitable surface treatments. Other cathodes include 5 V systems such as lithium manganese nickel spinel oxide and lithium cobalt phosphate. More futuristic cathodes will have multi-valent conversion cathodes in place of the intercalation systems.

Status: Several organizations, including NASA, DoE, DoD, and universities have undertaken R&D projects to develop both the high-capacity cathode and anode materials. These efforts were focused on Si anode with 800 mAh/g and Li-rich NMC cathode with a specific capacity of 250 mAh/g with a voltage of 4.5 V. While the Li-rich NMC materials could not be implemented in full cells due to problems related to irreversible capacity, electrolyte instability (at 4.8 V) and structural instability of the cathode, new cathode materials with Ni-rich NMC in the core and Mn-rich composition on the shell have emerged as possible alternates. They show specific capacities of 220 mAh/g (~25% improvement over SOP) at 4.3 V and excellent cycle life, often with new electrode coatings and electrolyte additives. Si anode development has also progressed well with new nano-silicon structures (nanorods) displaying high specific capacities (800 mAh/g) and good cycle life (500 cycles) as evident from the recent Amprius' data.

Key Issues: The difficulties with the higher capacity cathodes are: a) structural instability, b) dissolution of metal ions into electrolytes, c) low conductivity of the cathode materials ($LiCoPO_4$), d) poor oxidative stability of the electrolytes at the high voltages, and e) poor reversibility of the conversion cathodes. Problems with the silicon anode, more evident in electrodes with high electrode loadings, are related to its significant volume changes (up to 400%) upon lithiation causing electrode fracture, continued reactivity of the electrolyte, and high irreversible capacity. Finally, it is a challenge to have electrolyte stable at high voltages, and at the same time stable at the anode potentials.

Technical Directions: The approach to improving the stability of the cathodes is to have a gradient composition on the cathode, i.e., to identify suitable composition on the surface (Mn-rich), while maintaining a high capacity material in the core. Surface coatings on the cathode, for example AlF_3 and $AlBO_3$, have shown promise in stabilizing the cathode operating at high voltages. New electrolyte solutions, with new co-solvents, e.g., with fluorination, as well as with suitable electrolyte additives (such as VC, VEC, Lithium bis(oxalato)borate, and Lithium difluoro(oxalato)borate), have shown encouraging results. Stabilizing the silicon anode requires suitable nanostructures resilient to the volumetric stresses and interesting results have been obtained in laboratory cells, especially when mixed with graphite. However, their implementation in large cells with high loadings is yet to be verified.

Potential Capabilities: Advanced High Energy Li-ion batteries should have the following characteristics: a) Specific energy of 150–200 Wh/kg, b) Energy density of 300–400 Wh/l, cycle life of >500 at 100% depth of discharge, calendar life of ~5 years and an operating temperature range of −20°C to 40°C.

4.2.5 *Advanced Lithium – Sulfur (Li-S) Batteries*

Potential Benefits and Applications: Li-S batteries are projected to provide very high specific energy (>400 Wh/kg) and energy density (>500 Wh/l) compared to other advanced rechargeable battery systems. Although projected to exceed the other advanced systems, this technology is progressing slowly, presently only at an early stage of development, small capacity cells (2 Ah) are being made and tested. The system is being developed primarily by universities, research start-up companies, such as SION Power, EaglePicher, and Oxis Energy.

Chemistry: Li-S batteries are based on the lithium metal anodes and sulfur or polysulfide cathodes and the overall cell reaction is:

$$16\,Li + 8S \Rightarrow 8Li_2S \qquad \text{(Sulfur cathode)}$$

The reaction of sulfur involves the formation of various lithium polysulfides, which are soluble in many of the liquid electrolyte. They then diffuse to the anode to become oxidized to higher molecular weight polysulfides and shuttle back to the cathode to get reduced again, forming a redox shuttle (Figure 4-4). Some of the reduction production Li_2S and Li_2S_2 are less soluble, resulting in deposition on the anode and, thus, poisoning it. This problem with the polysulfide shuttle has been a serious deterrent to the implementation of this technology.

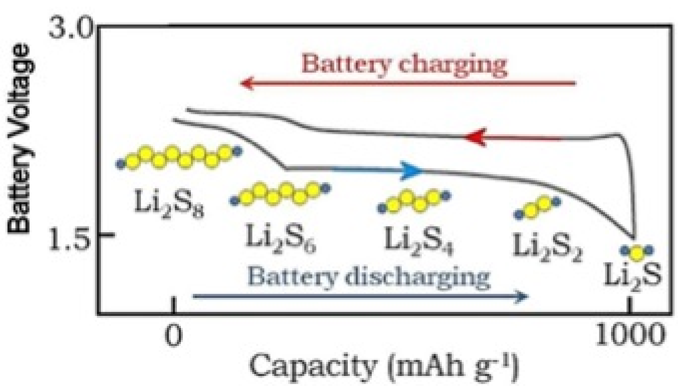


Figure 4-4. Reactions in a Li-S cell

Status: Sulfur has long been of interest as a cathode reactant because of its low equivalent weight and high reduction potential. Sulfur is an insulator, and needs to be mixed with a high proportion of a conductive diluent. Also, sulfur forms lithium polysulfides during reduction, which are soluble in many organic electrolytes and form a polysulfide shuttle, which affects the capacity, coulombic efficiency and cycle life. Among the different electrolytes, conventional carbonate-based electrolytes are incompatible. Only ether-based electrolytes seem to be stable towards sulfur and polysulfides. Recently, some success has been reported with hierarchical porous carbon structures that confine sulfur and its reduction products within the cathode structure and improve cycle life and, thus, this technology has gained considerable momentum. Graphene is also found to be superior in retaining sulfur products within the cathode. But the gravimetric and volumetric loading of sulfur is low in these cases. Other significant efforts include developing high capacity sulfur cathodes by blending them with the transition metal sulfides, electrolytes based on ionic liquids, solid electrolytes based on sulfide glasses, polysulfide blocking layers in the form of metal oxides (e.g., MnO_2, V_2O_5) and protected lithium anodes with either polymer or solid electrolytes. Glass electrolytes, such as the Thio-LiSi-CON family and LiPON and garnet oxide solid electrolytes, offer promise of higher cell efficiency and elimination of the polysulfide "shuttle". Construction materials also present significant challenges. Several organizations, including NASA, DoE, DoD, and several universities have undertaken R&D projects to develop high energy and long-life Li-S cells. A few battery companies, including Sion Power, Oxis Energy, and EaglePicher, have been fabricating experimental/prototype cells in pouch configuration with a capacity of 2–10 Ah capacity. These cells typically either have high specific energy (>350 Wh/kg) and short cycle life (<100 cycles) or moderate specific energy (300 Wh/kg) and long cycle life (500 cycles).

Key Issues: The polysulfide shuttle in still a major hurdle and there are not many electrolyte solutions compatible with the sulfur chemistry (e.g., conventional carbonates are not stable); only ether-based systems are known to be compatible. These problems are more evident in electrodes with high electrode loadings. Good cycle life has been achieved only with cathodes with low sulfur loadings, which may not lead to high specific energy density in the Li-S cells. The problems with the Li metal anode are known, i.e., the dendritic deposition of lithium during cycling, which causes premature cell failures and serious safety problems. Various electrolytes have been studied, even before the advent of lithium-ion batteries, but the problem continues to be unsolved and challenging.

Technical Directions: New approaches are needed for containing sulfur and its reduction products within the cathodes, by identifying proper cathode designs, which may include novel nanostructured porous structures, or blending with selected transition metal chalcogenides with stronger interaction with the sulfur in the cathode. Alternately, new electrolyte solutions compatible with the sulfur chemistry and with minimum solubility for polysulfides (either organic electrolytes or ionic liquids) are required to address this problem. The use of solid electrolytes is also a potential approach although it would require well-designed composite cathodes with an ionic conductor blend and their implementation in laboratory cells with high loadings and high cell capacity is yet to be verified.

Potential Capabilities: Advanced lithium-sulfur batteries will have the following characteristics: a) specific energy of 250–300 Wh/kg, b) energy density of 300–350 Wh/l, c) cycle life of 100–500 cycles at 100% depth of discharge, d) calendar life of ~5 years, and e) an operating temperature range of −40°C to 30°C.

4.2.6 *Lithium Rechargeable Batteries with Alternate Anodes*

Potential Benefits and Applications: In these systems, the carbonaceous anodes in Li-ion cells are replaced with high capacity alternates, such as Li alloys of Si or Sn or with lithium metal, and combined with the traditional Li-intercalating metal oxide cathode. Compared to a graphite anode, the Si alloy anode or the Li metal anode provides about 8–10× improvement in theoretical capacity or about 3–4× improvement in experimental specific capacities. This will result in rechargeable batteries with high specific energies and energy densities and good low temperature performance. These batteries will be attractive for planetary rovers, landers, and probes, which require short cycle life and good low temperature performance. They are also beneficial in various other space applications, such as CubeSats, planetary helicopters, where lightweight and compact batteries are desirable.

Chemistry: These batteries are based on lithium alloys with Si (or Sn) or Li metal as anode and lithiated metal oxides (LCO, NCA, or NMC) or phosphates (LFP) as cathodes. Silicon has higher capacity because of its ability to react with 4.4 atoms of lithium per each Si atom, while six atoms of carbon react with one lithium atom. But the volume change upon lithium alloying is substantial in silicon (400%). The experimental specific capacities are 800–1500 mAh/g, compared to ~372 mAh/g for graphite. Likewise, lithium metal has a specific capacity of 3.82 Ah/g, but typically about 2–4× excess lithium is used to account for the losses from Li passivation/isolation. Even with that excess Li, the specific capacity is 3–4× that of carbon. Electrolytes for both Li and Si anode need to be optimized to minimize dendrites in the former case and to provide a stable solid electrolyte interphase (SEI) in the case of Si. Addition of mono-fluoroethylene carbonate (FEC) to the conventional carbonate electrolytes seems to a successful approach for the Si anode.

Status: Several organizations including DoE, DoD, and industry are focusing on the development of durable Si anode for Li-ion cells. To stabilize the Si anode against volume stresses during cycling, various nanostructured silicon anodes have been developed, including forming nanocomposites with graphene, use of silicon whiskers and nano-fibers and silicon nanoparticles in graphite composites. Notable success has been achieved with silicon nanorods deposited using CVD onto a metallic substrate and are being used in prototype cells by Amprius. These electrodes are not compatible with wound cells and only pouch or flat plate cells are being made with these electrodes. These cells show specific energies of 300 Wh/kg and energy densities of 800 Wh/l and a decent cycle life of 300 cycles. In addition to Amprius, 3M has been developing a nanostructured Si, using graphite-nanosilicon composites and claim to achieve equally good performance in 18650-size cells. The commercial battery manufacturers have started introducing small amounts of silicon (5–10%), to achieve higher specific energy and more importantly higher gains in the energy densities.

In contrast to the silicon anode, the development of the lithium metal anode is much slower, due to the challenge associated with the tendency of Li to form dendrites during cycling. Various organic electrolytes, consisting of solutions comprised of ether and carbonate-based co-solvents, and ionic liquids have been extensively studies but with limited success. Polymer electrolytes seem to offer some benefit over liquid electrolytes. Gel polymer electrolytes behave much like the liquid electrolyte, but solid polymer electrolytes (such as polyethylene oxide-based systems) seem to have some advantages, but require operation at 80°C or above. Hydro-Québec utilized these PEO-based polymers in Li cells in 1990s. Recently, Seeo, Inc., has developed a polystyrene–cross linked PEO polymer, and has been producing prototype cells (TRL 4) with lithium iron phosphate (LFP) cathodes. More recently, Solidenergy claims to have developed a safe electrolyte that will enable the use of Li metal as the anode (Figure 4-5). This polymer electrolyte will also serve as the separator in these cells.

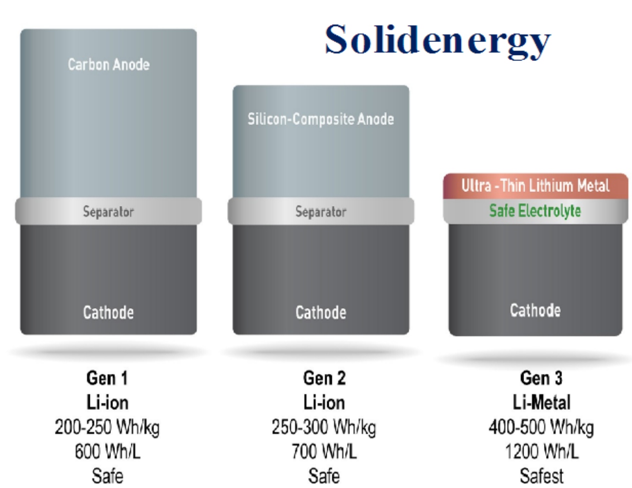


Figure 4-5. Projected performance of Li metal based technologies by Solidenergy

Key Issues: The problems with the Si anode are related to the volume expansion during lithiation (400%), which results on continuous fragmentation of the Si particle, which consumes more electrolyte for the electrode passivation (SEI formation). The SEI surface film formed on Si is not as stable and protective as with the graphite anode and leads to considerable irreversible capacity. As mentioned above, the challenge with the Li anode is its tendency to form dendrites during charging, which affects both performance and safety. In addition, the plated Li is known to be highly pyrophoric and the lithium surface needs to be protected either with an in-situ SEI or with an external coating of polymeric or ceramic electrolytes.

Technical Directions: New nanostructured silicon materials are required that can withstand the volumetric stresses during cycling. Silicon nanorods, whiskers, and graphene-nanosilicon composites look promising. New electrolytes are also needed that would allow the formation of stable solid electrolyte interface (SEI) on the Si anode. Additionally, the irreversible capacity has to be reduced, otherwise this needs to be compensated by the cathode, which has much lower specific capacity, which reduces the overall cell capacity. Pre-lithiation strategies, such as adding Li-rich compounds to the cathode (i.e., Li_2O) look promising. For the Li anode, new electrolytes need to be developed; electrolytes with high salt concertation, new solid polymer electrolytes and new ceramic electrolytes look promising, e.g., the protected lithium electrode (PLE) developed by Polyplus with ceramic electrolytes. More recently, Ionic Materials claim to have a safe polymer electrolyte for use with Li metal anodes.

Potential Capabilities: Advanced Li metal based system will have the following characteristics: a) specific energy of 250–350 Wh/kg (200 Wh/kg with Si), b) energy density of 300–400 Wh/l, c) cycle life of <500 at 100% depth of discharge, d) calendar life of ~5 years, and e) an operating temperature range of −40°C to 30°C.

4.2.7 *High Temperature Batteries*

Future long duration Venus missions require high temperature batteries. Only short duration Venus surface missions have been carried out so far using SOP primary $Li\text{-}SO_2$ batteries. These batteries cannot operate at high temperatures. Hence, these batteries were enclosed in an environmental chamber along with the payload and other spacecraft subsystems. These batteries have lasted for <2 h, i.e., before the batteries were heated to their maximum survivable temperature of ~80°C. Hence, the SOP batteries are not suitable for long duration Venus missions as they cannot survive high temperature Venus environments. Long duration surface missions require primary batteries capable of operating at Venus surface temperatures (460°C). Venus variable low altitude (low to surface) aerial platform missions require rechargeable batteries that can: a) operate at high temperatures aerial environments (25°C–350°C) for long duration, b) survive high temperatures surface environments (460°C) for short duration.

High Temperature Primary Batteries

Under NASA's Hot Operating Temperature Technology (HOTTech) program, JPL is developing high temperature primary batteries by modifying the design of SOP thermal batteries. SOP thermal batteries are heavy and are suitable only for short term (<60 minutes) operation at high temperatures (460°C) JPL proposes to modify the current thermal batteries to adapt to Venus surface environments. The proposed modifications include: a) eliminating pyrotechnic activation in lieu of in-situ activation by the Venus environment, b) reducing thermal insulation, and c) optimizing the battery components, e.g., thin battery cases. The chemistry will be similar to the SOP thermal batteries, i.e., Li-Si alloy anode, mixed alkali halide molten salt and FeS_2 cathode (or CoS_2 to reduce the self-discharge). The battery is projected to have a specific energy of ~100 Wh/kg and an energy density of 200 Wh/l, compared to the SOP thermal battery (e.g., MSL thermal battery: 40 Wh/kg and 90 Wh/l).

High Temperature Rechargeable Batteries

Several high temperature batteries were developed for electric vehicle applications. Three successful batteries that can operate from 250°C–450°C are: LiAl-FeS_2, Na-S, and Na-metal chloride. These batteries offer relatively high specific energy compared to the aqueous rechargeable batteries and also good specific power outputs. On this basis, the batteries are well suited for long-term Venus surface missions.

LiAl-FeS_2 Batteries: This system was developed extensively at Argonne National Laboratory in the early 1990s. This battery employs a lithium-aluminum alloy anode (Li-Al), a mixed halide electrolyte (LiCl +KCl) and in some cases LiBr as well, and an iron disulfide cathode (FeS_2). The operating temperature range is about 375°C–450°C. The overall cell reaction is:

$$2LiAl + FeS_2 \Leftrightarrow Li_2FeS_2 + 2Al$$

The most advanced version employs a cylindrical, bipolar configuration with disc-shaped elements. A unit cell is comprised of discs of anode and cathode, separator, electrolyte, and inter-cell connectors. The anode is made from pressed powders of the alloy and some electrolyte. The cathode is made of pressed FeS_2 and electrolyte. The separator is made from pressed MgO powder.

Sodium-Sulfur (Na-S) Batteries: This system was among the first of the high temperature batteries widely studied and extensively developed, following the development of the sodium beta alumina ceramic electrolyte that has high mobility for sodium ions at high temperatures. This battery employs a molten sodium anode, a molten sulfur cathode, and a sodium beta alumina ceramic electrolyte/ separator, which has a high sodium ion conductivity of 1–10 S/cm at the operating temperatures, combined with a low electronic permeation. The operating temperature range is 300°C–450°C. The overall cell reaction is:

$$2Na + xS \Leftrightarrow Na_2S_x \quad (x = 2.7 \text{ to } 5)$$

The cell has a cylindrical configuration with an outer metal case and an inner thin cylinder of the sodium beta alumina ceramic electrolyte. The sodium anode is located inside the ceramic electrolyte cylinder and partially contained within yet another thin safety can. The sulfur is contained in the annular space between the electrolyte and the outer can. A graphite-felt material and the outer can serve as the cathode current collector.

Sodium-Nickel Chloride (Na-$NiCl_2$) Batteries: This system is an improvement over the sodium-sulfur battery, with the sulfur cathode replaced with transition metal chlorides in contact with sodium tetrachloroaluminate melt for improved safety. This battery, pioneered in the 1980s by the Beta R&D Company and known as the “ZEBRA Battery” (Zero Emission Battery Research Activities), employs a molten sodium anode, a nickel or iron chloride cathode, a solid beta-alumina electrolyte/separator and sodium tetrachloroaluminate molten salt electrolyte. The operating temperature is 250°C–500°C (Figure 4-6).

The overall cell reaction is:

$$2Na + NiCl_2 \Leftrightarrow Ni + 2NaCl$$

The cell has cylindrical configuration with an outer metal case and an inner thin walled cylinder of the solid beta alumina ceramic electrolyte. The sodium anode is located in the annular space between the electrolyte and the metal case. The metal chloride (either $FeCl_2$ or $NiCl_2$) cathode is located inside the electrolyte tube (Figure 4-6). This cathode is made of porous and partially chlorinated nickel or iron powder. A secondary molten salt electrolyte, $NaAlCl_4$, is added to the cathode material to help conduct sodium ions from the ceramic to the cathode material. The metal case serves as the anode current collector and the metallic nickel inside the cathode material serves

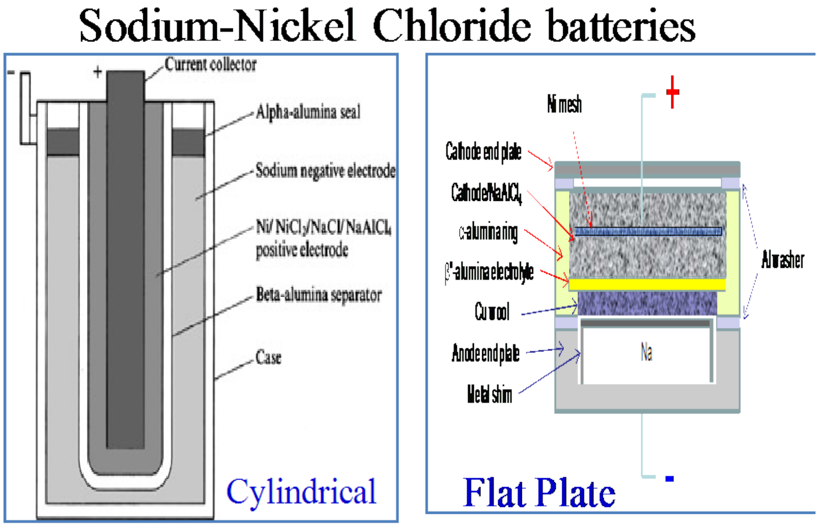


Figure 4-6. Schematic view of tubular and planar Na-MCl_2 batteries

as the positive current collector. Recently, planar Na-MCl_2 (where M indicates either Fe or Ni) is being developed with lower operating temperatures, e.g., 190°C–450°C for grid applications.

Among the three systems described above, only the Na-MCl_2 system is still being pursued, thanks to the efforts of General Electric that developed megawatt (MW) systems based on this technology for grid applications. Even though this technology has achieved a high degree of technology maturation for terrestrial applications, its TRL is rated as 3–4 for aerospace needs as described below under key issues. Although these batteries were designed as rechargeable versions they can function as a primary battery as well. These high temperature rechargeable batteries appear to be a good starting point for potential development of high-temperature primary and rechargeable batteries for Venus exploration. The table below (Table 4-1) shows a comparison of these three battery systems. At the cell level, the energy densities of these systems are in the range of 100–180 Wh/kg and 150–200 Wh/l. At the battery level, the specific energy is ~100 Wh/kg and the energy density is 150 Wh/l. All of the systems offer good coulombic efficiency (near 90%) and voltage efficiencies are also near 90% yielding an overall energy efficiency of near 80% for all three (assuming no heat losses). The cycle life of all the systems is promising, especially for the Na-MCl_2 batteries.

Key Issues: The major unresolved issues include: a) adapting cell and battery designs for space applications, b) Thermal stability of the components at the Venus surface conditions, c) stability of seals and terminals in the Venus environments of high temperatures and pressures, d) corrosion of current collectors at high temperatures, and e) effects of zero gravity upon performance.

Table 4-1. Characteristics of high-temperature batteries

Characteristic	LiAl-FeS_2	Na-$NiCl_2$	Na-S
Operating Temp Range, °C	400–475	250–500	290–450
Open Circuit Voltage, Volts	1.73	2.58	2.08
Theoretical Specific Energy, Wh/kg	490	800	755
Specific Energy for Cells, Wh/kg	90–130	100–130	130–180
Specific Energy for Batteries, Wh/kg	100	90–110	80–120
Energy Density for Cells, Wh/l	150–200	150–190	180
Energy Density for Batteries, Wh/l	Near 150	70–130	90–150
Cycle Life, cycles	>1000	>2000	2000

Technical Directions: Planar beta-alumina solid electrolyte with adequate conductivity at lower temperatures (~190°C) will result in batteries with wide operating temperatures of 190–450°C for Venus missions. Lower operating temperature will minimize the thermally-induced failures in the components and seals and will improve robustness and cycle life. In a similar fashion, new molten salts with lower melting points for the $Li\text{-}FeS_2$ batteries will be desirable for extending the operating range to Venus aerial missions. It is recommended that a system analysis of alternatives for high-temperature rechargeable and primary batteries be conducted for their applicability to Venus (surface and atmospheric) missions. A detailed development roadmap should then be developed for the one or two of the most promising battery concepts with milestones and eventual down-selects to a single battery chemistry.

Potential Capabilities: High temperature sodium and lithium batteries will have the following characteristics: a) specific energy of 100 Wh/kg, b) energy density of 150 Wh/l, c) operating temperature range of 190°C–460°C, which is crucial for Venus missions, d) cycle life of >2000 at 100% depth of discharge, and e) calendar life of 5–10 years.

4.3 Fuel Cells

Fuel cells are particularly attractive for human space missions (such as for crew exploration vehicles, reusable launch vehicles or human lunar precursor missions) that require multi-kilowatts of power for extended periods of up to 10 days. Conventional batteries are not suitable for such applications in view of their much lower specific energy and scalability issues. Planetary science missions require a few watts to 100s of watts for durations of fractions of an hour to a few hours. For these conditions, SOP fuel cells are not attractive due to miniaturization difficulties and system complexity. Fuel cells offer appreciable mass and volume savings (over primary batteries) for planetary science missions that require several days of operation and could be used on extended lunar and Mars missions as described below.

Several types of fuel cells have been under development for a number of commercial and military applications. These include: a) Proton Exchange Membrane (PEM) Fuel cell operating at 80°C, b) Alkaline, system at 175°C, c) Phosphoric Acid at 175°C, d) Molten Carbonate 650°C, e) Solid Oxide, 900–1000°C, f) Direct Methanol Fuel Cells at 80°C, and g) Regenerative Fuel Cells 80–175°C. Among these systems, both the $H_2\text{-}O_2$ PEM fuel cells and regenerative fuel cells are the most promising for future planetary missions and these are described below.

4.3.1 *Polymer Electrolyte Membrane Fuel Cell (PEM)*

Potential Benefits and Applications: Hydrogen-Oxygen PEM fuel cells offer significant improvements over the existing Alkaline Fuel Cells (AFC). PEM fuel cells are also attractive for applications such as Lunar and Mars Base Station power, and Lunar/Mars Surface Exploration Vehicles. PEM fuel cell systems would be ideal for PSD missions in place of lithium primary batteries, e.g., sample return capsules that require 100 kWh or higher (~100 watts for 1000 hours).

Development Status: PEM fuel cell technology is in an advanced stage of development (TRL 4–5). The advances in the PEM system have resulted primarily from a number of development efforts sponsored by Department of Energy, commercial organizations and NASA HEOMD. Most of these development efforts have been focused on terrestrial applications of the PEM for electric vehicles and stationary power applications. Leading companies include Plug Power Systems, and Siemens, International Fuel Cell (IFC).

PEM fuel cells rely on the use of a polymeric proton conducting membrane sandwiched between the platinum-catalyzed hydrogen and oxygen electrodes. Unlike the polyarylsulfonic acid membranes used in early PEM fuel cells, the commercial polyperfluorocarbonsulfonic acid membranes such as Nafion® have been shown to perform over 50,000 hours without significant degradation. Improved processing of catalyst layers and availability of thin membranes with very high conductivity has led to an increase in power density from 40 mW/cm^2 in the late 1960s to 1500 mW/cm^2. Also, cell sizes have increased from a few square centimeters to as high as 1000 cm^2. Stacks with an output as high as 250 kW have been demonstrated by Ballard Power Systems. Siemens has demonstrated submarine propulsion units using hydrogen and oxygen at the 50 kW level achieving an overall system efficiency of about 60–70% operating at 450 mW/cm^2. These performance characteristics represent at least an order of magnitude improvement over the early PEM fuel cells. NASA development programs have resulted in many of the advances in power density and life of the system. The projected advantages of the PEM over the AFC system are summarized in Table 4-2. Inspection of this table shows not only the advantage in power density and life mentioned above, but additional important advantages of the PEM. These additional advantages include: a) capability to withstand much higher pressure differentials (enhances safety) and b) reduced operating temperature (reduces degradation rates and extends life).

Table 4-2. Comparison of alkaline and PEM fuel cell technologies for space missions

Characteristic	Alkaline Fuel Cell	PEM Fuel Cell
Specific Power, Watts/kg	90	100
Power Density, Watts/liter	155	200
Efficiency	70%	300
Maintenance frequency	Every 2600 hours	70%
Differential Pressure Limit	41 kPa	>5,000 hours
Operating Temperature	90°C	300 kPa
Failure Mechanisms	Attack of epoxy frames and Noryl insulator plates by KOH	Degradation above 80°C

Key Issues: The key issues that need to be addressed for transitioning the PEM fuel cell technology to planetary missions are: a) optimization of the balance of plant design, especially with regard to water removal, and minimizing reactant storage mass and volume, b) validation of system performance, c) life demonstration at the system level, and d) miniaturization of fuel cell systems for planetary science applications.

4.3.2 *Regenerative Fuel Cells*

Potential Benefits and Applications: Regenerative fuel cells present an enabling mass-efficient solution for surface electrical energy storage for future long-duration human lunar and martian surface missions. Potentially this type of system can offer as high as 5–10× the storage capability of advanced rechargeable battery systems when the discharge time exceeds 10 hours.

Chemistry/Description: Regenerative fuel cells are used to store electrical energy from a power source, such as a photovoltaic array, to generate hydrogen and oxygen by electrolysis of water. The hydrogen and oxygen so generated are then recombined in the fuel cell as needed, to regenerate electrical energy. Thus, hydrogen/oxygen fuel cells along with water electrolyzers comprise the regenerative fuel cell system.

Early regenerative fuel cell configurations used discrete electrolyzers and fuel cell stacks. Also, early versions focused on using alkaline electrolyte because of the proven flight history with this type of technology. PEM electrolyzer and a PEM fuel cell have replaced the alkaline cell technology. More recently, advanced versions that combine the fuel cell and electrolyzer functions, called “unitized regenerative fuel cells” are under development.

Status: Regenerative fuel cell systems have been under development for over thirty years under NASA/DoD sponsored programs.

In 1995, under a NASA-funded effort, JPL completed a test bed for regenerative fuel cells and then installed and integrated a large, 25 kW, PEM fuel and a 50 kW photovoltaic-powered electrolyzer. The assembly was successfully cycled several times and demonstrated functionality of a complete large scale system. More recently, under a NASA-funded development of regenerative fuel cells, a 15 kW lightweight electrolyzer that can operate up to pressures near 400 psi was demonstrated by Giner, Inc. This electrolyzer operates at about 1000 mA/cm^2 at a cell voltage of 1.72 V operating at 80°C.

In 1998, NASA initiated development of single stack unitized regenerative fuel cells (URFC). Versions of the URFC have now been adapted in terrestrial applications for back-up power applications to replace bulky batteries. Lynntech, Giner, and Proton Energy, Inc., have separately produced unitized regenerative fuel cell designs that can operate in the range of 50–300 psi. The performance of these unitized configurations in the bifunctional mode is comparable to the discrete fuel cells and electrolyzers. Thus, the unitized designs now offer substantial mass reduction because only a single stack is used. Also, common gas and fluid handling subsystems could lead to further reduction in the system mass. Overall efficiencies for the PEM based system operating at 1000 mA/cm^2 in the electrolytic mode and 500 mA/cm^2 in the fuel cell mode have been shown to be 45%.

Key Issues: Although there has been significant demonstration of stack technologies over these years, there has been very little progress on the demonstration of complete systems for space applications. Lifetime studies on the stack and components need to be performed. Development of lightweight hardware, integration of fuel cell, and electrolyzer with high-pressure gas storage, efficient heat rejection strategies in vacuum, and trade-off studies between the unitized and discrete designs need to be addressed.

4.3.3 *Technical Directions*

In order to facilitate the introduction of advanced fuel cells into human space missions and selected planetary science missions, the following efforts are recommended in collaboration with HEOMD:

- A technology maturation program is required to transition the H_2-O_2 PEM fuel cell technology to human space missions.
- Assess the feasibility of miniaturization of H_2-O_2 PEM fuel cells for future planetary science missions.
- Assess relative merits of the unitized and discrete designs and select the most promising design for human space missions. A technology development program is required to improve the efficiency of regenerative fuel cells.

4.4 Capacitors

Capacitors are typically used in most spacecraft as elements of the Power Management and Distribution (PMAD) system for filtering; it is sometimes unclear whether capacitors on a spacecraft should be considered as part of the PMAD Subsystem or part of the Energy Storage Subsystem, but we include them here for completeness.

Supercapacitors, especially the most recent versions, have improved specific energy at the sacrifice of some power density. This is achieved through the substitution of one of the high surface area electrodes, with a lithium intercalating electrode. These capacitors, often termed asymmetric or lithium-ion capacitors, can achieve a specific energy of 15 Wh/kg. However, device characteristics are clearly capacitive, with charge and discharge behavior defined by capacitor equations. Further, these devices can have cycle life that is many orders of magnitude greater than that of any battery. And finally, the power performance of such devices is usually uncharacteristically high for a battery. Thus, classifying these components as capacitors is justified and appropriate.

A traditional capacitor has a specific energy up to 5–10 Wh/kg, orders of magnitude higher than traditional electrolytic based capacitor designs. These capacitors, however, operate at much lower voltage (2.7V to 3V). Specific power levels exceeding 10 kW/kg are achievable, depending on the nature of the load.

Emerging capacitor technologies should achieve 20 Wh/kg in the next several years using material systems presently identified. Trade-offs are possible with this technology to create a lower *energy* density capacitor that has exceptionally high *power* density. This optimization may become commercially available if a clear market develops. The state of the art is expected to progress to 25 Wh/g for energy-optimized devices, which has been demonstrated in laboratory scale devices using graphene and other high energy materials.

Advanced supercapacitors featuring a combination of asymmetric electrodes and organic electrolyte capacitors, are only now starting to appear. Since these feature an organic electrolyte, their operating voltage can be much higher. Many battery-type electrodes are under investigation to determine their suitability for this application.

4.5 Infrastructure

The team has determined that there are two major inadequacies present in the infrastructure that are of concern for the successful development of energy storage technologies required for future Planetary Science missions. The first concern involves the trend of vanishing domestic manufacturing capabilities, and the second involves the lack of adequate performance testing capabilities.

The team recommends that NASA partner with DoD in sponsoring domestic technology maturation and manufacturing technology programs to produce space quality energy storage systems for NASA and DOD. These actions are essential to preserve and maintain U.S. manufacturing capabilities in the area of energy storage technologies.

NASA must have available resources to maintain a healthy testing infrastructure for energy storage systems at GRC, JPL, GSFC/NWSC/Crane and other institutions. The testing infrastructure is essential to assure the quality of flight hardware and reduce mission risk. It is essential that the capability of this infrastructure be maintained and upgraded.

4.6 Summary of Advanced Energy Storage Devices

Primary Batteries

- Advanced lithium-primary batteries under development include advanced Li-CF_x, Li/CF_x-MnO_2, advanced Li-$SOCl_2$ and Li-O_2.
- Among these batteries, Li-CF_x and Li/CF_x-MnO_2 are the most promising for future planetary science missions in view of their higher specific energy, long shelf life, and potential for improved performance at low temperatures.

Rechargeable Batteries

- Advanced rechargeable battery systems under development include long life Li-ion, low temperature Li-ion, Li-inorganic solid electrolyte, lithium-sulfur, and lithium metal-based batteries. These advanced Li batteries are projected to offer one or more of the following advantages: a) higher specific energy and energy density (2–3× compared SOP Li-ion batteries, b) long cycle life and calendar life, and c) improved low temperature performance.

- Among these systems, the advanced Li-ion batteries have the highest potential to meet the near- to mid-term needs of planetary science missions in view of its high level of technical maturity, improved cycle life, and low temperature performance capabilities.
- NASA PSD funding of low temperature Li-ion battery technology is required to produce products in 5–10 years.
- In the long run (>10 years), advanced Li batteries with solid electrolytes may provide advantages over Li-ion batteries with liquid electrolytes.

High Temperature Batteries

- High temperature battery systems that are attractive for near term Venus surface mission applications are: a) LiAl-FeS_2 and b) Na-Metal Chloride. These systems were brought to fairly advanced stage of development (TRL 3–4) for the EV and grid scale applications.
- It is recommended that a *system* analysis of alternatives for high-temperature rechargeable and primary batteries be conducted for their applicability to Venus (surface and atmospheric) missions. A detailed technology plan should then be developed for the one or two of the most promising battery concepts.

Fuel Cells

- Fuel cells are attractive for human space missions that require multi kilowatts power for extended periods, of up to 10 days. Conventional batteries are not suitable for such applications in view of their lower specific energy and scalability issues.
- Advanced fuel cell systems under development include: Polymer electrolyte membrane (PEM) fuel cells, solid oxide fuel cells, and regenerative fuel cells. Among these systems, H_2-O_2 PEM fuel cells and regenerative fuel cells are the most promising systems for future human space missions, in view of their performance advantages and advanced stage of development.
- Small PEM fuel cells are attractive for *planetary* science missions that require power levels of 100–500 W and above for 20–30 hours. Initial system studies indicate *system level* specific energies of 400 to 700 Wh/kg are achievable for applications with discharge times of 20–30 days.

Capacitors

- Advanced capacitor technologies under development include ultracapacitors and supercapacitors. These capacitors have 2–3× higher specific energy compared to the SOP double-layer capacitors and can deliver thousands of cycles with minimal degradation in performance. They also offer wide temperature operation, with cells operating at a low temperature of <−40°C, with other cells operating to 150°C. These are useful for applications with short high discharge pulses and in hybrid systems. Supercapacitors are currently baselined for several small probe applications, CubeSat power supplies, small Mars probes with milliwatt power supplies (MASER), and ice transceivers used with melt probes.

5 Major Findings & Recommendations

This section gives a summary of major findings and recommendations of the assessment team on the energy storage technologies required for the next decadal planetary science missions.

5.1 Major Findings

Findings of the study are grouped into three major areas: 1) energy storage system needs of future planetary science missions, 2) capabilities and limitations of SOP energy storage systems, and 3) status of advanced energy storage technologies.

5.1.1 *Energy Storage System Needs of Future Planetary Science Missions*

Energy storage systems required for planetary exploration missions have several unique needs compared to Earth orbital or human space flight missions and the energy storage systems requirements vary significantly based on the destination, environment and mission type. The major findings are described below and summarized in Table 5-1.

- Outer Planet orbital/flyby mission concepts require advanced rechargeable batteries with long calendar life (>15 years), high specific energy (>250 Wh/kg), high energy density (>500 Wh/l), and Ocean Worlds missions need to be compliant with planetary protection requirements.
- 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), and be compliant with planetary protection requirements.
- Venus aerial mission concepts (upper-medium atmosphere) require advanced rechargeable batteries with high specific energy (>1000 Wh/kg) and with an ability to operate over a wide temperature range (25°C–350°C). Lower atmosphere aerial systems require rechargeable batteries that can operate at high temperatures (up to 460°C).
- Venus surface mission concepts require advanced primary batteries or fuel cells with high specific energy (>200 Wh/kg) and can operate at high temperature (up to 460°C), high pressure (92 bar), and in corrosive environments.
- Mars orbital mission concepts would benefit significantly from the use of advanced rechargeable batteries with high specific energy (>250 Wh/kg), long cycle life (>50,000 cycles), and long calendar life (>15 years).
- Mars aerial mission concepts require advanced rechargeable batteries with high specific power (3000 W/kg), high specific energy (250 Wh/kg), low temperature (<−40°C) operational capability, and compliance with planetary protection requirements.
- Mars surface mission concepts would benefit significantly with the use of advanced rechargeable batteries with high specific energy (>250 Wh/kg), long cycle life (>1000 cycles), long calendar life (>5 years), wide operating temperature range (−40°C to 40°C), and compliance with planetary protection requirements.
- Small Body flyby/orbital mission concepts would benefit significantly with the use of advanced rechargeable batteries with high specific energy (>250 Wh/kg), long cycle life (>50,000 cycles), and long calendar life (>15 years).
- Small body surface (landers/rovers) would benefit significantly with the use of advanced rechargeable batteries with high specific energy (>250 Wh/kg), long cycle life (>1000

cycles), long calendar life (>5 years), wide operating temperature range (−40°C to 40°C), and compliance with planetary protection requirements.

- Small Body Sample Return Capsules would benefit significantly with the use of advanced primary batteries with high specific energy (>500 Wh/kg), long calendar life (>5 years), high specific power (1000 W/kg), wide operating temperature range (−40°C to 40°C), and compliance with planetary protection requirements.

Table 5-1. Energy storage technology needs for future planetary science missions

Mission Destination	Mission Type	Energy Storage Type		Energy Parameters		Life Parameters		Environmental Parameters			Planetary Protection
		Primary	Rechargeable	High Specific Energy Wh/kg	High Specific Power W/kg	Long Calendar Life (yrs)	Long Cycle Life	High Temp. °C	Low Temp. °C	Radiation*	
Outer Planets	Orbital		X	>250		>15	1,000			Jup	OW
	Surface	X		>500		>15	NA		−180	Jup	OW
	Probes	X		>500		>15	NA		−180	Jup	OW
Inner Planets/ Venus	Orbital		X	>250		>10	>50,000				
	Aerial		X	>100		>4	>500	25–350			
	Surface	X		>200		0.5–1	NA	~460			
Mars	Orbital		X	>250		>15	>50,000				
	Aerial		X	>250	3000	>5	>1000		−40		X
	Surface		X	>250		>5	>1000		−40		X
	Sample Return Missions		X	>250		>10			−40		X
	Human Precursor Missions		X	>250		>15	>1000				X
Small Bodies	Orbital		X	>250		>15	>50,000				
	Surface		X	>250		>5	>1000		-40 to 40		
	Sample Return	X		>500		>15	NA		-40 to 40		

X: required; JUP: Jupiter system; OW: Ocean Worlds

5.1.2 *Capabilities and Limitations of SOP Energy Storage Systems*

The major findings of the assessment team on the capabilities and limitations on SOP energy storage systems are given below:

- Primary batteries that are presently in use in planetary space missions are lithium-sulfur dioxide (Li-SO_2), and lithium-thionyl chloride (Li-$SOCl_2$).
  - SOP Li-SO_2 and Li-$SOCl_2$ batteries have moderate specific energy (150–250 Wh/kg) and operate over a temperature range of −40°C to 60°C. These batteries have a calendar life of about 10 years.
  - SOP Li-SO_2 and Li-$SOCl_2$ batteries are heavy and bulky and not attractive for Ocean World lander missions because those missions require several weeks of operation on battery power. They also have limited low temperature operational capabilities and are not attractive for missions that require operation below −40°C.
- Rechargeable batteries that are presently in use in space missions include: nickel-hydrogen (Ni-H_2), and lithium-ion (Li-ion) batteries.

  - $Ni\text{-}H_2$ batteries have low specific energy (~30 Wh/kg) and low energy density (30 Wh/l). However, they have excellent cycle life capability (>50,000 cycles @ 30% depth of discharge).
  - The state of practice Li-ion batteries have high specific energy (~100 Wh/kg), high energy density (>200 Wh/l) and operate over a temperature range of −20°C to 40°C. Li-ion batteries offer significant mass and volume advantages (three- to four-fold) compared to SOP $Ni\text{-}H_2$ batteries. Two types of Li-ion batteries are currently in use: a) batteries made with large-capacity prismatic or cylindrical Li-ion cells, and b) batteries made with small capacity cylindrical Li-ion cells (18650).
  - Major limitations of the SOP Li-ion batteries are: a) limited resilience to high temperature exposure (>60°C), b) limited low temperature operational capability (<−20°C), c) poor abuse tolerance (inadvertent over charge/over discharge and short circuit), and d) incompatibility to the standard planetary protection methods.
- Several changes are happening in battery industry, as listed below. Implications of these changes on future NASA missions are uncertain and need to be evaluated by PSD:
  - $Ni\text{-}H_2$ batteries will no longer be available for the next decadal planetary missions, since their production is being phased out.
  - Availability of heritage large-format Li-ion batteries is uncertain for future missions.
  - EaglePicher Industries acquired Yardney, the primary supplier of large format aerospace Li-ion cells/batteries for Mars missions. It is not known if EaglePicher will continue to offer these products in the heritage format.
  - ABSL, the supplier of small formal Li-ion cells/batteries, was acquired by Enersys and the heritage Sony HC Li-ion cells has been discontinued.
- Tantalum capacitors (solid and wet slug designs) were used in the Galileo and Cassini deep space missions. The major limitations of SOP capacitors are low specific energy and low energy density.

5.1.3 *Status of Advanced Energy Storage System Technologies*

The major findings of the assessment team on the status of advanced energy storage technologies are given below:

- Advanced lithium-primary batteries currently under development include $Li\text{-}CF_x$, $Li/CF_x\text{-}MnO_2$, and $Li\text{-}O_2$.
  - $Li\text{-}CF_x$ and $Li/CF_x\text{-}MnO_2$ are the most promising batteries for future space science missions, in view of their higher specific energy, long shelf life, and potential for improved performance at low temperatures.
  - The projected specific energy of these advanced primary batteries at the cell level are: $Li\text{-}CF_x$ (400–500 Wh/kg) and $Li\text{-}CF_x\text{-}MnO_2$ (350–400 Wh/kg).
  - These batteries are being developed for DoD applications and NASA will need to perform appropriate evaluations and tests to adapt them for space missions.
- Advanced rechargeable batteries currently under development include advanced Li-ion, Li-inorganic solid electrolyte, and Lithium-Sulfur. Among these systems, the advanced Li-ion batteries have the highest potential to meet the future planetary science missions in view of their high level of technical maturity, improved cycle life, and low temperature performance capabilities.
  - The projected specific energy of these advanced rechargeable batteries are: advanced Li-ion (150–200 Wh/kg), Li-solid state electrolyte (250–350 Wh/kg), and Li-S (250–350 Wh/kg).

   - Li-inorganic solid electrolyte and Lithium-Sulfur batteries are presently at low TRL levels.
   - In the longer run, batteries with Li inorganic solid electrolytes may provide advantages over Li-ion batteries with liquid electrolytes.
   - DoE is funding the development of these batteries for future electric vehicle applications
   - Increased NASA funding of advanced Li-ion and lithium battery technology is required to develop products for future planetary missions.
- High temperature battery systems that are attractive for near term Venus surface mission applications include: a) $LiAl\text{-}FeS_2$ and b) Na-Metal Chloride.
   - These systems were brought to fairly advanced stage of development (TRL3–4) for EV and grid scale applications.
   - PSD has initiated some funding for the development high temperature batteries required for future Venus missions.
- Advanced fuel cell systems under development include: Polymer electrolyte membrane (PEM) fuel cells, solid oxide fuel cells, and regenerative fuel cells.
   - Among the fuel cell systems, $H_2\text{-}O_2$ PEM fuel cells and regenerative fuel cells are the most promising systems for future human space missions, in view of their performance advantages and advanced stage of development.
   - Small PEM fuel cells are attractive for planetary science missions that require power levels of 100–500 W and for several days of operation. Initial system studies indicate system level specific energies of 400 to 700 Wh/kg are achievable for applications with discharge times of 20–30 days.
- Advanced capacitor technologies currently under development include ultracapacitors and supercapacitors.
   - Ultracapacitors and supercapacitors have 2–3× higher specific energy compared to the SOP double-layer capacitors and can deliver thousands of cycles with minimal degradation in performance.
   - Ultracapacitors and supercapacitors also have wide temperature operation (−40°C to 150°C).
   - Ultracapacitors and supercapacitors are attractive for applications with short high discharge pulses and in hybrid power systems.
   - Supercapacitors are currently baselined for several small probe applications, CubeSat power supplies, small Mars probes with milliwatt power supplies (MASER), and ice transceivers used with melt probes.

5.2 Summary and Recommendations of the Assessment Team

The assessment team has formulated the following overall and specific recommendations to NASA-PSD. These recommendations were formulated after reviewing the energy storage system needs of next decadal planetary science missions and after examining the capabilities and limitations of SOP energy storage systems and the status of the advanced energy storage technologies currently under development.

5.2.1 *Overall Recommendations*

NASA PSD should:

- 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.

5.2.2 Specific Technical 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.

5.2.3 Technology Development Roadmaps

Technology development roadmaps for the recommended energy storage systems is given Figure 5-1. It is recommended that partnerships be formed with various universities and industries for the initial phase of the development TRL (2–4) and establish partnerships with industry to advance the technology beyond TRL 4 to TRL 6.

Figure 5-1. Energy storage systems technology readiness levels

<table>
<tr><th rowspan="2">Energy Storage Technology</th><th colspan="9">Years of Development</th><th rowspan="2">Required Funding, $M</th></tr>
<tr><th>Y1</th><th>Y2</th><th>Y3</th><th>Y4</th><th>Y5</th><th>Y6</th><th>Y7</th><th>Y8</th><th>Y9</th></tr>
<tr><td>High Specific Energy (~250 Wh/kg) and long life (50,000 cycles and 15 years) rechargeable Li-ion batteries</td><td>2</td><td colspan="2">3</td><td colspan="2">4</td><td colspan="2">5</td><td>6</td><td></td><td>25</td></tr>
<tr><td>Low-Temp Rechargeable Li-ion Batteries (150 Wh/kg @ <−40°C)</td><td>3</td><td colspan="2">4</td><td colspan="2">5</td><td>6</td><td></td><td></td><td></td><td>15</td></tr>
<tr><td>Low Temperature Primary Batteries (500 Wh/kg @RT, 300 Wh/kg @ <−60°C)</td><td>3</td><td colspan="2">4</td><td colspan="2">5</td><td>6</td><td></td><td></td><td></td><td>15</td></tr>
<tr><td>High Temperature Primary/ Rechargeable Batteries (460°C)</td><td>3</td><td colspan="2">4</td><td colspan="2">5</td><td>6</td><td></td><td></td><td></td><td>15</td></tr>
<tr><td>High Specific Energy Fuel Cells (>500 Wh/kg)</td><td>3</td><td colspan="2">4</td><td colspan="2">5</td><td>6</td><td></td><td></td><td></td><td>20</td></tr>
</table>

TRL Legend (colors associated with levels):

2	3	4	5	6
Electrode materials and component development and performance demonstration	*Analytical and experimental critical function demonstration in experimental/laboratory cells*	*Prototype cell development and performance demonstration in laboratory environment*	*Breadboard battery development and performance validation*	*Prototype battery performance demonstrated in a relevant environment*

APPENDIX 1: Abbreviation, Acronyms, and Glossary of Relevant Terms

°C	Celsius (temperature degrees)
AFC	alkaline fuel cell
AFRL	Air Force Research Laboratory
Ag-Zn	silver-zinc
Ah	Amp Hour
ANL	Argonne National Laboratory
APL	Applied Physics Laboratory
ARL	Army Research Laboratory
ARM	Asteroid Redirect Mission
AU	astronomical unit (distance from Earth to Sun is 1 AU)
BMS	battery management system
BrCl	bromine chloride
C	capacity, charge or discharge rate
CECOM	(U.S. Army) Communications-Electronics Command
CF_x	carbon monofluoride
CIS	copper indium diselenide
CNSR	Comet Nucleus Sample Return
CONTOUR	COmet Nucleus TOUR
CPV	common pressure vessel
CVD	chemical vapor deposition
DAVINCI	Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging
DHMR	dry heat microbial reduction
DLR	Deutsches Zentrum fur Luft und Raumfahrt (German Aerospace Center)
DME	Dimethoxyethane
DoD	Department of Defense
DOD	depth of discharge
DoE	Department of Energy
DSCOVR	Deep Space Climate Observatory
DUS&T	Dual Use Science and Technology
EDL	entry, descent and landing
energy density	watt hour/liter
ESA	European Space Agency
ESR	equivalent series resistance
EV	electric vehicle
EVA	extra-vehicular activity
F	Farad
FEC	fluoroethylene carbonate
FeS_2	iron disulfide cathode
GEO	geosynchronous Earth orbit

GRAIL	Gravity Recovery and Interior Laboratory
gravimetric energy density	watt hour/kilogram
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
HC	hard carbon
HCM	hard carbon mandrel
HEO	highly elliptical orbit
HEOMD	Human Exploration and Operations Mission Directorate
HQ	Headquarters
HST	Hubble Space Telescope
IFC	international fuel cell
InSight	Interior Exploration using Seismic Investigations, Geodesy and Heat Transport
ISRU	in situ resource utilization
ISS	International Space Station
ITO	indium tin oxide
JPL	Jet Propulsion Laboratory
JPSS	Joint Polar Satellite System
JUICE	JUpiter ICy moons Explorer
JWST	James Webb Space Telescope
LADEE	Lunar Atmosphere and Dust Environment Explorer
LaRC	Langley Research Center
LATP	lithium aluminum titanium phosphate
LCROSS	Lunar Crater Observation and Sensing Satellite
LEO	low Earth orbit
LFP	lithium iron phosphate
Li	lithium
Li-Al	lithium-aluminum alloy anode
$LiAlCl_4$	lithium tetrachloroaluminate
$LiAl\text{-}FeS_2$	lithium aluminum-iron disulfide
LiBr	lithium bromide
$LiGaCl_4$	lithium tetrachlorogallate
Li-ion	lithium ion
LiPON	lithium phosphorus oxynitride
$Li\text{-}SO_2$	lithium-sulfur dioxide
$Li\text{-}SOCl_2$	lithium-thionyl chloride
LLZO	lithium lanthanum zirconium oxide
LMA	Lockheed Martin Astronautics
LMSC	Lockheed Missiles and Space Co.
LVA	launch vehicle adapter

M	molar concentration
MASER	Meteorology and Seismology Enabled by Radioisotopes
MAVEN	Mars Atmosphere and Volatile EvolutioN
MEP	Mars Exploration Program
MER	Mars Exploration Rover
MESSENGER	MErcury: Surface, Space ENvironment, GEochemistry and Ranging
MJ	multi-junction
MMS	Magnetospheric Multiscale Satellites
mrad	milliradian
MSFC	Marshall Space Flight Center
MSL	Mars Science Laboratory
MSR	Mars Sample Return
MOCVD	metal organic chemical vapor deposition
MW	megawatt
$Na\text{-}NiCl_2$	sodium-nickel chloride
Na-S	sodium-sulfur
NASA	National Aeronautics and Space Administration
NF	New Frontiers
$Ni\text{-}H_2$	nickel-hydrogen
NM	New Millennium
NM DS	New Millennium Deep Space
NRC	National Research Council
NREL	National Renewable Energy Laboratory
NRL	Naval Research Laboratory
NRO	National Reconnaissance Office
NTS	Navigational Technology Satellite
NuSTAR	Nuclear Spectroscopic Telescope Array
OCV	open circuit voltage
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer
PC	propylene carbonate
PEM	polymer electrolyte membrane
PEO	poly(ethylene oxide)
PDR	Preliminary Design Review
PLE	protected lithium electrode
PMAD	power management and distribution
power density	watts/kg
PSD	Planetary Science Division of the Science Mission Directorate at NASA
PTC	positive temperature coefficient
PV	photovoltaics
PVMP	Pioneer Venus Multiprobe
R&D	research and development

RBAU	rover battery assembly unit
RHU	radioisotope heater unit
RPS	radioisotope power source
RT	room temperature (25°C)
RTG	radioisotope thermal generator
S/C	spacecraft
SAVANT	Solar Array Verification and Analysis Tool
SBAG	Small Body Assessment Group
SEI	solid electrolyte interphase
SMAP	Soil Moisture Active Passive
SMD	Space Mission Directorate
SOA	state of the art
SOAC	system on a chip
SOC	state of charge
$SOCl_2$	liquid thionyl chloride
SOP	state of the practice
specific energy	watt-hour/kilogram
SPV	single pressure vessel
SS	stainless steel
STMD	Space Technology Mission Directorate
STS	Space Transportation System
TESS	Transiting Exoplanet Survey Satellite
TFC	thin film cells
THF	tetrahydrofuran
TOPEX	Topex/Poseidon Ocean Topography Mission
TRL	Technology Readiness Level
TRMM	Tropical Rainfall Measuring Mission
URFC	unitized regenerative fuel cells
V	voltage
V&V	verification and validation
VERITAS	Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy
VISE	Venus In-Situ Explorer
VEXAG	Venus Exploration Analysis Group
V_{oc}	open circuit voltage
Volumetric Energy Density	watt-hour/liter
W	watt
Wh	watt-hour
WISE	Wide-field Infrared Survey Explorer
ZEBRA	Zero Emission Battery Research Activities