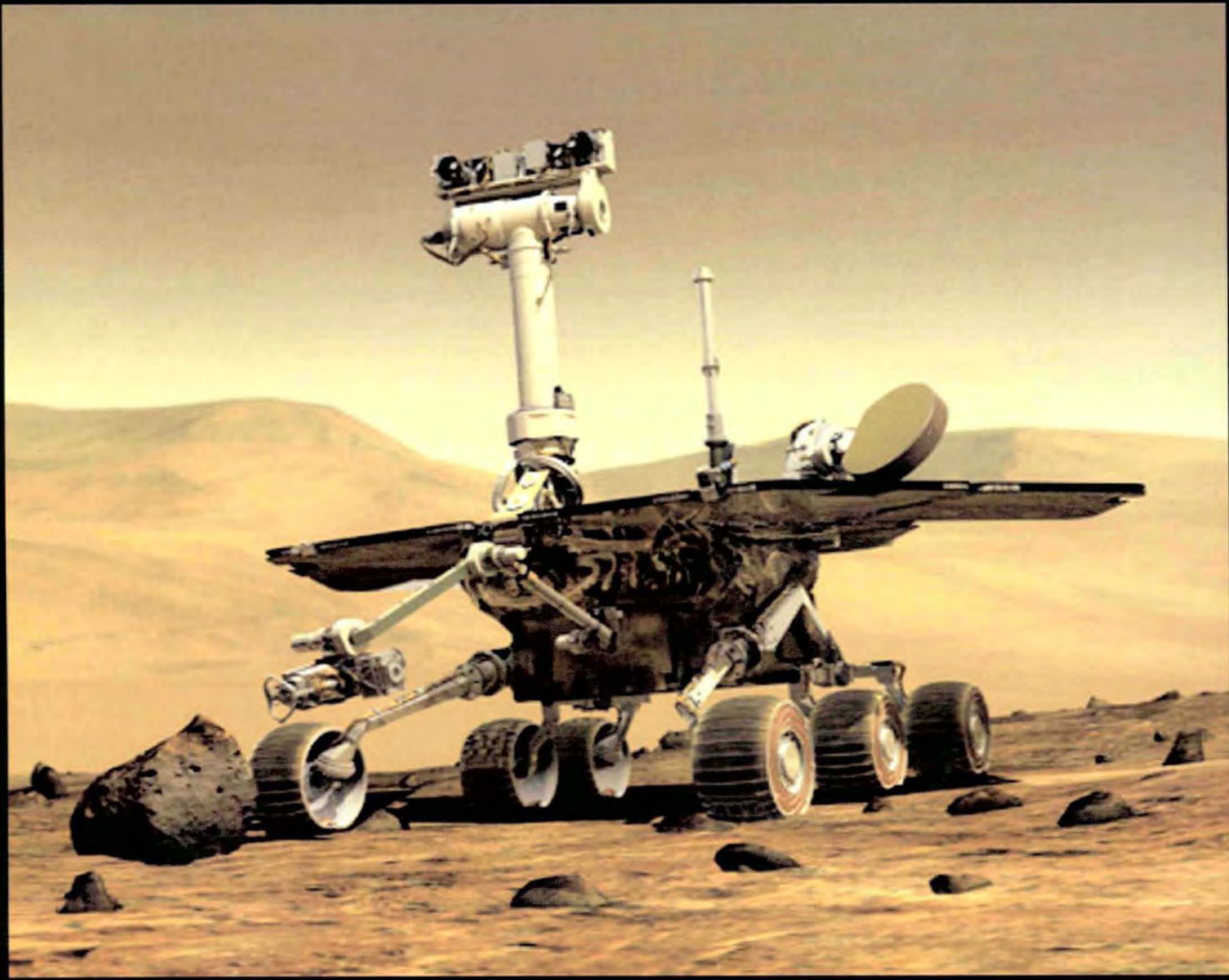
Energy Storage Technology for Future Space Science Missions



D-30268

JPL D-30268

Energy Storage Technology for Future Space Science Missions

NASA-Jet Propulsion Laboratory
Jack Mondt, Chair
Gerald Halpert, Sec'y
Donald Rapp
Subbarao Surampudi
Craig Peterson
Harvey Frank
Richard Marsh

NASA-Glenn Research Center
Kenneth Burke
Michelle Manzo
Fred Wolff

NASA-Johnson Space Center
Bob Bragg

NASA-Goddard Space Flight Center
Gopalakrishna Rao

DOE Argonne Laboratory
Robert Sutton

DoD
Valerie Browning
George Methlie

Aerospace Corporation
Warren Hwang

Case Western Reserve University
Robert Savinall

Original Issue: November 2004

Jet Propulsion Laboratory
California Institute of Technology

The authors are indebted to James A. Cutts, Satish Khanna and Stephen L. Prusha of JPL,
and James R. Robinson and Harley A. Thronson of NASA
for support, both financial and technical, during preparation of this report.

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

Energy Storage Technology for Future Space Science Missions

November 2004

Funding for these assessments was provided jointly by the Assistant Associate Administrator (Technology) and the Program Executive for Power and Propulsion of the Science Mission Directorate at NASA.

Approved:

James A. Cutts, Chief Technologist (Solar Systems Exploration Programs Directorate)

Stephen L. Prusha (Manager, Strategic Systems Technology Program Office)

Table of Contents

Executive Summary

The goal of the study was to assess the potential of advanced energy storage technologies to enable and/or enhance next decade (2010–2020) NASA Space Science missions, and to define a roadmap for developing advanced energy storage technologies that will enable or enhance future missions. The study was jointly sponsored by the Office of Space Science and by the Solar System Exploration Division at NASA HQ.

The specific objectives of the study were as follows:

- Assess the capabilities of current State of Practice (SOP) energy storage devices currently used in Code S missions and their potential for future improvement.
- Determine the impacts of potential advances in energy storage technology on future Code S missions.
- Review the status of the development of emerging energy storage technologies and determine the potential for developing technologies that enable or enhance Code S missions.
- Review non-NASA energy storage technology programs and assess the potential for meeting Code S needs through collaboration between NASA and other agencies.
- Formulate energy storage technology development plans to fill any gaps remaining between development programs and Code S mission needs.

The study was led by JPL and conducted by an assessment team with relevant experience in energy storage technology drawn from NASA Centers, other agencies, and universities with relevant experience in energy storage technology. Three meetings were held at which representatives of the aerospace and energy storage industry participated. The study was completed before the announcement of the President's Vision for Space Exploration in January 2004 and the formation of NASA's Exploration Office. Accordingly, none of the requirements of new exploration missions were included in the report.

State of Practice of Space Energy Storage Technologies

Since the launch of Sputnik and Explorer in 1958, energy storage devices have been used in most of the spacecraft/launch vehicles, either as a primary source of electrical power or for storing electrical energy. The energy storage technologies that have been used in space science missions are primary batteries, rechargeable batteries, and capacitors. Fuel cells have been used in human missions but not in space science missions. Batteries are needed for a wide variety of applications while capacitors fill a narrow niche for pulsed high power delivery.

Primary batteries (single discharge batteries) are used in missions that require one-time use of electrical power for few minutes to several hours. Primary batteries have been used in planetary probes and sample return capsules (Stardust, Genesis, Deep Impact, Galileo), Mars Landers (MER), and Mars Rovers (Sojourner).

Primary batteries that are presently being used in various space missions are: a) Zn-AgO, b) Li-SO_2, c) Li-$SOCl_2$, and d) Li-CFx. Zn-AgO batteries have low specific energy (100–150 Wh/kg) and short shelf life (6–12 months) and they are not attractive for future pace science missions. Zn-AgO batteries are fully developed and offer little opportunity for further improvement.

Li-SO_2 and Li-$SOCl_2$ batteries deliver moderate specific energy (100–250 Wh/kg), can operate over a temperature range of –40°C to + 60°C, and have proven lifetimes of up to 10 years. The major limitations associated with these batteries are limited performance capabilities at temperatures lower than –40°C and voltage delay. These batteries are not attractive for missions that require operation below –40°C. Li-SO_2 batteries are fully developed, and offer very little opportunity for further improvement. Li-$SOCl_2$ batteries on the other hand have potential for further improvement, particularly in the area of low temperature performance.

The Li-CFx battery has the highest specific energy of primary batteries and has a minimum voltage delay. The major limitations of the existing versions are very low specific power and limited operating temperature range. This system has substantial potential for further improvement, particularly in the areas of rate capability and low temperature performance.

Rechargeable batteries (also referred to as secondary batteries) have been used mainly for load-leveling and for providing electrical power for survival during eclipse periods in solar powered missions. They have been used in orbital missions (TOPEX, Mars Global Surveyor, Mars Reconnaissance Observer), as well as Mars landers (Mars Pathfinder) and Mars rovers (Spirit and Opportunity).

Rechargeable batteries that are currently used in space missions include: Silver-Zinc (Ag-Zn), Nickel-Cadmium (Ni-Cd), Nickel-Hydrogen (Ni-H_2), and Lithium-Ion (Li-Ion) batteries. Ag-Zn batteries are fully developed and offer little opportunity for further improvement. Ni-Cd batteries have been successfully used in many space missions, particularly LEO and GEO missions. However, manufacture of these batteries is being phased out and only certain versions (super Ni-Cd) may be available for future use. Ni-Cd batteries are also fully developed and offer little opportunity for further improvement.

Ni-H_2 batteries have been successfully used in many space missions, particularly LEO and GEO missions. Ni-H_2 batteries have a superior demonstrated cycle life performance (>50,000 cycles at 30-40% DOD) and calendar life (>15 years of GEO operational life) when compared to any other SOP rechargeable batteries. While Ni-H_2 batteries are heavy and bulky, they can be considered for future orbital missions where mass and volume requirements are not stringent and the driving requirement is cycle life. Ni-H_2 batteries are unsuitable for future space science surface missions (such as landers, rovers) that have critical mass and volume requirements. Ni-H_2 batteries are fully developed and offer little opportunity for further improvement.

The Li-Ion battery is a relative newcomer to aerospace applications. Li-Ion batteries offer significant mass and volume advantages (three- to four-fold) compared to SOP Ni-Cd and Ni-H2 batteries. Recently, JPL successfully implemented Li-Ion technology for the MER Mars Surface missions in collaboration with NASA GRC and AFRL. This battery technology played an enabling role on the MER mission which was highly mass- and volume-constrained. A Ni-H_2 battery of comparable capacity would have been impractical; a lower power battery would have severely limited rover operations. However, the limitations of SOP Li-Ion batteries are limited cycle life and limited operational temperature range. Nevertheless, the Li-Ion system has potential for further improvement in these characteristics.

Capacitors are typically used on spacecraft as filtering elements for power management and distribution. However on two occasions, capacitors have been used to store energy and supply short pulses of high power (Galileo and Cassini). The most important advantage of capacitors is the capability to supply high pulses repeatedly for hundreds of thousands of cycles. The recent development of super-capacitors increases the range of options for utilizing capacitors in spacecraft by increasing specific energy at a sacrifice in pulse power. Nevertheless, we have not identified any unique Space Science need for further development of capacitors.

Impact of Advanced Energy Storage Technologies on Future Missions

The Space Science Enterprise implements missions within five themes: Exploration of the Solar System (ESS), Mars Exploration Program (MEP), Sun-Earth Connection (SEC), Astronomical Search for Origins (ASO), and Structure and Evolution of the Universe (SEU). The impacts of advances in energy storage on missions within each theme were considered with particular focus on:

- Energy parameters (specific energy and energy density)
- Lifetime (cycle time, calendar life, self discharge rate)
- Extreme Environments (high and low temperatures and radiation)

The Space Science Enterprise implements a mix of strategic missions that are planned many years, sometimes decades, in advance and competitive missions that are selected through periodic announcements of opportunity. For strategic missions the mission designs are reasonably well defined and mission impacts are comparatively straightforward to discern. For competitive missions even the nature of these missions is uncertain and determining mission impacts of technology are less well defined.

The two themes where advances in energy storage technologies have the greatest impact are the Mars Exploration Program (MEP) and the Exploration of the Solar System (ESS). The MEP theme utilizes both strategically selected and competitively chosen missions; the ESS theme mainly utilizes competitive missions. The impact of advances in energy storage technology on missions within these themes is summarized in Table ES-1. It is clear from this table that the critical needs for new Space Science missions are high specific energy and energy density, long life, and low-temperature operation.

Table ES-1. Mission Impact of Energy Storage Technologies on MER and ESS Missions

ENERGY SYSTEM PARAMETERS	Mission Category & Priority	Energy Storage Type		MISSION IMPACT (H=High, M=Medium)							
				Energy Parameters		Lifetime			Extreme Environments		
TARGET OF EXPLORATION/ Type of Mission	S-Strategic C-Competitive **Boldface = High Priority** **NF = New Frontier**	**Primary**	**Rechargeable**	Specific Energy (WH/Kg)	Energy Density (WH/l)	Long Cycle Life	Long Calendar Life	Low Self Discharge Rate	High Temperature	Low Temperature	High Radiation
MARS EXPLORATION											
Orbiters	**S,C**		**Yes**	**H**		**H**	**H**				
Landers	**C**		**Yes**		**H**		**M**			**H**	
Rovers	**S**		**Yes**		**H**		**H**			**H**	
Probes and low cost mission	**C**	**Yes**	**Yes**		**H**		**M**			**H**	
Sample Return	**S**		**Yes**	**H**	**H**		**H**			**H**	
OUTER PLANET EXPLORATION											
Orbiter - New Frontier Class	**C**		**Yes**	**M**	**M**		**H**				
Orbiters - JIMO Class	**S**		**Yes**	**M**	**M**		**H**				**H**
Atmospheric probe	**C (NF)**	**Yes**		**H**	**H**		**H**		**H**		**M**
Europa Icy Body Lander	**C or S**	**Yes**	**Yes**	**H**	**H**		**H**			**H**	**H**
Titan In Situ Exploration	**C or S**	**Yes**	**Yes**	**H**	**H**		**H**			**H**	
SMALL BODY EXPLORATION											
Fast Flyby /Sample Return	**C**		**Yes**	**M**	**H**		**H**			**M**	
Fast Flyby Impactor	**C**	**Yes**	**Yes**	**M**	**M**		**H**			**M**	
Comet Rend./Sample Return	**C (NF)**		**Yes**	**H**	**H**		**H**			**H**	
VENUS EXPLORATION											
Orbiters	C		**Yes**			**H**	**M**				**M**
Atmospheric Probe	C	**Yes**		**H**	**H**		**M**	**H**	**M**		**M**
Landers-Short Duration	**C (NF)**	**Yes**		**H**	**H**		**M**	**H**	**M**		**M**
Landers-Medium Duration	C		**Yes**	**H**	**H**		**M**		**H**		**M**
Aerial Platforms- Short Duration	C	**Yes**		**H**	**H**		**M**		**M**		**M**
Aerial Platforms- Long Duration	C		**Yes**	**H**	**H**		**M**		**M**		**M**
Surface Sample Return	**S**	**Yes**		**H**	**H**		**M**		**H**		**M**
Long Duration Exploration Systems	C		**Yes**	**H**	**H**		**M**		**H**		**M**
MOON & MERCURY EXPLORATION											
Orbiters	C		**Yes**	**M**	**M**	**H**	**H**				
Landers & Rovers	C		**Yes**	**H**	**H**	**M**	**M**		**H**	**H**	**M**
Surface Sample Return	**S (NF)**		**yes**	**H**	**H**	**M**	**M**				

Mars Exploration Program

The mission categories examined included orbiters, surface missions (landers, rovers), aerial platforms (balloons, airplanes), probes, and sample return. Mars surface missions that utilize solar power must survive overnight when temperatures will fall to the -60° to -100°C range, depending on location and season.

- ***Mars Orbital Missions*** will benefit from advances in specific energy which can be applied to increase science payload or for increasing instrument power for observations on the night side of the planet for use of active sensors such as lidar, microwave, or radar
- ***Mars Surface Missions*** can benefit from improvements in rechargeable energy storage for the reasons that Li-Ion technology had such an impact on the MER missions. The benefits will be greatest for solar powered mobile missions where low-temperature performance will be particularly beneficial.
- ***Aerial Platform missions*** include short duration airplane or glider missions with lifetimes measured in minutes for gliders, hours for powered flight, and days to months for balloon missions. For airplane missions, gains in specific energy for primary storage have high impact. For balloon missions, gains in specific energy are particularly important at low night time temperatures for rechargeable batteries.
- ***Mars Sample Return*** missions are highly sensitive to mass and volume for ascent vehicles and orbital rendezvous and would be a significant beneficiary of gains in specific energy for rechargeable storage.

Exploration of the Solar System (ESS)

The ESS theme, which covers exploration of all solar system bodies except the Sun, the Earth, and Mars, is subdivided into Outer Planet Exploration, Small Body Exploration and Venus Exploration.

Outer Planet Exploration missions include orbiters in the New Frontier class, outer planet orbiters, atmospheric probes, and icy body landers such as the Titan Explorer.

- ***New Frontier Class Orbiter****s* would use radioisotope power generation systems. The missions involve long trip times and may require energy storage with long life (typically > 10 years, and in some cases up to 20 years) for load-leveling.
- ***Nuclear Reactor Powered Missions*** such as the Jupiter Icy Moon Orbiter (JIMO) have a unique need for high-capacity, long storage life batteries that are needed for startup and maybe be needed for restart in the event of a reactor shut-down.
- ***Outer Planet Atmospheric Probes*** require primary energy storage technologies that can operate effectively at low and high temperatures (increasing as the probe descends into the atmosphere), are capable of withstanding high acceleration loads, and have increased mass and volume efficiency. Advances in primary storage would enable larger science payloads and increased data return.
- ***Icy Body Landers*** utilize primary energy storage in a very low-temperature environment for a limited period of time. Titan and Europa probes may encounter temperatures as low as -200°C. No battery will function at such temperatures. Therefore, it must be enclosed in a thermal protection system. However, the lower the operating temperature of the battery, the longer the power system will endure in that cold environment.

Small Body Exploration **missions** examined included fast flyby sample return, fast flybys with impactors and comet and asteroid rendezvous sample returns.

- **Fast Fly-By Sample Return and Impactor missions** use primary batteries to power the impactor or the return capsule. In each case, extension of the operating temperature range to lower temperatures would be beneficial.
- **Fast Fly-By Comet and Asteroid Sample Return**: Detached probes to obtain samples from comet or asteroid surfaces will require low-temperature primary energy storage similar to that required for outer planet icy moon surface probes. Spacecraft that directly approach comets and asteroids for acquisition of samples will require substantial rechargeable energy storage as comet and asteroid rotation periods will subject the spacecraft to possibly lengthy eclipse periods. Dust mitigation may require stowage of solar arrays and use of rechargeable energy storage capacity.

Venus Exploration

Venus exploration missions pose challenges for energy storage systems. The temperature and pressure on Venus ranges from 460°C and 90 bars at the surface, to 0°C and 1 bar at an altitude of 55km. In addition, very little sunlight reaches the surface and nuclear power generation presents severe technical challenges for operation at these temperatures because of the difficulty in heat rejection. There is very little atmospheric motion near the surface. However at 55 km altitude the winds are strong enough to carry a balloon around the planet in 4 days which is much faster than the solid surface of the planet rotates.

Venus mission types examined included orbiters, atmospheric probes, short and medium duration landers, short and medium duration aerial platforms, surface sample return, and long duration exploration systems.

- **Venus Orbiters** will require energy storage systems with large cycle times similar to Mars and Earth orbiters.
- **Venus Landers** are limited to very short operating periods (hours) on the surface with sensors, avionics and batteries enclosed in a thermal protection system. Increases in the specific energy of conventional primary storage could free up space in the containment vessel for science or allow operation at higher power levels. Alternatively, if energy storage systems could be developed to operate at 460°C (with power densities comparable to the SOA), the primary energy storage could be entirely removed from the containment vessel.
- **Venus aerial systems** in the upper atmosphere will benefit from rechargeable batteries that can provide power for extended periods of solar occultation. In the lower atmosphere the needs are similar to those of landers.
- **Venus sample return** will have similar energy storage needs to Mars sample return for ascent vehicles and sample rendezvous in orbit.

Lunar and Mercury Exploration

Both the Moon and Mercury are airless bodies subjected to high daytime temperatures and low night time temperatures because of their long diurnal cycles. Both the Moon's and Mercury's polar regions have permanently shadowed areas that may contain volatiles and are of great scientific interest. Missions to these bodies may include orbiters, landers and rovers and surface sample return.

Lunar and Mercury Orbiters will require energy storage systems requiring large cycle life performance comparable to those for Mars and Earth orbiters.

- **Lunar and Mercury surface missions** will need to tolerate hot and cold temperature extremes. The range of those temperatures will depend on the design of the thermal control system.
- **Lunar and Mars sample return missions** will require power systems where mass is at a premium and specific energy will be an important characteristic.

Sun-Earth Connection (SEC) Missions

SEC missions generally operate far from objects that occult the Sun, and therefore energy storage is not usually a major issue. However, the SEC Theme is planning several missions that approach very closely to the Sun where thermal protection and heat rejection become increasingly difficult, and these missions will likely benefit from batteries that can function at higher temperatures.

Astronomical Search for Origins (ASO) and Structure & Evolution of Universe (SEU)

The ASO and SEU missions usually operate in a region of space where they are not subject to the power cycling that has impeded the adoption of lithium-based rechargeable batteries. In the wake of the MER flight of Li-Ion batteries, this technology is now being adopted for these missions (e.g. Kepler). ASO and SEU are likely to continue to be followers rather than leaders in this technology, since advances have less significant impact on performance and are more likely to be adopted mainly for reasons of cost.

Impact of Advanced Technology on Office of Space Science Missions - Summary

Based on an assessment of the likely payoff from performance improvements in energy storage technology, the following technology advances were identified as having potentially high impact on space science missions:

- Primary energy storage systems with substantially improved specific energy and extended temperature range. Low temperature operation is important for missions to Mars, small bodies and the outer solar system. Primary storage systems that could operate at 460°C are of interest in Venus exploration and potentially to SEC missions.
- Secondary (rechargeable) energy storage systems with high specific energy (200Wh/kg) that can operate for up to 15 years and sustain up to 50,000 cycles of operation. Extension of the operating range to as low as –80°C would offer significant advantage to many mission categories.

Potential Advances in Space Energy Storage Technologies

Knowing where advances in energy storage technology performance yields the most benefit for Code S missions, the assessment team identified technologies that have the promise to yield those performance gains. The scope of this assessment included the categories of energy storage systems currently used in Code S missions, namely primary batteries, rechargeable batteries, and capacitors. It also included two other technologies: fuel cells that represent an alternative to primary batteries, and flywheels that could provide an alternative to rechargeable batteries.

Primary Batteries

Advanced lithium-primary systems under development include advanced Li-MnO2, Li-CFx, Li-SOCl2 and Li-O2. Among these systems, Li-CFx and Li-SOCl2 (new liquid cathode types) are the most promising for future space science missions, in view of their higher specific energy, long shelf life, and potential for improved performance at ultra-low temperatures.

Rechargeable Batteries

The lithium-based battery systems offer the greatest potential for performance advances in rechargeable batteries. Four types of lithium battery were evaluated: Li-Ion, Li/Li-Ion polymer electrolyte, Li-inorganic solid electrolyte and Lithium sulfide (Li-S). These advanced Li batteries are projected to offer one or more of the following advantages:

- Higher specific energy and energy density (3-6 X compared SOP Ni-Cd/Ni-H2 batteries,
- Long cycle life and calendar life,
- Improved low temperature performance,
- Low self-discharge,
- High charge/discharge efficiency, and
- Lower cost compared to SOP rechargeable batteries.

The Li-Ion system has the highest potential to meet the near- to mid-term needs of space science missions in view of its high level of technical maturity, improving cycle life, and potential low temperature performance capabilities. Two directions of development are envisaged with impact on different types of missions:

- Low temperature Li-Ion batteries, that would provide performance gains in Mars surface missions, lunar surface missions and some outer planet missions
- Long calendar life and high cycle life storage for Mars, Venus, and outer planet flyby and orbiter missions.

The AFRL/NASA program that led to the successful implementation of first generation Lithium Ion batteries for MER required approximately a $25M investment over 10 years. The program involved low-TRL in-house research on materials for electrodes and electrolytes, development by industrial partners, and a rigorous in-house testing program. However, current NASA funding of Li-Ion battery technology is inadequate to produce significant progress toward the goals outlined above.

Advanced Li batteries using polymer or inorganic electrolytes may provide advantages over Li-Ion batteries with liquid electrolytes in the long run. However, these technologies are currently much less mature. The primary impact will be in improved specific energy and specific volume. NASA/GRC is conducting research on the development of lithium polymer electrolytes.

High-Temperature Batteries

The most attractive high temperature battery systems are a) LiAl-FeS_2, b) Na-S, and c) Na-Metal Chloride. These systems were brought to a maturity level of TRL 3-4 under prior DOE sponsored programs for electric vehicles. However, they were supplanted by lithium-based technologies that provided the specific power and energy of the high temperature batteries without the need for operation at an elevated temperature. There are also some other promising high temperature battery concepts that are in early stages of development, 1) Li-Cl_2, 2) Li-CoS_2 and 3) Li-CO_2.

In the case of Venus missions, and potentially for near-Sun SEC missions, there may be significant advantages to operating the battery unprotected from the ambient environment rather than operating at ~300K within containment. This operating mode is the subject of an ongoing trade study that will be reported in a separate document on Technologies for Extreme Environments.

Fuel Cells

Fuel cells are attractive for human space missions that require multi-kilowatts power for extended periods of up to 10 days. In the size and duration range of interest for human missions, fuel cells provide higher specific energy and power than conventional primary batteries. Advanced fuel cell systems under development include: polymer electrolyte membrane (PEM) fuel cells, direct methanol fuel cells, solid oxide fuel cells and regenerative fuel cells. Among these systems H2-O2 PEM fuel cells are most promising for future human space missions, in view of their performance advantages and advanced stage of development.

Fuel cells have not been utilized on any Code S mission to date. Fuel cells would represent a competitive alternative to primary batteries for applications if they provided greater specific energy and could tolerate the required environmental conditions. However, fuel cells do not scale easily 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 about 20-30 hours or more.

Flywheels

Flywheels are being developed by NASA as an alternative to rechargeable batteries. Two types of flywheels are under development: a) Fixed-axis energy-only system, and b) Fixed-axis energy/momentum system that furnishes attitude control as well as energy storage.

The potential benefits of flywheels include the capability for many cycles at high depth of discharge, wider operating temperature range, and radiation tolerance. The major issues associated with flywheels are difficulty in scaling to small systems with low energy storage, system complexity, and relative immaturity. Flywheels may prove to be attractive for low-Earth orbital missions that require a re-usable energy storage capability of 5 KWh or more. The TRL level of this technology is around 3. While flywheels may have advantages in some applications, this technology has never been used in space and is not currently baselined for application in any planned missions.

Capacitors

Advanced capacitor technologies under development by private industry (known as ultra capacitors or super capacitors) have 2-3 times higher specific energy compared to the SOP double layer capacitors. They can deliver thousands of cycles with minimal degradation in performance and are attractive for applications that require repeated short high discharge pulses.

Energy Storage R&TD Programs at NASA and Other Agencies

Our objective here was to review NASA and non-NASA energy storage technology programs and assess their potential for meeting Code S needs. The resources currently being expended in these areas by NASA and elsewhere dictate the current pace of energy storage development. In the past, common interests have been identified, and collaboration between NASA and other agencies has played a vital role in meeting NASA and other agencies' needs. Such mutually profitable cooperation should be encouraged in the future where appropriate.

NASA R&D Programs

Within NASA Code R (now Code T) is funding several technology programs including:

- A small program to test Li-Ion batteries
- A significant program in Li-Ion batteries with polymer electrolytes (ends in '04)
- A moderate program in fuel cell development
- A significant program in flywheel development.

As noted above, neither the fuel cell nor the flywheel development is likely to be applicable in the short run for space science missions. The ongoing Li-Ion work in both liquid and polymer electrolytes is relevant to space science needs, but is not of the scope or direction to fulfill these needs in a timely way.

Whereas Code S has previously supported development work on Li-Ion battery technology focused on Mars Landers and specifically MER, this work was not continued. There are no programs in high-temperature battery development at NASA. At current funding levels, ongoing energy storage technology programs will not result in tangible advances in battery technology in time to impact future space science missions.

Non-NASA Programs

The DOD and the DOE have invested and continue to invest considerable funding into energy storage technology. However most of this current work is not directly applicable to Code S needs for space science missions as identified in this report.

The DOE is presently investing in fuel cell and Li-Ion technologies, but this work is primarily driven by the goal of high rate power delivery at low depths of discharge and low cost. Many of the NASA needs, such as long life and operation at low and high temperatures, are not relevant.

The DOD has several sub-agencies that invest in energy storage technology. The Army requires and sponsors work on low-cost, portable, short-life batteries, or fuel cells for field communications. The Air Force requires and sponsors work on large batteries for high power levels for aircraft. The Navy has a program in Li-Ion batteries with polymer electrolytes that might someday be applicable to NASA missions, but this appears to be long-term development. In addition, the CIA has a program in long cycle-life Li-Ion batteries, but this is not readily available to NASA.

Potential for Collaborative Program to Meet Code S Needs

Based on our assessment of ongoing NASA programs, and that of other agencies, we have arrived at the following assessment concerning the potential for collaboration between NASA and other agencies in developing battery technology that is important to Code S needs:

- There is very limited interest in a collaborative program on primary lithium-based battery technologies, in the size range of interest to NASA, with an emphasis on operation in extreme environments.
- There is excellent potential for collaboration on rechargeable Lithium-based batteries with long life and cycle time.
- There is limited interest in a collaborative program in rechargeable batteries at very low temperatures.
- There may be some niche interests at other agencies in high temperature batteries, but it appears unlikely.

These issues need to be revisited in the context of the formation of NASA's Office of Exploration, which has a mandate to invest in power technologies.

Roadmap for Energy Storage Technologies

The goal of the Office of Space Science and the Solar System Exploration Division in sponsoring this study was to determine the most productive areas of investment in energy storage technology. Developing new technology and infusing it into space science missions is expensive. Accordingly, three factors must be considered in selecting the investment areas of highest priority, and in formulating the technology roadmaps for these areas:

- The potential for advanced energy storage technologies to enable and/or enhance future space science missions
- Prospects for achieving the needed technological advance with acceptable risk and affordable investment
- Potential for collaboration with other agencies with similar interests in these technologies and their willingness to share the costs.

Using these criteria, three areas of technology development programs were recommended where the primary impact will be on Mars Exploration Programs and Exploration of the Solar System missions. They are:

- Low-Temperature Primary Batteries
- Long-Life Rechargeable Batteries
- Low-Temperature Rechargeable Batteries.

In a fourth area, High-Temperature Batteries, with primary application to Venus Exploration, there is not yet enough information to define an appropriate program of technology development. A related study on Technologies for Extreme Environments is expected to make this determination in the next several months.

Development Approach

In preparing a technology roadmap for the three recommended areas of technology development defined above, the following guidelines were adopted:

- Pursue parallel technology developments where alternative approaches exist and there is significant uncertainty as to which approach is most likely to succeed. Use technology readiness gates to monitor progress and down-select to the most promising technology for at the earliest feasible time.
- Conduct a test and validation program to demonstrate the electrical performance and life capabilities of advanced energy storage technologies. In this connection, it is recommended that Code S augment and modernize the existing infrastructure at various NASA centers that are needed to support missions.
- Capitalize on the U.S. industrial base for aerospace battery development and the capabilities of the NASA centers in cell research, testing and validation, to achieve an affordable development program.
- Collaborate with AFRL and other DoD agencies to transition advanced energy storage technologies developed under joint programs to industry for mission insertion.
- Estimate costs using recent experience with cell research, testing work done within NASA, and battery development in industry.

Low Temperature Primary Batteries

Objective: Develop lithium-based primary batteries with improved performance capabilities (specific entry, discharge rates and operating voltage) at low temperatures, as shown in Table ES-2. These batteries should be producing significant power at temperatures as low as –80°C. The performance targets over 5 year and 10 year periods are shown in Table ES-2.

Table ES-2. Primary Energy Storage Performance Goals

Primary Energy Storage Characteristics	Present State of Practice	Goal (5 years)	Goal (10 years)
Specific Energy at 0°C (Wh/kg)	250	400	600
Specific Energy at –40°C (Wh/kg)	100	200	300
Specific energy at –80°C (Wh/kg)	50	100	200
Discharge rate (hrs)	> 20	> 20	> 20

Approach: Conduct parallel development efforts on the two most promising systems: Li-CFx and Li-$SOCl_2$. Down-select to the most promising technology for maturation to TRL 6. The technology roadmap for this effort is shown in Figure ES-1. Cell research and cell and battery testing can be conducted within NASA and the university community. The industrial base developed in the Li-Ion Battery program will be important in the battery development phase. The estimated total cost of this effort is $14M ($FY04).

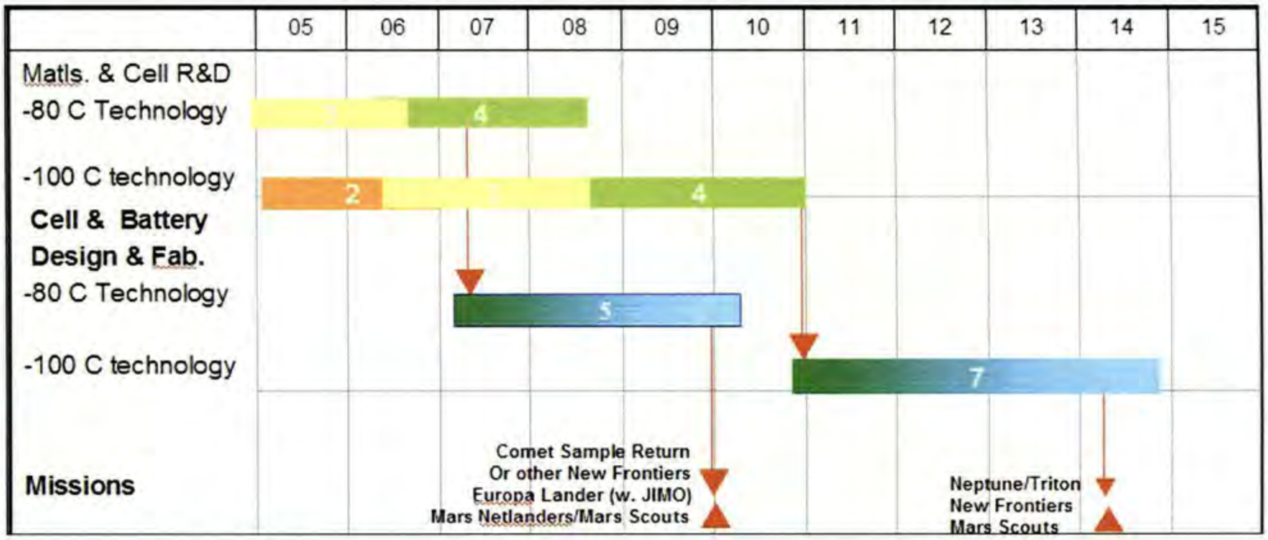


Figure ES-1. Low Temperature Primary Battery Technology Roadmap

Long-Life Rechargeable Batteries

Objective: Develop long-life rechargeable batteries with specific energy between 4X and 7X the state of the practice in long life rechargeable batteries. The long-range target is calendar life of 15 years and cycle life of 50,000 cycles. The performance targets for this technology are listed in Table ES-3.

Table ES-3. Rechargeable Energy Storage Performance Goals

	Ni-Hydrogen	Lithium Technology		
Rechargeable Energy Storage Characteristics	Present State of Practice	Present State of Practice	Goal 5 years	Goal 10 years
Specific Energy (Wh/kg)	30	100	120	200
Energy Density (Wh/liter)	10	200	200	400
Cycle Life at 30% DOD *	50,000	10-15,000	30,000	50,000
Calendar Life (years)	15	3	10	15

* DOD = Depth-of-discharge

Approach: Conduct parallel development of the two most promising approaches: Lithium-ion/liquid electrolyte batteries and Lithium polymer and solid-state batteries.

The Lithium-Ion technology is the most promising approach for reaching the five-year goal because of its relatively advanced stage of development. Lithium polymer and solid-state battery technologies have greater theoretical potential for reaching the 10-year goal but they currently are at a low TRL level (1-2). The technology goals are provided in Table ES-3. Cell research and cell and battery testing can be conducted within NASA and the university community. The industrial base developed in the Li-Ion Battery program will be important in the battery development phase. The technology roadmap for this effort is given in Figure ES-2. The estimated total cost of this development effort is $29M ($FY04).

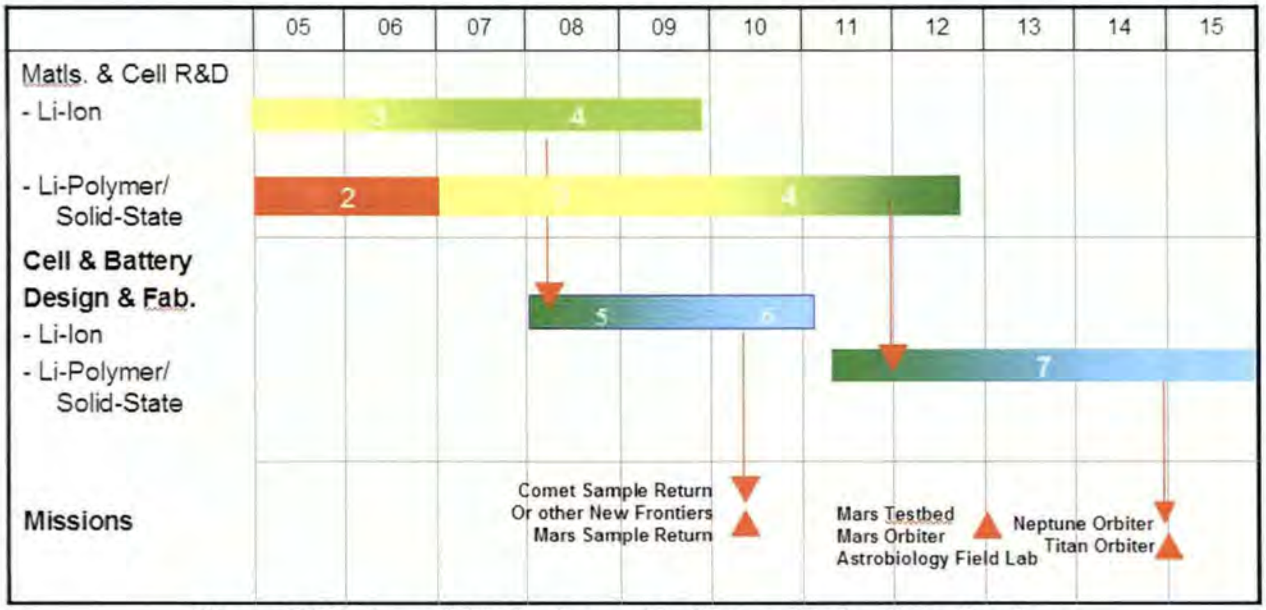


Figure ES-2 Long Life Rechargeable Battery Technology Roadmap

Low Temperature Rechargeable Batteries

Objective: To develop rechargeable batteries that retain a significant fraction of their specific energy at temperatures as low as -80°C. At the same time, the goal is to increase specific energy for operation at 0°C by a factor of two while maintaining cycle life above 500 cycles. The performance targets for this technology are given Table ES-4.

Table ES-4. Rechargeable low temperature batteries – performance goals

	Lithium Ion Technology		
	Present State-of-Practice	5 years	10 years
Specific energy at 0°C (Wh/kg)	100	120	200
Life Time (yrs)	5 yrs	10 yrs	15 yrs
Cycle Life (# of cycles) (80%DOD)	> 500	> 500	> 500
Low Temperature Performance			
Specific Energy at –20°C	70	100	160
Specific Energy at –40°C	40	80	140
Specific Energy at –60°C	0	65	120
Specific Energy at –80°C	0	40	80
Discharge rate (hours)	>10	> 10	> 10

Approach: Continue development work on Li-Ion cells (MER cells with -20°C capability) to improve their low temperature performance to -60°C and below. Investigate advanced liquid organic electrolytes with improved conductivity and stability to achieve these goals. Cell research and cell and battery testing can be conducted within NASA and the university community. The industrial base developed in the Li Ion Battery program will be important in the battery development phase. The technology roadmap for this effort is given in Figure ES-3. The estimated cost is $18M ($FY04).

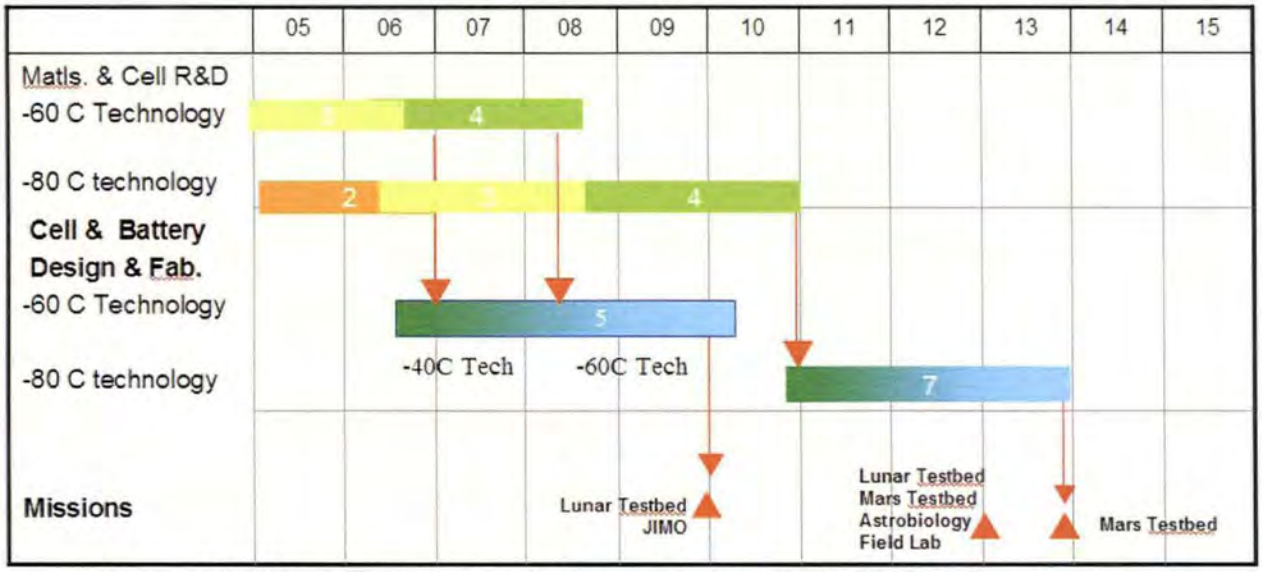


Figure ES-3. Low Temperature Rechargeable Battery Technology Roadmap

1.0 Study Overview

1.1 Introduction

NASA's Office of Space Science requested JPL to lead an assessment of advanced power source and energy storage technologies that will enable and enhance future NASA Space Science missions, and prepare technology road maps and investment strategies. In the first phase of this work, an assessment of *Advanced Radioisotope Power System* (ARPS) technology was conducted. The *Advanced Radioisotope Power System Report* # JPL D-20757 was published in June, 2001. The second phase was an assessment of *Photovoltaic Power Technology for Future Space Science Missions,* which was completed and reported as JPL Report # D-24454, and was published in February, 2004. The present report provides the results of the third and final phase of this assessment program, on *Energy Storage Technologies for Future Space Science Missions.* However, it is possible that a fourth assessment, on Power Management and Distribution (PMAD) technology and space power systems may be appropriate.

1.2 Objectives

The purpose of this study is to recommend optimal strategies for NASA Code S to invest in emerging and evolving energy storage technologies that will enable or enhance future NASA solar system exploration missions.

The following itemized topics were studied in our review process:

- Review NASA Code-S future mission needs for energy storage technologies, and opportunities to enhance missions through advanced energy storage technologies, on a Theme-by-Theme basis.
- Assess the status of energy storage technologies presently being used in various space missions and thereby establish a baseline.
- Assess the status and potential of advanced energy storage technologies to enable or enhance future missions including:
  - High-efficiency and low-mass primary and rechargeable energy storage systems
  - Enhanced performance and reliability in low-temperature environments of the outer solar system
  - Radiation-tolerant energy storage systems
  - Performance and reliability in high-temperature environments (Venus, Mercury, Sun)
  - Performance and reliability in the cold, dusty environment on Mars.

1.3 Study Approach

The study began with the appointment of a technical assessment team made up of knowledgeable energy storage experts and system engineers. Their purpose was to gather technical information, discuss the technical data in detail, draw conclusions, make recommendations, and document the results in this report. The assessment team conducted one multi-day meeting to obtain NASA OSS mission requirements and constraints for energy storage technology, and two multi-day meetings to obtain the technical status of energy storage technologies applicable to space missions. A fourth meeting was devoted to finalizing the conclusions and recommendations.

To make the study tractable, the technology needs of a large number of potential future missions were condensed into a limited number of generic types of technology needs (e.g. low temperature operation, etc.). For each generic type of need, we summarized the needs, available technology, gaps between current capabilities and needed capabilities, and defined the steps needed to develop technology in order to fill the gap.

These results were analyzed and interpreted to identify the most promising advanced technologies with the greatest potential impact (per dollar invested) to enhance future NASA OSS missions. The team then prepared roadmaps for developing these technologies.

The assessment team examined each energy storage technology to try to answer the following questions:

- What is the present status of the technology?
- What programs are presently funded?
- What is the future potential of the technology in terms of performance parameters under various conditions?
- What would be the impact of such improvements on future missions?
- What technical challenges remain and are they well defined?
- Approximately what level of effort is needed to advance the technology to NASA TRL 5-6?

The final results are documented in this report.

1.4 Schedule

The assessment team conducted three multi-day meetings between September and November, 2002. The first meeting was held at JPL, the second was held at NASA-GSFC, and the third meeting was at NASA-GRC. A fourth meeting was held at JPL in early 2003. The final report was prepared as a draft in April, 2003 for review by the assessment team, and was revised to final form in June, 2003.

1.5 Participants

The names of the Energy Storage Technology Evaluation Team members and alternates are shown in Table 1-1.

Table 1-1. Energy Storage Technology Evaluation Team Members

	Name	Organization
1	Jack Mondt, Chair	JPL
2	Bob Bragg	NASA / JSC
3	Valerie Browning	DARPA
4	Kenneth Burke	NASA / GRC
5	Gerald Halpert, Sec'y	JPL
6	Michelle Manzo	NASA / GRC
7	Richard Marsh	AF, Consultant
8	George Methlie	DoD
9	Gopalakrishna Rao	NASA / GSFC
10	Donald Rapp	JPL
11	Robert Savinall	Case Western Reserve Univ.
12	Robert Sutton	DOE / Argonne National Lab.
13	Fred Wolff	NASA / GRC
14	Warren Hwang	Aerospace Corp
15	Subbarao Surampudi	JPL
16	Craig Peterson	JPL
17	Harvey Frank	JPL

Participants who generously provided presentations and supporting material, as well as their time and effort, are listed below:

First Meeting at JPL

Jim Cutts -- Chief Technologist, JPL Solar System Exploration Programs Office
Steve Prusha -- JPL Strategic Systems Technology Program Office
Craig Peterson -- JPL Exploration of the Solar System (ESS) Mission Program
Samad Hayati -- JPL Mars Exploration Program
Steve Dawson -- JPL Mars Lander and Scout Missions
Mohammad Mojarradi, JPL Micro Missions
Juan Ayon -- Sun-Earth Connection (SEC) Missions
J-P Fluerial -- JPL Energy and Power Technology Needs for Nuclear Missions
Tsun-yee Yan -- JPL Proximity Network Missions
Ratnakumar Bugga -- JPL Battery Programs
S. R. Narayanan -- JPL Fuel Cell Program
Bob Sutton -- DOE Fuel Cell Program
Harlan Lewis -- Navy Crane Battery Programs
Warren Hwang -- Aerospace Battery Programs
Chuck Lurie -- TRW Battery Programs
Fred Cohen -- Boeing-Rocketdyne Battery Programs
Vince Teofilo -- Lockheed-Martin Sunnyvale Battery Programs
Jerry Byers -- Lockheed-Martin Denver Battery Programs

2nd Meeting at GSFC

Gary Rawitscher -- NASA Headquarters
Chris Schwartz -- GSFC Structure and Evolution of the Universe
John T. VanSant -- GSFC Sun-Earth Connection
Bob Beaman -- GSFC Battery and Flywheel Program
Valerie Browning -- DARPA
David Chua -- Max-Power Battery Program
George Dakermanji -- JHU/APL
Joe DiCarlo -- Yardney Battery Program
Tien Duong -- DOE
Jack Kosek -- Giner Battery Program
Pat McDermott -- MDA Battery Program
George Methlie -- DoD Programs
John Olson -- Boundless Energy
Rhett Ross -- Teledyne Battery Program
Pinakin Shah -- Mine Safety Appliances
Rob Spurrett -- AEA Corp.
Robert Staniewicz -- Saft America
Hari Vadyanathan -- Comsat Battery Program

3rd Meeting at GRC

Valerie Lyons -- NASA/Glenn Research Center
Mike Zernic -- NASA/GRC Missions Analysis
Michelle Manzo -- NASA/GRC Battery Programs
Kenneth Burke -- NASA/ GRC Space Fuel Cell Programs
Fred Wolff -- NASA/GRC Space Flywheel Programs
Bob Bragg -- NASA/JSC Batteries/Fuel Cells
Joe Barrella -- Ultralife Life – Polymer Program
Bob Bartlett -- AFS Trinity
Bob Bauer -- LMCO Flywheels for Space
Joe Beno -- Univ. Of Texas Flywheels for Space
Henry Brandhorst -- Space Power Program, Auburn University
Kent Dekker -- TRW – Flywheels
Joe Fellner -- AFRL – Space Battery and Fuel Cell Programs
Bob Higgins -- Eagle – Picher Batteries
Frank Little -- Texas A&M Battery Programs
Oliver Murphy -- Lynntech – H2-O2 Fuel Cell Programs
Bob Savinall -- Case Western Space Fuel Cell Programs
Steve Blackmun -- Optimal Energy
Joe Weimer -- AFRL Space Capacitor Program

4th Meeting at JPL

Jack Mondt -- JPL – Chairman
Robert Bowman -- JPL – Hydrogen Storage
Ratnakumar Bugga -- JPL – Electrochemical Technology
Bill Nesmith -- JPL -- Power Technology
S. R. Narayanan – JPL – Electrochemical Technology
Harvey Frank -- JPL – Electrochemical Technology
Marshall Smart -- JPL – Electrochemical Technology
Will West -- JPL – Micro Batteries
Jay Whitacre -- JPL – Micro Batteries
Elton Cairns -- Lawrence Berkley National Laboratory
Dan Doughty -- Sandia National Laboratory
Werner Hafelfinger -- Quallion LLC
Mike Heben -- National Renewable Energy Laboratory
Ashok Joshi -- Ceramatec Co.
Jim Miller -- Argonne National Laboratory
John Miller -- JME Capacitors Inc
Piotr Zelenay -- Los Alamos National Laboratory

In addition, we are particularly indebted to Harvey Frank (JPL), Craig Peterson (JPL), We Fee Chan Leung (U. S. Army CECOM, Ft. Monmouth, NJ), and Gregory Carr (JPL), for their valuable inputs to this report.

1.6 Critical Parameters

Over the years, engineers have worked to improve energy storage systems in terms of the following important figures of merit:

- Specific Energy (Wh/kg)
- Energy Density (Wh/l)
- Specific Power (W/kg)
- Cycle Life
- Calendar Life
- Discharge/Charge Efficiency (%)
- Operating temperature range (°C)
- Radiation resistance (allowable dosage) (Mrad)
- Self discharge rate (% Capacity loss - per year for primary batteries, per day or month for rechargeable batteries)
- Cost per unit power and per unit energy ($/W), ($/Wh)

1.7 NASA Technology Readiness Level (TRL)

The team used the NASA TRL scale to characterize the relative maturity of energy storage technologies. A brief description of this scale is provided in Figure 1-1. The NASA Office of Research and Technology is responsible for developing new technologies in the TRL range 1-3, and the NASA Office of Space Science advances space science technologies from the TRL ~3 range to the TRL ~6, at which point missions can adopt them for implementation. JPL requires that a technology be at TRL 6 by Preliminary Design Review (PDR) in order to be chosen for implementation by a project.

The primary emphasis in this study is on energy storage technologies presently at TRL 2 to 3 (or higher) that have potential to significantly enhance future NASA Space Science missions. We define a Code S technology program to develop these technologies to TRL 5-6.

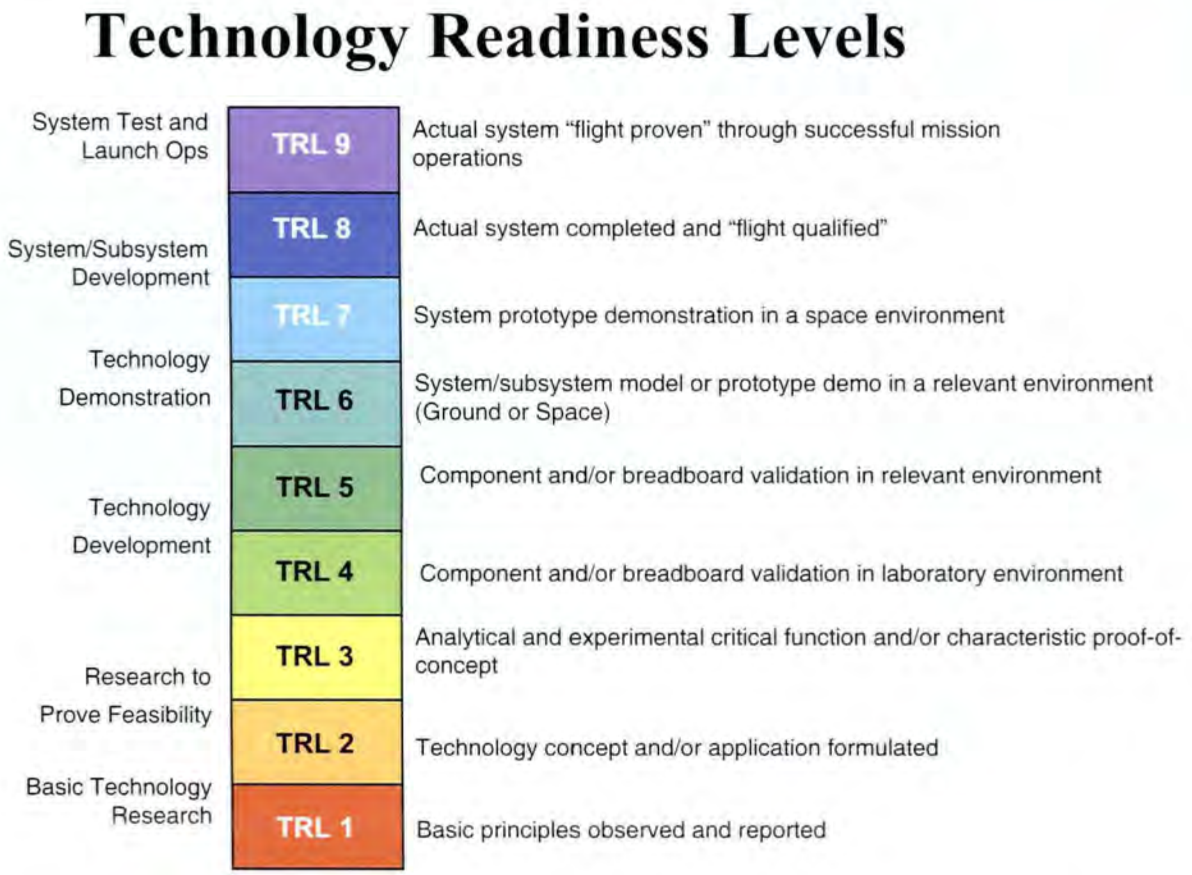


Figure 1-1. Technology Readiness Levels

Unfortunately, it is not always possible to characterize a technology by a single TRL level. It is not uncommon in battery technology for cells to be at a higher TRL than the battery. Furthermore, even after a form-fit-and-function engineering model battery is built and performance-tested to TRL ~6, it usually lacks lifetime data. In such cases, the hardware may be at TRL ~ 6 but the lack of lifetime data preclude its acceptance by missions. Lifetime data under various environmental stresses using accelerated cycling tests can usually be obtained. However, derivation of probable performance over mission life under various scenarios for cycling depth of discharge from these data is difficult and often of uncertain reliability. Very often, a great deal of validation work is required even after a battery reaches a nominal TRL 5-6. This typically leads to rather long periods (sometimes more than a decade) during which an older technology continues to be used by risk-averse missions, while missions with a critical need for higher performance are willing to live with the risks involved in the new technology. This is the current situation where the newcomer Lithium-Ion (Li-Ion) liquid electrolyte battery is being used in many consumer applications but is only gradually wending its way into space science missions with very severe limits on mass and volume, and relatively short mission life. More space science missions are likely to adopt Li-Ion technology as its long-term properties become verified.

We will make use of "spider diagrams." In a spider diagram, each critical parameter is plotted along an axis radiating from a common origin, with the direction such that the least desirable values are at the origin. For any given technology at any particular stage of evolution, the state of the technology is described by a polygon that intersects each axis at an intercept equal to the current value of the appropriate parameter. Such diagrams can be used in several possible modes:

1) **Requirements Spider Diagram** - compares needs of various types of missions for a single technology.
2) **Capabilities Spider Diagram** - compares capabilities of technologies that are competing to perform the same mission function.
3) **Gap Analysis Spider Diagram** compares mission requirements for a technology with the state of the art of a technology to identify the gap between them. This is the ultimate means of identifying gaps between mission requirements and the state of the art.

2.0 State of Practice (SOP) - Energy Storage

This section provides an overview of State of Practice (SOP) energy storage devices used in space missions to date. The term SOP refers to reliable devices that have been widely used in space applications.

2.1 Introduction

Since the launching of Sputnik and Explorer in 1958, energy storage devices have been used in most of the spacecraft/launch vehicles, either as a primary source of electrical power or for storing electrical energy. Space missions impose several critical performance requirements on energy storage devices. Generally, they must be custom-designed, fabricated, and tested to ensure reliability and to meet a broad range of requirements including:

- Operation in vacuum
- Vibration, shock, and acceleration environments
- Long calendar life and cycle life and over a range of mission scenarios
- Thermal environments
- Radiation fields
- Size /Foot print
- Safety

The energy storage devices used in space science missions include primary batteries, rechargeable batteries, and capacitors. In addition, fuel cells have been used in human space missions but not in space science missions. A list of the first use of energy storage devices on all space missions is given Table 2.1-1.

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 and sample return capsules (Stardust, Genesis, Deep Impact, Galileo), 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), Lithium-Thionyl Chloride (Li-$SOCl_2$) and Lithium- Carbon Monofluoride (Li-CF_x).

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, Mars Reconnaissance Observer), Mars landers (Mars Pathfinder), and Mars rovers (Spirit and Opportunity). 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 were 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 Shuttle), but they have not been used on space science missions. Capacitors were used for applications that required repeated high power short duration pulses (seconds). The Galileo and Cassini missions used capacitors for firing pyros and stepping motorized instrument platforms.

Table 2.1-1. A Chronological List of First Use of Energy Storage Devices in Space

Battery Type	Launch Year	Spacecraft	Life in Space	First Use of Technology
Primary Batteries				
Zn-HgO	1956	Vanguard	Failed in launch	First U.S. Launch
Zn-HgO	1958	Explorer 1	3.8 Months	Van Allen Rad. Belt
Ag-Cd	1961	IMP 1	3.5 Years	Non/Magnetic
Ag-Zn	1962	Ranger 3	Solar Orbit	Moon Photos
Ag-Zn	1962	Mariner 2	Venus	1st Planetary
Li-BCX	1983	STS/3	Days	Astronaut Use
Li Primary	1984	LDEF	6 Years	Exposure to Space
$Li-SO_2$	1989	Galileo	Hours	Jupiter Probe
$Li-SOCl_2$	1995	Centaur	1st Mission	28v, 250ah Battery
Rechargeable Batteries				
Cylindrical Ni-Cd	1959	Explorer 6	2 Years	First Earth Photos
Prismatic Ni-Cd	1962	Ariel I	14 Years	1st in LEO
Cylindrical Ni-Cd	1963	Syncom/2	N/A	1st in GEO
Ag-Zn	1965	Com'd Mod	Short Life	Apollo
$Ni-H_2$	1977	NTS/2	5 Years	12 Hour Polar
$Ni-H_2$	1977	Air Force	Classified	LEO
Ni-Cd	1980	Solar Max	8 Years	LEO "Standard Battery"
$Ni-H_2$	1983	Intelsat V	14 Years	GEO
$Ni-H_2$	1990	HST	In Orbit	NASA LEO
"Super" Ni-Cd	1990	Leasat	Orbiting	GEO
SPV $Ni-H_2$	1994	Clementine	5 Months	Lunar Mapping
2 Cell CPV	1994	Tubsat/B	4 Years	Store Messages
50Ah SPV	1996	Iridium/1	Commercial	88 S/C in LEO
Na-S (High temp)	1997	Flight Exp.	A.F. Mission	7 Day Experiment
Fuel Cell Systems				
PEM Fuel Cell	1962	Gemini	7 Days	PEM Fuel Cell
PEM Fuel Cell	1967	Biosatelite 2	3 Months	1st Use of Nafion
Alkaline. Fuel Cell	1968	Apollo 7	11 Days	Apollo
Alkaline Fuel Cell	1981	STS/1	2 Days	Shuttle
Capacitors				
Tantalum	1989	Galileo	14 years	Pulse Support for RTG

2.2 SOP - Primary Cells and Batteries in NASA Spacecraft

2.2.1 Overview

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.
- Supply power for very short one-time needs such as firing a pyro or firing a rocket motor for mid-course correction.
- Supply power for short encounters in which no rechargeable battery is employed or no energy source is available for recharging a rechargeable battery.
- Supply very low power for extended periods (years) for clocks and computer memory.

Primary batteries used in early spacecraft were largely of the aqueous alkaline type (e.g., Ag-Zn). They exhibit high specific power, relatively low voltage, limited life, moderate specific energy and energy density, and are limited in operating temperature range. In the past two decades these aqueous alkaline batteries have been largely replaced by more energetic lithium-based systems, e.g., Li-SO_2 and Li-$SOCl_2$, which yield much higher voltages, 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 are lower specific power than aqueous batteries, and voltage delay anomalies. Operational temperature range is much greater for the lithium than for aqueous batteries but is still inadequate to meet future mission needs. Another limitation of lithium systems is that the batteries can exhibit unsafe behavior when abused. Important characteristics of SOP Primary batteries used in space science and other missions are provided in Table 2.2-1.

2.2.2 The Silver- Zinc (Ag-Zn) Primary Cell and Battery

Primary Ag-Zn batteries have been used mainly in launch vehicles to power pyro devices and onboard electronics guidance and control systems. They were also used in a number of military applications such as missiles and aircraft because of their attractive high specific energy, high power density and high energy density (see Table 2.2-1).

The Ag-Zn cell utilizes a powdered zinc anode, a silver oxide cathode, and an aqueous alkaline electrolyte comprised of potassium hydroxide (40-45%) with dissolved zincate. The most popular configuration is parallel-plate prismatic for sizes from a few Ah to hundreds of Ah. Ag-Zn prismatic (box-like) cells contain alternate silver oxide and zinc plates separated by layers of polymeric separator. Cells are available in sizes from a few ampere hours (Ah) to hundreds of Ah. Ag-Zn batteries are available from Yardney Technical Products, Eagle Picher Industries & BST Systems Inc.

Table 2.2-1. State of Practice of Primary Batteries

Type	Cell Parameters and Battery Parameters by Mission Application	Nominal Voltage (a)	Specific Energy, Wh/kg (b)	Energy Density, Wh/l (b)	Specific Power, W/kg (c)	Operating Temp. Range, °C	Capacity Loss % Per Year	Mission Life (yrs)	Manufacturer	Configuration
Ag-Zn	Cell	1.61	200	550	1100	0-55	60	1	Yardney	Prismatic
	Typical Launch Vehicle	28	119	280	120	5 to 40	60	1	Eagle Picher	Manually Activated
Li-SO$_2$	Cell	2.9	238	375	680	-40 to 70	<1			Cylindrical
	Galileo Probe Battery	38	91	145	260	-15 to 60	<1	9	Alliant Tech	Three 13 cell batteries
	Genesis Battery	24	142	125	400	-20 to +30	<1	6	SAFT	Two 8 cell batteries
	MER	30	136	**390**	390	0 to 60	<1	4	SAFT	Five 12 cell batteries
	Stardust	20	192	182	519	-26 to +50	<1	10	SAFT	Two 8 cell batteries
Li-SOCl$_2$	Cell	3.2	390	875	140	-30 to- 60	<2.5			Cylindrical
	Sojourner	9	245	515	100	-20 to 30	<2.5	4	SAFT	Three 3 cell batteries
	Deep Impact	33	221	380	105	-20 to +30	<2.5	4	SAFT	Three 13 cell batteries
	DS-2	14	128	340	65	-80 to +30	<2.5	4	Yardney	Two 4 cell batteries
	Centaur Launch batteries	30	200	515	85	-20 to +30	<2.5	6	Yardney	One 9 cell batteries
Li- BCX	Cell	3.4	414	930	150	-40 to 70	<2		Wilson GB	Cylindrical
	Astronaut Equipment	6	185	210	115	-40 to +72	<2	3	Wilson GB	2 cell radio batteries
Li-CF$_x$	Cell	2.6	614	1050	15	-20 to 60	<1		Eagle Picher	Cylindrical DD
	Range Safety battery	39	167	150	15	-20 to 60	<1		Eagle Picher	15 Cell Battery

The nominal cell operating voltage is 1.5 V/cell. The Specific Energy of a cylindrical cell is 200 Wh/kg and Energy Density is >500 Wh/l with a very high specific power. The battery parameters are generally 50% of the cell values depending on structure, wiring, connectors and sensors. This system has the highest rate capability compared to other primary battery systems. The major limitations of this battery are short storage life (in the range of 6 months to 1 year) due to dissolution of the active materials, reduced performance at low temperature (70% of capacity at 0°C and 35% at –20°C), limited operating temperature range as for all aqueous systems, and orientation sensitivity. Life is also diminished sharply at elevated temperatures.

This battery system has limited applicability to future space science missions primarily because of its limited shelf life.

2.2.3 The Lithium – Sulfur Dioxide (Li-SO_2) Cell and Battery

NASA has used Li-SO_2 cells and batteries in planetary probes (Galileo, Cassini), sample return capsules (Genesis, Stardust), and the Mars Exploration Rover (MER) Lander (See Table 2.2-1). In these batteries, Li is used as the anode material and SO_2 is the active cathode reactant. The electrolyte is comprised of SO_2 dissolved in an organic solvent containing Lithium Bromide (LiBr). The electrode pack is comprised of strips of Lithium and Carbon on a metallic substrate (cathode current collector) separated by a polymeric ion-conducting separator membrane. The electrode pack is spirally wound to fit into a cylindrical case. Only one U.S. manufacturer, SAFT America, produces Li-SO_2 cells for space applications.

Li-SO_2 cells exhibit a relatively high open circuit voltage of 3.0 V. Li-SO_2 cells have a high specific energy (>225 Wh/kg) and high energy density (~375 Wh/l). Deliverable battery outputs depend on the battery design and construction and have varied from 50–80% of cell values in actual applications. The cell has the highest rate capability (specific power) of lithium primary cells, and can operate between -40°C and 60°C. When the load is initiated, this cell exhibits a short delay in reaching full voltage due to passivation of the lithium electrode. Application of a conditioning discharge prior to use minimizes this problem. The other limitations of this battery system for space science missions are reduced capacity at low temperatures, moderate specific power, uncertain radiation tolerance, and uncertain life capabilities beyond ten years. Some actual mission experience with these batteries is provided in Table 2.2-1.

This system can be considered for future space applications that require operation between –40°C and 60°C and 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.

2.2.4 The Lithium - Thionyl (Li-$SOCl_2$) Cell and Battery

Li-$SOCl_2$ batteries have been used on the Mars Pathfinder Rover –Sojourner (Figure 2-2-1), New Millennium Deep Space-2, astronaut equipment and Centaur launch vehicles (Air Force). These are also planned for use in the forthcoming Deep Impact mission (see Table 2.2-1).

Figure 2.2-1. Sojourner Rover Li-$SOCl_2$ Battery

Lithium functions as 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, carbon cathode current collector, and organic 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 tetra-chloro-gallate ($LiGaCl_4$), allowed cell operation down to -80°C. Li-$SOCl_2$ 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 (–20°C), and significant voltage delay especially after storage, due to Li electrode passivation. 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 improvement in rate capability, operation at low temperature, and reduced voltage delay. Several modifications are needed to effect these improvements (e.g., use of alternative liquid cathodes and cathode salts).

2.2.5 The Lithium-Carbon Monofluoride (Li-CF_x) Cell and Battery

Li-CF_x batteries have had limited use in space applications because of their limited rate capability and safety concerns (see Table 2.2-1).

Li-CF_x cells employ Li as the anode material, solid CF_x as the cathode material together with conducting carbon powders, and a liquid organic electrolyte. Several solvent-electrolyte salts combinations have been used including dimethylsulfite (DMSI) as the solvent and BrCl or

$LiAsF_6$ as the salts. The cells are made in a cylindrical configuration. $Li\text{-}CF_x$ cells and batteries are available from Eagle Picher Industries.

This cell exhibits an operating voltage of 2.5–2.7V and has the highest specific energy (400-600 Wh/kg) and energy density (up to 1000 Wh/l) of the lithium systems. The major limitations of this battery system are its extremely low power capability (~15 W/kg) and limited performance at low temperatures.

This battery has the highest potential among the lithium systems for high specific energy, but the specific power needs to be greatly increased. The modifications required to realize significant improvements in power include use of thin plates, and advanced electrode and electrolyte materials.

2.2.6 Summary of Current Capabilities of State of Practice Primary Batteries

The major findings of the assessment team are:

- The $Li\text{-}SO_2$ and $Li\text{-}SOCl_2$ batteries provide high energy, moderately high short-term power capability, and operation within the temperature limits of –40 to +70°C. Performance (power and energy) of both types declines significantly as the temperature is reduced. Performance of both types increases somewhat with temperature, but neither is recommended for use above approximately 70°C for safety reasons. Lifetimes beyond 10 years are possible, but not yet demonstrated.
- The $Li\text{-}CF_x$ battery has only been fabricated with thick electrodes (low surface area) and this yields cells and batteries with high energy but low power capabilities. Existing $Li\text{-}CF_x$ batteries yield the highest energy, potentially long life, but very low power capability within temperature limits of –40 to +70°C. Performance (power and energy) decreases as the temperature is reduced. Performance increases somewhat with temperature, but it is not recommended for use beyond 70°C due to safety reasons.
- The Li-BCX system batteries have slightly higher energy and comparable temperature limits and performance to the $Li\text{-}SOCl_2$ system. However, lifetime beyond a few years is uncertain. Safety of the batteries has been demonstrated by extensive testing,
- Limited information is available on the radiation tolerance of the SOP batteries. Maximum survivable dosage demonstrated to date is 200 krad for the Galileo $Li\text{-}SO_2$ battery. Limited data are available on the survivability of the $Li\text{-}SO_2$ and others to lower dosage levels.
- All of the SOP batteries have been shown to meet shock levels to about 5000 g. However, limited information is available on the high impact shock resistance of these batteries for Impactors. The maximum demonstrated resistance was 80,000 g for a specially designed $Li\text{-}SOCl_2$ DS-2 cell. However, this demonstration was for a limited number of trials and shock parameters.
- None of the above SOP batteries can survive extended periods of storage above 50°C as self-discharge rates increase sharply above this temperature.
- No definite rule applies to allowable to depth of discharge (DOD) for these SOP batteries. In general the DOD is limited to about 80% to avoid the possibility of the hazardous condition of reversal. Furthermore many of the designs call for a completely

redundant battery. Assuming no battery faults, the DOD in this case would be 1/2 of the single battery DOD, or typically 40%.

- There is little to be gained by attempting to improve Li-SO_2 batteries. The effort would be better spent on battery technologies with more potential. By contrast, the Li-$SOCl_2$ system has the potential for improvement in rate capability, operation at low temperature and reduced voltage delay. Several modifications are needed to effect these improvements (e.g., use of alternative liquid cathodes and cathode salts). The LiCF_x battery has the highest potential amongst the lithium systems for high specific energy but the specific power needs to be greatly increased. The modifications needed to realize significant improvements in power include use of thin plates, and advanced electrode and electrolyte materials.

2.3 SOP - Rechargeable Batteries

2.3.1 Overview

Rechargeable batteries are electrochemical devices that convert chemical energy into electrical energy during discharge, and electrical energy into chemical energy during charge. Rechargeable batteries are also referred to as secondary batteries and can be charged and discharged (cycled) numerous times, depending on the operating conditions. Rechargeable batteries are mostly used in solar powered orbital missions and Mars surface missions, 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
- Supply power for very short one-time needs such as firing a pyro or firing a rocket motor for mid-course correction.
- Supply power during cruise anomalies where stored energy may be needed for events requiring power.
- Supply power to the spacecraft, its equipment, and instrumentation during Sun eclipse periods,
- Provide peak power for operations such as data transmission and communication
- Provide peak power for surface mobility
- Provide power for interim power outage

Some of the important parameters that characterize rechargeable batteries are illustrated in Figure 2.3-1 where the requirements of an Earth-orbiting satellite are compared to those of a Mars surface mission.

Important characteristics of SOP rechargeable batteries used in space science and other missions are provided in Table 2.3-1.

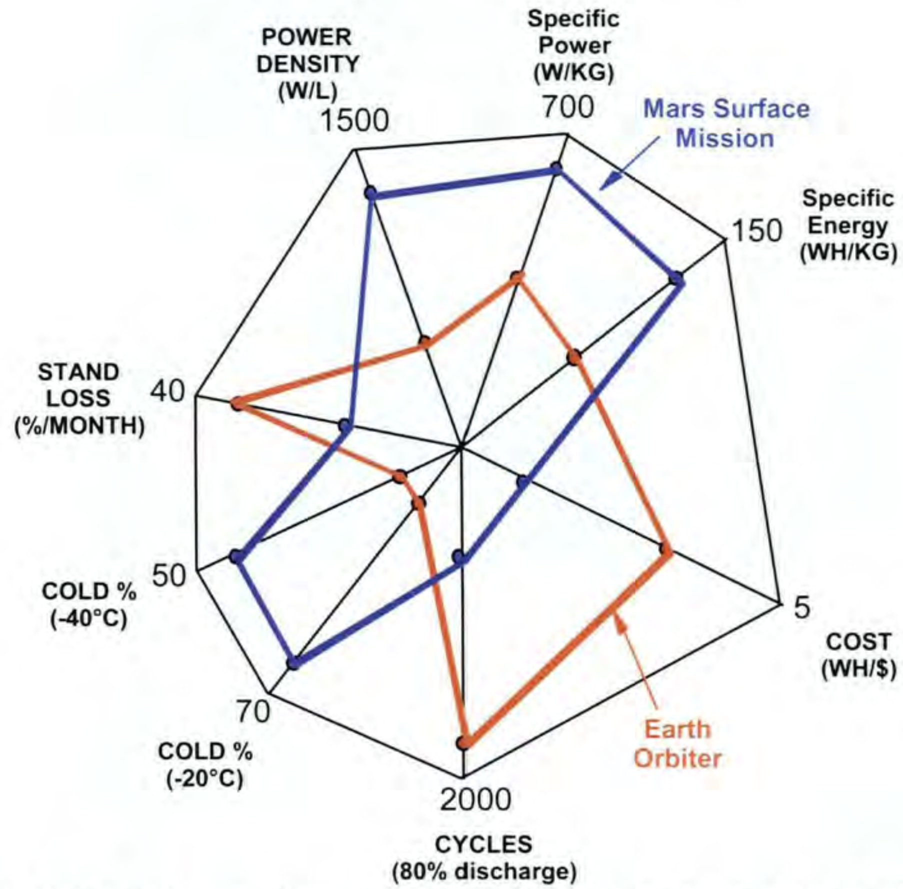


Figure 2.3-1. Schematic Difference in Requirements for Earth Orbiter and Mars Surface Missions

Table 2.3-1. State of the Practice of Rechargeable Cells and Batteries and Mission Performance

Technology	Use	No of Batteries & Cells	Ah Rated/actual	Operating Voltage	Specific Energy, Wh/kg	Energy Density, Wh/l	Operating Temp. Range, °C	Design life, Years	Cycle life to Date	Manufacturer
Ag-Zn	Cell	1	40/58	1.5	130	248	-20 to 25			BST
	Pathfinder Lander	1/18	40/58	27	85	190	-20 t0 25	2	100	Yardney
Ni-Cd	Standard 50 Ah	1	50/62	1.25	31	111	-20 to 25	3		Gates
	Landsat	3/22	50 /60	22-36	27	61	-20 to 26	3	25K	MDAC
	TOPEX	3/22	50/60	22-36	27	61	-10 to 30	3 to 5	40K	MDAC
Super Ni-Cd	9 Ah Cell	1	9/12	1.25	31	93	-20 to 30			EPI
	50 Ah Cell	1	50/63	1.25	32	100	-20 to 30			EPI
	Sampex Battery	1 /22	9/12	28	28	72	-20 to 30	5	58K	EPI
	Image	1/ 22	21/24	28	33	71	-20 to 30	5	14K	
IPV Ni-H_2	IPV Cell	1	98/83	1.25	48	71	-10 to 30		10K	EPI
	Space Station	6/76	81/93	48	24	8.5	-10 to 30	6.5	11K	Boeing
	HST	6/22	80/85	28	8	4	-10 to 30	5	65K	EPI
	Landsat 7	2/17	50 / 61.7	24			-10 to 30	5	>50K	LMAC
CPV Ni-H_2	CPV Cell	2	16/17.5	2.50	43.4	77	-10 to 30	10		EPI
	MIDEX MAP	1/11	16/17.5	28	36	21	-10 to 30	5	50K	
	Odyssey	2/11	16/17.5	28	36	21.1	-3 to 8	10 to 14	1K	LMAC
	Mars 98	1/11	16/17.5	29	37	41	5-10	3		LMAC
	MGS	2/16	20/23	20	35	25	5-10	5 Mars Yr	50K	LMAC
	EOS Terra	2/54	50/	67		21	-5 to 10	5		
	Stardust	1/11	16/17.5	28	36	21	-5 to 11	7	1135 days	LMAC
SPV Ni-H_2	SAR 10065	1/12	50/60	28	54.6	59.3	-10 o 30	10		JCI/EPI
	Clementine	1/22	15/18	28	54.8	78	-10 to 30	1	200 cycles	JCI/NRL
	Iridium	1/22	60/70	28	53.4	67.7	-20 to 30	3 - 5	50K	JCI/ EPI
Li-Ion	Cell	1	8.6/10	4.0	133	321	-20 to 30			Yardney
	MER-Rover	2/8	16-20	28	90	250	20 to 30	3	n/a	Yardney

2.3.2 The Silver Oxide - Zinc (Ag-Zn) Cell and Battery

Ag-Zn batteries are generally considered primary batteries (See Section 2.2.2). However, they have been used in a number of NASA applications as rechargeable batteries with limited cycle life. An Ag-Zn battery (Figure 2.3-1) on the Mars Pathfinder Lander provided ground station power and relayed data from the Sojourner to the ground station and then back to Earth for about three months.

Figure 2.3-1. Mars Pathfinder Silver Zinc Battery

Rechargeable Ag-Zn batteries are similar to the primary Ag-Zn cells and batteries. The major differences are the use of improved separator materials (to extend cycle life) and alternate electrode designs. The nominal cell operating voltage is 1.5 V/cell. The cell has specific energy of >100 Wh/kg and energy density ~250 Wh/l. Deliverable battery outputs are 50 to 75% of the cells depending on design and construction of the battery case. This system has comparable high rate capabilities to other rechargeable aqueous alkaline electrolyte cells. The major limitations of this battery are limited shelf life, limited operating temperature range and orientation sensitivity. Important characteristics of Ag-Zn batteries are given in Table 2.3-1. Ag-Zn batteries are available from Yardney Technical Products, Eagle Picher Industries & BST Systems Inc.

This battery system has limited use in the future space science missions primarily because of its limited cycle life and shelf life. There does not appear to be much potential for further improvement of these batteries, and efforts would be better directed to upgrade Li-Ion batteries.

2.3.3 The Nickel – Cadmium (Ni-Cd) Cell and Battery

From the 1960s through the early 1990s, Ni-Cd batteries were the workhorses for space missions. Explorer 6 (launched in 1959) was the first spacecraft that used a Ni-Cd battery and was followed closely by the first of a series of successful long-term weather satellites (TIROS). From that time on, Ni-Cd cells and batteries became a dominant source of energy storage for NASA spacecraft. The NASA "Standard Battery," containing NASA "Standard Cells" (developed in the 1970s), was used successfully in many low-Earth orbital (LEO) missions (LANDSAT, TOPEX), geo-synchronous Earth orbital (GEO) missions, and early Mars orbital missions (MO, Magellan). Recently, missions utilized "Super" Ni-Cd batteries. TOPEX Ni-Cd batteries are shown in Figure 2.2-3. Some of the important characteristics of SOP Ni-Cd batteries are given in Table 2.3-1.

Figure 2.3-2 TOPEX Ni-Cd Battery

Ni-Cd cells consist of a NiOOH positive electrode (cathode on discharge), cadmium negative electrode (anode on discharge) and a liquid alkaline electrolyte of 31% aqueous potassium hydroxide. Prismatic (box-like) cells replaced the early cylindrical cells to extend technology to large capacity cells and for efficient battery packaging. Space quality Ni-Cd cells are significantly different from commercial Ni-Cd cells in design aspects such as: electrochemical design, electrode construction, separator system, and types of seals. The unique aspect of Ni-Cd cells is that O_2 generated at the NiOOH electrode during charging is recombined at the Cadmium electrode within the cell. Thus, even during overcharge there is no build up in oxygen pressure.

Space Ni-Cd batteries are available in two versions: a) NASA standard Ni-Cd and b) super Ni-Cd. NASA standard Ni-Cd batteries contain electrodes prepared by chemical impregnation methods and employ nylon separators. The Super Ni-Cd batteries contain electrodes produced by electrochemical impregnation methods and an inorganic separator material. Standard Ni-Cd batteries are not in production presently in the US and only super Ni-Cd batteries are being produced. Super Ni-Cd cells are available from Electro Energy Mobile Products (formerly Eagle-Picher Ind., Colorado Springs, CO). The availability of these super Ni-Cd batteries is also uncertain due to shift in manufacturing emphasis to other battery systems. However, Ni-Cd cells may be available from Japan or France. (See Appendix 1)

Ni-Cd batteries have demonstrated very long cycle life capability and reliability. These batteries have achieved more than 30,000 LEO cycles at 20-30% depth of discharge (DOD), and more than 1000 GEO cycles at 50% depth of discharge and higher. The cells have a low specific energy of only 30-35 Wh/kg and 60-90 Wh/l (batteries are 10-20% less based on design and construction). Super Ni-Cd batteries were found to have outstanding radiation tolerance because of the absence of a polymeric separator. (See Appendix 1). The major limitations regarding these batteries are that they are heavy, bulky (low specific energy and energy density), have limited operating temperature range, and exhibit a memory effect.

These batteries are not suitable for future surface missions where mass and volume are critical (such as landers, rovers) and require operation in low or high temperatures.

However, these batteries can be considered for orbital missions where mass and volume requirements are not as stringent, and where cycle life is the primary driver.

2.3.4 The Nickel – Hydrogen (Ni-H_2) Cell and Battery

Since their first use on NTS-2 spacecraft in 1977, Ni-H_2 batteries have been used in various Earth and planetary orbital space missions. Initially, these batteries were used primarily on commercial GEO synchronous communication satellites. They were first used by NASA for the Hubble Space Telescope (HST) in 1990. These batteries are also in use on the International Space Station. Ni-H_2 batteries have also been used in space science missions, such as Mars Global Surveyor, Mars Odyssey, Stardust and, Genesis (See Table 2.3-1).

In this battery system, NIOOH is the cathode active material, and hydrogen is the anode active material. The construction of the positive electrode in these batteries is similar to nickel electrodes of the Super Ni-Cd cell. The negative plate is a platinized catalyzed surface where hydrogen is oxidized during the discharge process and reduced during the charge process. The electrolyte is a solution of 30% potassium hydroxide and the separator is an inorganic material based on Zirconium Oxide (Zircar). The cell pack is contained in an Inconel pressure cylinder that can contain pressures >1000 psi. The pressure in the cell is a measure of the charge state of the cell.

There are three versions of Ni-H_2 cells presently in use:

a) Individual Pressure Vessel (IPV), one cell per pressure vessel, (Figure 2.3-3)
b) Common Pressure vessel (CPV), two cells per pressure vessel, (Figure 2.3-4)
c) Single Pressure Vessel (SPV), 22 cells per pressure vessel, comprising a full battery in one pressure vessel. (Figure 2.3-5)

Figure 2.3-3. Space Station Ni-H2 Battery

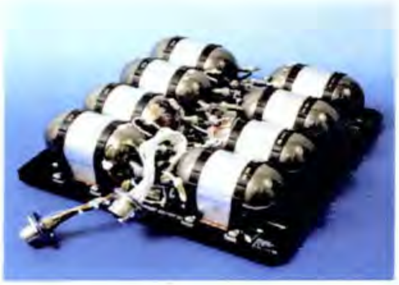


Figure 2.3-4. Mars Odyssey CPV Ni-H2

Figure 2.3-5. SPV Ni-H2

CPV and SPV batteries are intended to provide mass and volume savings compared to IPV batteries, because the number of pressure vessels is reduced. IPV Ni-H_2 batteries have been used in several GEO and LEO spacecraft including HST and Space Station. CPV batteries have been used in planetary orbital missions and Single Pressure Vessel (SPV) Ni-H_2 batteries have been used on Clementine and numerous commercial Iridium spacecraft with success. IPV Ni-H_2, CPV Ni-H_2, and SPV Ni-H_2 cells and batteries are available from Eagle-Picher Industries and Boeing Space Systems.

Ni-H_2 batteries have demonstrated superior cycle life performance (>50,000 cycles at 30-40% DOD) and calendar life (>15 years of GEO operational life) compared to Ni-Cd batteries. Another important advantage of these batteries is that they do not have the memory effect that was experienced with Ni-Cds. The IPV cell has a specific energy of 40 Wh/kg and an energy density of 70 Wh/l. Because of the pressure vessel configuration, the IPV battery exhibited only <20 Wh/kg and <10 Wh/l. CPV batteries have 50% higher specific energy, and SPV batteries have still higher specific energy than CPV because there is only one pressure vessel.

Because of their low specific energy, energy density, and high self-discharge, these batteries are not suitable for future surface missions that have limited mass and volume (such as landers, rovers). Further, some of the surface missions require operation at low temperatures, which is not appropriate for the Ni-H_2 aqueous system. These batteries can be considered for future orbital missions where mass and volume requirements are not stringent, and the key-driving requirement is cycle life. It is unlikely that these batteries will compete favorably with Li-Ion batteries in the future, and future research will be better directed to Li-Ion batteries than Ni-H_2 batteries.

2.3.5 The Lithium – Ion (Li-Ion) Cell and Battery

The Lithium Ion battery is a relatively a newcomer to aerospace applications. These batteries are currently being considered for a number of missions that have demanding mass and volume requirements and moderate cycle life requirements. Small capacity (<1 Ah) commercial Li-Ion batteries were employed in the space shuttle to power camcorders and other tools used by the astronauts. Batteries made with commercial small capacity cells have also been used on STRV-1d and PROBA missions. Li-Ion batteries made from small commercial cells were also used on the Mars Express spacecraft and Beagle-2 Mars Lander. NASA/Jet Propulsion Laboratory recently used 28 V, 10 ah Li-Ion batteries on

Mars Exploration Rovers, Spirit and Opportunity, to provide power (Figure 2.3-6). Recently Li-Ion batteries, developed by SAFT France, were used on Eutelsat's W3A, a European GEO communication satellite. Based on this success, these batteries are being considered for a number of future surface missions. Li-Ion batteries are base-lined for the Phoenix mission (Mars Lander) scheduled for launch in 2007.

Figure 2.3-6. MER Li-Ion Battery

Advantages and Disadvantages: The two most significant advantages of Li-Ion cells are their high specific energy (Wh/kg) and energy density (Wh/l). These batteries provide three to four times mass and volume savings compared to the SOP Ni-Cd and $Ni-H_2$ batteries. These savings are even higher at low operating temperatures, due to an inherent capability of Li-Ion cells to function better at sub-zero temperatures (as permitted by their non-aqueous electrolyte solutions). The cell voltages are typically higher than aqueous cells (3.6 V vs. 1.2 V for Ni-Cd and $Ni-H_2$ cells). This higher voltage translates into fewer cells and interconnects, and hence higher innate reliability and lower cost. Due to the absence of any parasitic reactions (which are common in aqueous electrolytes), the coulombic efficiency of Li-Ion cells is nearly 100% with an overall energy efficiency near 95%. By comparison, the overall efficiency of aqueous batteries is about 70%. The latter characteristic simplifies thermal management in a spacecraft. The self-discharge rate of Li-Ion cells is about three to five times lower than for Ni-Cd cells and about ten to fifteen times lower than for $Ni-H_2$ cells.

Background: Most of the earlier work involving the development of rechargeable lithium cells was focused on utilizing metallic lithium as the anode material with an insertion cathode in a liquid organic electrolyte. The initial development of rechargeable cells based on lithium metal as the anode was actively pursued beginning in 1970. These efforts were hampered by several technical impediments associated with inadequate stability of the electrolytes at the lithium electrode potential. These problems resulted in poor utilization efficiency for lithium, and safety issues due to the dendrite formation and reactivity of metallic Li. The use of lithium alloys in place of metallic lithium did not produce the desired durability in cycling the cells.

The breakthrough in this technology came from AT&T laboratories in the form of carbon materials that can function as intercalation lithium anode material. In 1991, SONY Corp. introduced a commercial Li-Ion cell based on this anode material for use in camcorders and personal electronics. The Li-Ion cell utilized a Li: C intercalation anode and an intercalation cathode of $LiCoO_2$. Some small deficiencies in specific energy and energy density resulted from replacement of a metallic lithium anode by the intercalation anode. However, the benefits of these modified Li-Ion cells in terms of stability, cycling, safety, and reliability were overwhelming and have enabled a rapid insertion of batteries with these cells in commercial electronics devices in a few years. (See Appendix 1)

The advent of practical Li-Ion rechargeable cells and batteries occurred a time when the consumer market was flooded with the introduction of new modern portable electronics devices, such as camcorders, laptop computers and cell phones. The advances in these electronics devices demanded a more efficient battery system; in other words, a lightweight and compact rechargeable battery to complement the miniaturization efforts of portable electronics devices. Thus, there was a symbiotic relationship between the emergence of Li-Ion batteries and modern miniaturized portable electronics. As a result, many of the commercial Li-Ion cells are limited to small sizes (i.e. 1-4 Ah capacity).

Description: The original Li-Ion cells introduced by Sony employed coke type carbon as the anode material, lithium cobalt oxide as the cathode material, and an organic electrolyte containing 1.0M LiPF6 in propylene carbonate and diethyl carbonate. Since then, Li-Ion cells have undergone several changes with respect electrode materials and electrolytes and cell design. Most Li-Ion cells presently in production use graphitic type carbons as anode materials, mixed metal oxides ($LiNiCoO_2$) as cathode materials, and electrolytes based on mixtures linear and cyclic carbonates. Finally, it is important to point out that the chemistry of Li-Ion cells is still evolving and many cathode materials, anode materials and electrolytes are under investigation. The alternate cathode materials under investigation include Li-MnO_2, aluminum doped mixed transition metal oxides ($LiNiCoO_2$, LiNi/CoMnO_2) and $LiFePO_4$. The anode materials under investigation include alternate carbon materials.

Most of the commercial cells are available in small capacities and are of cylindrical configuration. Aerospace cells are in being developed in U.S., Japan and France. The U.S. manufacturers of large capacity Li-Ion cells include Yardney, SAFT and Eagle Picher. The overseas manufacturers of large capacity aerospace Li-Ion cells include SAFT (France) and Japan Battery Storage Company (Japan). Recent advancements in this area are described in Section 4.3.1.

Characteristics of Li-Ion Cells: SOP Li-Ion cells have a specific energy of 100 to 150 Wh/kg and energy density of 250–350 Wh/l (depending on cell size and chemistry/vendor). These values are 20–50% lower at the battery level. SOP Li-Ion cells can provide over 1000 cycles at 100% DOD and can operate over the temperature range of –20–40°C. Important characteristics of Li-Ion cells and batteries are summarized in Table 2.3-1.

Recently 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 AFRL and NASA/GRC. This technology was only qualified for limited cycle life at the time of the mission. JPL successfully used these batteries for the first time 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 28V, and the nominal capacity of the battery is 10 Ah at room temperature. It was designed for operation at temperatures as low as –20°C. The battery has successfully supported the mission for more than 100 Mars days. Based on this success, these batteries are being considered for a number of future surface missions. Despite their outstanding energy performance, the current generation of Li-Ion batteries has had some shortcomings. These include, unproven long cycle and operational life (<5 years) and a limited operating temperature range (-20°C – 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 Ni-based cells.

The assessment team found that state-of-practice Li-Ion batteries are adequate to support missions that have mass and volume constraints and modest cycle life and operational life requirements. The assessment team also found that development of advanced Li-Ion batteries is required to meet the demanding requirements of long cycle life (> 30,000 cycles), long operational life (> 20 years), and of future orbital missions and outer planetary spacecraft. Advances are also required to meet the low temperature operational requirements of future Mars and lunar surface missions. Another key issue is that there are no prominent U.S. manufacturers of commercial Li-Ion cells. Many of the manufacturers are Japanese, and more recently Taiwanese or Chinese. There is a distinct need to develop a consistent U.S. supplier for producing larger cells of significantly higher capacity for aerospace applications.

2.3.6 Summary of Current Capabilities of SOP Rechargeable Batteries

The major findings of the assessment team are as follows.

- Rechargeable batteries that are presently in use in space missions include: Silver-Zinc Nickel-Cadmium, Nickel-Hydrogen, and Li-Ion batteries.
- Ag-Zn batteries, although having highest specific energy and energy density of the aqueous battery systems, are suitable only for short term launch vehicle applications This battery system is unlikely to be appropriate for future space science missions primarily because of its limited cycle life and shelf life capabilities.
- Ni-Cd, and Super Ni-Cd, batteries have demonstrated many years of operation in LEO and GEO applications when controlled within a temperature range of –10°C to 20°C. Super Ni-Cd batteries have outstanding radiation resistance. However, repetitive cycling to <25% depth of discharge further reduces the low specific energy of these aqueous alkaline systems to <10 Wh/kg. These batteries are not suitable for future surface missions that are critical in mass and volume (such as landers, rovers). In addition, the aqueous electrolyte limits the allowable range of temperatures. Only "Super Ni-Cd" cells and batteries are available for use in NASA missions.
- $Ni\text{-}H_2$ batteries have superior demonstrated cycle life performance (>50,000 cycles at 30-40% DOD) and calendar life (>15 years of GEO operational life) compared to any other SOP rechargeable batteries. However, these batteries are

heavy and bulky. In view of this, Ni-H_2 batteries are considered unsuitable for space science surface missions that are critical mass and volume (such as landers, rovers). These batteries can be considered for future orbital missions where mass and volume requirements are not stringent and the driving requirement is cycle life.

- Li-Ion batteries have a four-fold higher specific energy (Wh/kg) and almost an eight-fold higher energy density (Wh/l) than other SOP rechargeable batteries. These advantages were the primary drivers for the selection and use of Li-Ion batteries on the MER Rover. Although Li-Ion batteries were qualified for the 90-day Mars baseline mission, they have not been qualified for long durations required by future Space Science missions. However, they are ready for use in applications where mass and volume are critical, and operational temperature range and life requirements are moderate. Furthermore, the potential exists for significant improvements in lifetime and low-temperature capability.

The transition from Ni-based to Li-Ion batteries is attractive for Code S missions in view of the savings in mass, volume and cost of the power subsystems. The reduction in complexity resulting from the higher voltage per cell and the superior performance in terms of energy efficiency, self-discharge and low-temperature performance, provide significant benefits for Code S missions. The improvement over Ni-based systems is shown in Figure 2.3-7.

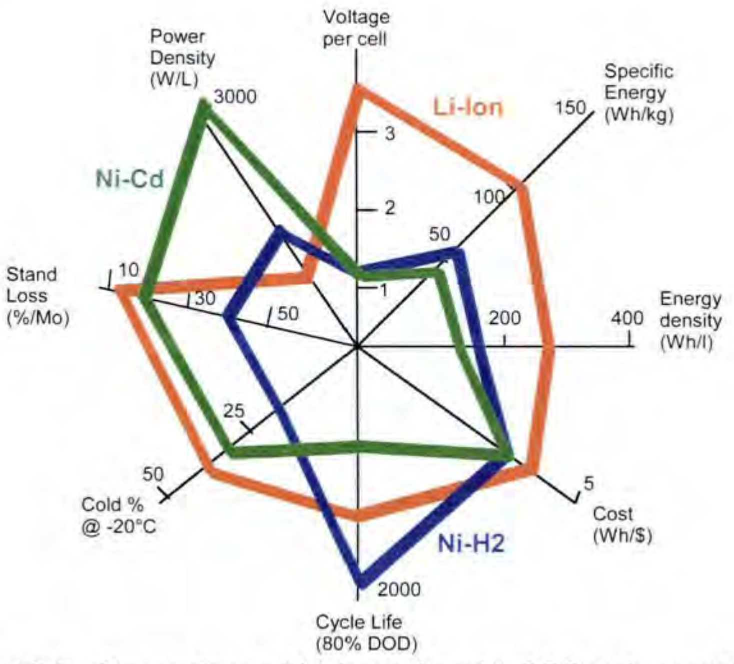


Figure 2.3-7. Comparison of Li-Ion cells with SOP rechargeable cells.

2.4 Radiation Effects on Batteries

2.4.1 Super Nickel-Cadmium Cells

Super Ni-Cd cells developed for NASA, contain a zirconia-based material (Zircar) as the separator in place of the Nylon in conventional Ni-Cd cells. The zircar was projected to have little degradation from exposure to radiation. The other inorganic cell components – including aqueous electrolyte, metallic oxide electrodes, stainless steel cell case and ceramic seals – were also projected to be radiation-tolerant.

In a 2001 JPL investigation, 37 Ah Super Ni-Cd Mars Observer cells from Eagle-Picher Industries were subjected to radiation testing. These cells were tested and placed into cold storage for ten years. After removal from storage and a short 10-cycle burn-in, the cells showed no adverse effects from storage. Radiation tests were then performed using JPL's High Rate Cobalt-60 Source. The radiation was imposed at a high rate on one pack of 3 cells and at a low rate on a second pack of 3 cells for a dose of 1 megarad. The high-rate was 30 rad/sec for 9.26 hours and the low-rate was 1 rad/sec for 277 hours. After each 1 megarad of radiation, a capacity test was performed to determine the effect of the radiation. The packs of three cells were oriented with the cell edges normal to the impinging radiation. The high-rate pack was placed closer to the source than the low-rate pack. The cell capacities, determined after 29 megarads of radiation, were essentially unaffected by exposure to intensive radiation.

2.4.2 Lithium-Ion Cells

Lithium Ion cells contain organic electrolytes and polymeric separators that could be affected by high levels of radiation. A detailed experimental evaluation was therefore undertaken by JPL to determine the performance of these cells after exposure to various levels of cumulative radiation levels up to about 25 Mrad. Prototype cells were obtained from two domestic sources utilizing two different chemistries as test articles. Typical materials and components in these cells included graphite anodes, mixed nickel cobalt oxide cathodes, electrolytes with 1M Lithium hexaflurophosphate ($LiPF_6$) dissolved in mixtures containing cyclic and linear organic carbonates, copper anode and aluminum cathode substrates, fluoropolymer binders, polypropylene/ polyethylene separators, glass to metal seals, and molybdenum pins and stainless steel cases.

The cells were then incrementally exposed to gamma radiation, using a ^{60}Co source both at high dosage rates of 30 rads/sec (corresponding to 1.5 Mrad over 14 hours) and a low level of rad/sec (corresponding to 1.5 Mrad over two weeks). After each irradiation, the cell capacities were measured both at ambient and low temperatures. The fade rates were established from charge-discharge cycles. Finally, the irradiated cells were subjected to extensive cycling to determine their cyclability in comparison to cells not exposed to such radiation levels. The discharge characteristics of cells were determined at ambient temperature after step-wise radiation exposure up to 18 Mrad in intervals of 1.5 Mrad.
The data for Yardney cells shows marginal capacity loss and voltage decrease after radiation exposure through 18 Mrad, in intervals of 1.5 Mrad. The decreases in the discharge voltage and capacity were more noticeable at low temperature, due to corresponding changes in cell impedance. The effects on cell discharge characteristics of

low rate radiation to the same cumulative radiation levels showed little difference in capacity and voltage reduction between the cells exposed to high rate radiation and low rate radiation.

After exposure to 18 Mrad in intervals of 1.5 Mrad, the SAFT "DD" cylindrical cell capacity showed similar small decreases in the capacity and discharge voltage. As was the case for Yardney cells, the decreases were more noticeable in the low temperature discharges at $0^{o}C$. The reductions in both capacity and voltage were slightly lower for these cells, compared to the prismatic cells. As with the Yardney Li-Ion cells, there is little difference in the behavior of the cells exposed to high-rate and low-rate radiation, implying that the cumulative radiation level, rather than the radiation rate, has a the major effect on cell behavior. Although there were some changes in the electrochemical impedance behavior of the Li-Ion cells exposed to γ-radiation, it was difficult to ascribe the changes to radiation affects.

From this study, it is clear that Li-Ion cells are tolerant to radiation levels as high as 18 Mrad and exhibit a loss of less than 5% upon such high levels of radiation exposure. Furthermore, a portion of this 5% loss can be attributed to the cycling or storage during this incremental radiation exposure. Both Yardney and SAFT cells, with their differences in configuration and also in chemistry, showed nearly identical high-capacity retention. The performance was also independent of the rate of radiation dose.

It is important to note that these tests were performed on “fresh” cells (typically a few months after manufacture). Results then apply to these “fresh” cells and not necessarily to “aged” cells (stored for several years.). An important follow-on investigation would be repetition of such tests on cells that have been stored for about a decade, which is what would be encountered in a Jupiter mission.

2.5 Capacitors

Traditional capacitors were 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 store considerably more energy per kg, 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 wet slug designs) were used in the Galileo and Cassini 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 since 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). Ganged capacitors in parallel were used in the Galileo and Cassini missions for power "keep-alive" and for voltage-leveling during radar operations. The devices used in the two missions were rated at 1200 microfarads and were capable of providing 20 amps in one millisecond.

The latest of the capacitor technologies is the ultracapacitor, or "super-capacitor." These are electrochemical devices (also known as an electrochemical double-layer capacitor) that 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 ultracapacitors are intermediate between conventional capacitors and batteries. These are presently being developed for commercial and military use.

2.6 Summary of SOP - Energy Storage Devices

2.6.1 Primary SOP Batteries

- Primary batteries that are presently being used in various space missions are: a) Zn-AgO, b) Li-SO_2, c) Li-$SOCl_2$, and d) Li-CFx.
- Zn-AgO batteries have low specific energy (100–150 Wh/kg) and short shelf life (6-12 months) and they are not attractive for future pace science missions. Ag-Zn batteries are fully developed and offer little opportunity for further improvement.
- Li-SO_2 and Li-$SOCl_2$ batteries deliver moderate specific energy (100-250 Wh/kg), can operate over a temperature range of –40°C to + 60°C and have proven lifetimes up to 10 years. The major limitations associated with these batteries are limited performance capabilities at temperatures lower than –40°C and voltage delay. These batteries are not attractive for missions that require operation below –40°C. Li-SO_2 batteries are fully developed and offer very little opportunity for further improvement. Li-$SOCl_2$ batteries on the other hand have some potential for further improvement particularly in the area of low temperature performance.
- The Li-CFx battery has the highest specific energy of primary batteries and it also has a minimum voltage delay. The major limitations of the existing versions are very low specific power and limited operating temperature range. This system has some potential for further improvement particularly in the areas of rate capability and low temperature performance.
- Radiation tolerance and lifetime beyond 10 years remains uncertain for all these batteries.

2.6.2 Rechargeable SOP Batteries

- Rechargeable batteries that are presently in use in space missions include: Silver-Zinc Nickel-Cadmium, Nickel-Hydrogen, and Li-Ion batteries.

- Ag-Zn batteries, although having highest specific energy and energy density of the aqueous battery systems, are suitable only for short term launch vehicle applications This battery system is not attractive for future space science missions primarily because of its limited cycle life and shelf life capabilities. Ag-Zn batteries are fully developed and offer little opportunity for further improvement.
- Ni-Cd batteries have been successfully used in many space missions (particularly LEO and GEO missions). They have low specific energy and long cycle life capability. These batteries can be considered for future orbital missions where mass and volume requirements are not stringent and the driving requirement is cycle life. These batteries are not suitable for future surface missions that are critical in mass and volume (such as landers, rovers). Manufacturing of these batteries is being phased out and only certain versions (super Ni-Cd) may be available for future use. Ni-Cd batteries are fully developed and offer little opportunity for further improvement.
- Ni-H_2 batteries have been successfully used in many space missions (particularly LEO and GEO missions). Ni-H_2 batteries have superior demonstrated cycle life performance (>50, 000 cycles at 30-40% DOD) and calendar life (>15 years of GEO operational life) compared to any other SOP rechargeable batteries. However, these batteries are heavy and bulky. These batteries can be considered for future orbital missions where mass and volume requirements are not stringent and the driving requirement is cycle life. Ni-H_2 batteries are unsuitable for future space science surface missions that have critical mass and volume (such as landers, rovers) requirements. Ni-H_2 batteries are fully developed and offer little opportunity for further improvement.
- The Lithium Ion battery is a relative newcomer to aerospace applications. Li-Ion batteries offer significant mass and volume advantages (three to four fold) compared to SOP Ni-Cd and Ni-H2 batteries. Recently, JPL has successfully implemented this technology for Mars Surface missions (MER in collaboration with NASSA GRC and AFRL. The limitations of the SOP Li-Ion batteries are limited cycle life and operational temperature range. This system has significant potential for further improvement in its capabilities.

2.6.3 Capacitors

SOP capacitors are typically used on spacecraft as filtering elements for power management and distribution. However, on two occasions capacitors have been used for energy storage to pulse power (Galileo and Cassini). The most important advantage of capacitors is the capability to supply high pulses repeatedly for hundreds of thousands of cycles. The recent development of super-capacitors increases the range of options for utilizing capacitors in spacecraft by increasing specific energy at a sacrifice in pulse power. However, there does not seem to be an identifiable need for further improvement in this technology for space science missions.

3.0 Impact of Advanced Energy Storage Technologies on Space Science Missions

The assessment team reviewed information on destinations of the Space Science Enterprise in the next decade, and identified major energy storage technology challenges. The information on the destinations was provided by the theme technologists, mission planners, and architects of the Solar System Exploration (SSE), Mars Exploration Program (MEP), Sun-Earth Connection (SEC), Astronomical Search for Origins (ASO), and Structure and Evolution of the Universe (SEU) Themes. Gaps between potential mission needs and capabilities of State of Practice (SOP) technologies were identified.

Many space science missions utilize some form of energy storage on their spacecraft. The continuing evolution of ever-improving battery performance benefits a wide gamut of space science missions. That is not our principal concern here. Instead, we are interested in space science missions for which advanced energy storage technology is likely to produce a significant positive impact in terms of greatly improved performance – or in some cases, enabling new more effective mission scenarios.

The following paragraphs review the energy storage needs of past missions and how they benefited (or might have benefited) from application of more advanced energy storage technology. In most cases, no attempt was made to determine the "ripple effect" of mass savings of the energy storage system on other spacecraft systems (e.g., structure, propulsion, thermal control). Only those mass- or volume-savings directly attributable to changes in the energy storage system were included. Nevertheless, this ripple effect will further increase the value of advanced energy storage technology. Potential future missions were also examined.

In some cases, a reduced-order trades model developed at the California Institute of Technology's Laboratory for Spacecraft and Mission Design (LSMD) called CoMET (for Cost and Mass Evaluation of Technology) was used to estimate the relative benefits of advanced energy storage technology. CoMET is designed to use a mission point design, developed by JPL's Advanced Products Development Team (Team X), as a basis for calculation of mass and cost savings that may result from the use of advanced technology. It is important to remember that these results are tentative since they are based on mission designs that are still in the conceptual stage, and for which substantial architectural changes may still occur as these missions are further studied. Such changes would naturally result in corresponding changes in the estimated values of mass benefits for energy storage systems. However, these calculated benefits are still illustrative of the scope and range of the impacts of advanced energy storage technology, and provide a relative (but not absolute) measure of the potential benefits.

3.1 Mars Missions

Existing and planned Mars missions using solar and nuclear radioisotope power are reviewed below. The choice of power generation source influences the requirements for energy storage and accordingly the needs and benefits of the new technology. For solar powered missions, rechargeable energy storage systems are required to provide power during nighttime (for landers and rovers), eclipse periods (for orbiters) and supplemental power for peak loads required to support telecommunications, higher power instrument operations, and separation or deployment mechanisms. Radioisotope powered missions utilize energy storage for load leveling.

3.1.1 Mars Surface Missions

Mars surface missions include many forms, such as static landers, rovers, and micro-landers or penetrators. The requirements and the benefits vary from one to the other.

3.1.1.1 Landed Missions

This class of mission requires energy storage technologies that are mass and volume efficient. Cycle life requirements depend on the mission duration and the power source of the lander. Solar powered missions require rechargeable energy storage with low-to-moderate cycle life capability. Missions using Radioisotope Thermal Generators (RTGs) may benefit from rechargeable energy storage systems, depending on the power output of the RTGs and the power load levels required. Missions using fission reactors will require a substantial primary energy storage device for start-up and for re-start after an emergency shutdown. In all cases, improved tolerance to low temperatures is desirable.

The difficulty of landing on the surface of Mars results in mass and volume constraints due to the scaling impacts on the entry descent and landing system. In particular, entry aeroshell volume is constrained, and the capability of parachutes, propulsive landing systems and landing shock attenuation systems (such as airbags) is entirely driven by the landed mass. As a result, payloads are constrained to approximately 10 to 20% of the landed mass. Mass allocated to other subsystems, such as power, compete with the payload for allocation of landed mass. Reductions in power system mass, such as energy storage systems, allow increased allocation of payload mass or can be used to reduce the mission risk by reducing impact loads. Mission life was reduced in the Mars Pathfinder mission in order to reduce energy storage system mass to an acceptable level. The low nighttime temperatures also provide a lifetime challenge to many systems, including energy storage. Energy storage systems that can withstand and operate at lower temperatures will reduce thermal control system mass (and bulk) otherwise required to maintain the energy storage system at operating temperatures.

Past solar-powered landed missions include Mars Pathfinder and Mars 2001 (which was not launched, but is now being resurrected as Phoenix). In the Mars Pathfinder mission, a Silver-Zinc rechargeable battery was chosen over Nickel-Hydrogen, saving approximately 35 kg in mass and 140 liters in volume. If this choice had not been made, there would have been no room for the Sojourner rover in the lander, and it would have been eliminated from the design. However, this was traded against the potential mission lifetime, as Silver-Zinc can only cycle at most 100-200 times, while Nickel-Hydrogen can provide up to 5000 cycles at 50% Depth of Discharge (DOD).

For the planned Phoenix Lander (launching in 2007), a Li-Ion rechargeable battery has been baselined. This battery provides the mass and volume advantage of the Silver-Zinc battery, but has the additional benefit of increased lifetime (>2000 cycles) and improved low temperature operation (-20 C vs. 0 C for Silver-Zinc). Another key factor in the selection was the successful first use of the technology in the Mars Exploration Rover (MER) – see Section 3.1.1.2.

Future solar powered missions, such as the Mars Sample Return (MSR) mission would similarly benefit from advanced rechargeable energy storage systems. Further improvements in energy density and specific power will provide future solar-powered landers with increased payload capacity. Improvements in lifetime (number of cycles) will increase mission life. Improved low-temperature tolerance will reduce dependence on thermal control and improve performance in more challenging environments, such as the Martian winters or polar regions. Additional study will be required to quantify these benefits as these mission concepts are further developed.

Table 3.1-1. Mars Lander Energy Storage Comparison

Mission	Mars Pathfinder (1996)		Phoenix (2007)
Energy Storage Technology	Nickel-Hydrogen (REFERENCE)	Silver Zinc (SELECTED)	Li-Ion (SELECTED)
Capacity (AH)	45-60	45-60	45-60
Specific Energy (Whr/kg)	30	100	110
Energy Density (Whr/liter)	10	160	200
Lifetime (cycles)	>5000	~100	~2000
Operating Temperature	0 C	0 C	-20 C
Volume (liters)	150	10	10
Battery Mass (kg)	50	15	15
Total Landed Mass (kg)	360	360	NA
Instrument Payload (kg)	🟧	8	NA

3.1.1.2 Rovers

Energy storage needs of Rovers are similar to those of Landers, but in general are even more constrained in mass and volume. Energy storage requirements also depend on whether the rovers are solar or radioisotope powered.

Past rover missions include Sojourner, and the recent Spirit and Opportunity Mars Exploration Rovers (MER). The Sojourner rover was planned with a limited lifetime and a primary battery was chosen to supplement the solar power provided during that lifetime. If a standard secondary battery had been chosen, the Sojourner could not have fit in the volume available to it. Even a rechargeable Li-Ion battery would have been unacceptably bulky and heavy. Therefore Sojourner used the most efficient primary battery available at the time. The Spirit and Opportunity rovers considered several options for secondary energy storage, however space limitations in the warm electronics box (WEB) forced selection of Li-Ion batteries because Nickel-Hydrogen batteries would have been unacceptably bulky and heavy, and Silver-Zinc, while far less bulky, was still twice as massive and provided inadequate lifetime. The MER figures in Table 3.1-3 include battery packaging and electronics, not included in the Sojourner case shown in Table 4.1-2. It is apparent that without new technology, batteries to provide the required power level would have required a very large fraction of the total rover mass.

The planned Mars Science Laboratory (MSL) Rover mission (for launch in 2009) has adopted RPS power as a tentative baseline as of April, 2004, but solar power is being considered as a potential descope option. If solar power is used, a secondary battery will be mandatory for survival. If RPS power is used, a secondary battery will likely be needed for load-leveling. Due to the planned increases in capability and lifetime of the MSL Rover compared to the MER rovers, the energy density, specific power, and lifetime of the energy storage systems will be important to the MSL mission. Substantial mass and volume savings are likely if advanced secondary energy storage technology is used. It is likely that a solar-powered version of MSL would achieve a landed mass saving of ~ 40 kg from use of Li-Ion batteries, and an even greater reduction in launch mass. The required 500 Sol life and cycle life of Li-Ion batteries has been demonstrated.

Table 3.1-2. Mars Sojourner Energy Storage Comparison

Mission	Sojourner (1996)	
Energy Storage Technology	Li-SO_2 (REFERENCE)	Li-$SOCl_2$ (SELECTED)
Capacity (Whr)	270	270
Specific Energy (Whr/kg)	136	245
Energy Density (Whr/l)	390	515
Low Operating Temperature (C)	0	-20
Volume (liter)	1.5	<1
Battery Mass (kg)	3	1.5
Total Rover Mass	10.6	10.6
Science Instrument Mass (kg)	🟥	<1

Table 3.1-3. 2003 MER Energy Storage Comparison

Mission	Mars Exploration Rover			
Energy Storage Technology	Nickel-Cadmium	Nickel-Hydrogen	Silver-Zinc	Lithium-Ion (SELECTED)
Capacity (Wh)	300	300	300	300
Specific Energy (Wh/kg)	25	30	~100	>100
Energy Density (Wh/lit)	100	50	~150	>250
Cycle Life 50% DOD)	>1000	>1000	<100	>1000
Wet life (Storageability)	Excellent	Excellent	Poor	Good
Self-Discharge (per month)	15%	30%	15-20%	<5%
Low Temperature Perf. (-20°C)	Moderate	Moderate	Moderate	Excellent
Temperature Range, °C	-10- 30	-10- 30	-10- 30	-20 to +40
Charge Efficiency %	80%	80%	70%	~100%
Battery Volume (Liter)	9	17	6	2.2
Battery Mass (kg)	33	28	11	6
Total Rover Mass (kg)	~174	~174	~174	174
Science Payload (kg)	🟥	🟥	17	~22

The Astrobiology Field Laboratory (AFL) Rover is projected for launch in 2013. This RPS-powered rover will have an even more powerful scientific exploration capability than MSL. It has been conceived with a sophisticated sample gathering and analysis payload, requiring power levels well beyond that of even the MSL Rover. Analysis is still required to determine the precise benefits of advanced secondary energy storage systems for this mission and is worthy of further study as this mission concept evolves.

Finally, planetary protection considerations may limit the sites that RPS-powered landers and rovers may access, forcing the use of solar power for those sites classified as sensitive. Should this occur, the need for efficient secondary energy storage systems will become paramount for these scientifically important missions.

3.1.1.3 Probes/Microlanders and Other Low-Cost Missions

Another class of potential future Mars in situ missions includes probes (such as the DS-2 probes), microlanders, or other small, low-cost missions with limited power generation capability due to their small size. These may include aerial vehicles such as airplanes, gliders or balloons. Highly capable energy storage systems will have a major impact on the performance of these missions. Some of these missions may be subjected to severe g forces during landing and to the full diurnal range of temperatures of the Mars environment because of limitations on thermal insulation.

One reference mission illustrating the importance of energy storage technology was the DS-2 mission that was deployed to Mars in 1998. Two experimental high technology probes were deployed and neither was heard from after it was deployed to impact the Mars surface. However, there was a significant test program to validate the performance of the primary batteries selected for the mission. At that time (1998) only a lithium thionyl chloride battery could provide the necessary power density. Future missions of this type may use a small radioisotope power system (RPS) with secondary or primary energy storage systems.

Table 3.1-4. Mars New Millennium DS-2 Comparison of Battery Options

Mission	New Millennium DS-2	
Energy Storage Technology	Li-SO_2 primary (REFERENCE)	Li-$SOCl_2$ primary (SELECTED
Capacity (Ahr)	2	2
Specific Energy (whr/kg)	136	245
Energy Density(whr/liter)	390	515
Operating Temperature ©	0	-20
Axial acceleration (g)	10,000	10,000
Volume (liter)	1.5	<0.1
Battery Mass (kg)	~0.6	~0.37
Total Landed Mass (kg)	3.6	3.6
Science Payload (kg)	<0.25	<0.5

Small low-cost landed or airborne missions may benefit from low-voltage designs that eliminate power conversion components that would reduce battery size and simplify electronics. The ability to withstand high g-loads from surface impacts would also be of value to missions that utilize penetrators. The energy efficiency of Li-Ion batteries is near 95%. Because there is little heat released during charge and discharge cycles, thermal control complexity is reduced. This also results in improvement in mass and volume efficiency of these rechargeable batteries. The capability to operate at temperatures to –

60°C and below for both primary and rechargeable batteries would allow increased science payloads, data return, and reduce risk for almost any conceivable small mission.

3.1.2 Mars Orbiters

Mars orbiters use solar energy as their primary power source and require secondary batteries to provide power during eclipse periods. Improvements in specific energy of batteries can provide measurable mass savings (10s of kilograms), provided that the cycle life of advanced batteries can be extended to several years and several thousand cycles. Both the Mars Global Surveyor (MGS) and the Mars Odyssey orbiter could have achieved benefits similar to those shown for MRO in Table 3.1-3 if advanced energy storage technology with adequate lifetime had been available.

3.1.2.1 Mars Reconnaissance Orbiter

This highly capable orbital remote sensing mission to be launched to Mars in 2005 will be equipped with a 6 kW solar array and is designed to operate from launch through the relay phase for 5.4 years. At the time of design, an advanced rechargeable battery was not feasible because of the requirement to demonstrate 22,000 cycles of Mars orbit cycling after 1 year of cruise. A 50 Ah Ni-H_2 battery was selected to perform this orbital mission. Table 3.1-3 illustrates potential mass savings that would result from a hypothetical Li-Ion battery with adequate cycle life. In addition to the energy storage mass and volume savings (~28 kg and 37 liters), additional savings in structural and propulsion mass would amplify the benefits. However, relative to landed missions the impact of new technology on overall performance is significantly less. Nevertheless, there may be future missions which could capitalize on this additional performance to provide much higher peak communications rates than are available on MRO or supply higher instantaneous power to power-hungry instruments.

Table 3.1-5. MRO Comparison

Mission	MRO Baseline Technology	Advanced Li-Ion (if available)
Technology Used	Ni-H_2	Li-Ion
Capacity (Whr)	1400	1400
Specific Energy (whr/kg)	34	110
Energy Density (whr/l)	32	200
Lifetime (cycles)	>5000	>5000[1]
Volume (liter)	44	7
Battery Mass (kg)	41	13
Total Orbiter Mass (kg)	2180	2180
Science Payload (kg)	~135	~170

3.1.2.2 Future Mars Orbiters

Future Mars orbiter missions are typified by the Mars Telecom Orbiter (MTO), scheduled for launch in 2009. While the design for this mission is still being developed, it is clear that the communication bandwidth necessary for the relay of data from future Mars surface missions will likely require substantially greater power levels than those used on previous orbiter missions. It is expected that the mass and volume savings from use of Li-Ion batteries will be even greater than it would have been for previous orbiters.

3.2 Outer-Planet Missions

Missions to the outer planets, Jupiter, Saturn, Uranus, and Neptune, require a wide range of capabilities for success. In addition to large, highly capable orbiters powered by radioisotope power systems (RPS) that require advanced rechargeable batteries for communication and peak power, these missions also typically include atmospheric probes or icy moon landers. Probes and landers require low mass and volume primary energy storage devices that can operate at low temperatures.

3.2.1 Outer Planet Orbital Missions

The two recent major orbital missions are Galileo (which completed its mission in the Jupiter system in 2003), and Cassini (which will be inserted into Saturn orbit in July of 2004). Both Galileo and Cassini used Radioisotopic Thermionic Generators (RTGs) to supply power. Each RTG weighed about 60 kg per 280 W RTG. Galileo used two RTGs producing nearly 600 W at beginning of life and Cassini used three RTGs with nearly 900 W of initial power. With these high power levels, it was not necessary to use batteries for load-leveling, and because of the long operational lives of these missions, providing long-life batteries would have been a challenge. There were a few operations such as firing pyros and stepping the scan platform that require short pulses of high power, and for these purposes, the Galileo and Cassini spacecraft employed capacitors. The New Horizons mission to Pluto is using the last RTG developed for Galileo. New Horizon is the first of the New Frontier Class of mission described below.

Future outer planet orbital missions will differ from Galileo and Cassini. The Flagship class missions typified by the Jupiter Icy Moon Orbiter (JIMO) will use nuclear reactors for power and will operate at very high power levels 10s to 100s of kilowatts. Future outer planet spacecraft developed under the New Frontier program for example have the option of using RPS. In the past, outer planet missions (to Jupiter) have been proposed (but not selected) under the Discovery program, which does not permit the use of RPS.

3.2.1.1 Promethius I

Nuclear reactor powered spacecraft (such as the Jovian Icy Moon Orbiter) must plan for the possibility of a reactor shutdown. Very high capacity rechargeable batteries (several kilowatts) will be required to maintain spacecraft systems in a healthy state and provide power for telecom to assist in diagnosing problems. However, the main battery capacity is required to restart the reactor. This requires high specific power. Li-Ion batteries have demonstrated very high rates of discharge. However, for these missions large capacity batteries are required. The largest Li-Ion to date is a 10 Ahr cell used on MER. Radiation tolerance (from both the reactor radiation and the environmental radiation) would provide savings in shielding mass as well. Given the large quantity of propellant required for a Nuclear Electric Propulsion (NEP) mission, it is likely that there would be a strong multiplier effect on reduction of battery mass by use of advanced battery technology.

3.2.1.2 New Frontier Class Outer Planet Missions

It is likely that future outer planet orbital missions in the New Frontier Class, if any are approved, will use lower power energy generation units than employed by Galileo and

Cassini. Therefore long-life (>10 years, and in some cases up to 20 years) rechargeable batteries will be needed for load-leveling. These missions require energy storage devices with capacity up to 1-2 kWh. Other requirements include mass and volume efficiency. SOP Ni-H2 rechargeable batteries are adequate in terms of life requirements but the radiation tolerance of these batteries is unknown and these have poor mass- and volume-efficiency. Availability of Ni-Cd batteries for next decade missions is uncertain as the production of these batteries is likely to be discontinued. Although these have good radiation resistance, their mass- and volume-efficiency is even lower than that of $Ni-H_2$ batteries. The use of advanced long-life rechargeable Li-Ion batteries that provide a mass savings of 60–75% over the Ni-based batteries appear to be attractive for most for these missions. More detailed studies of some of these missions (a Neptune/Triton Orbiter with probes and a Titan orbital mission) are in progress and will assist in further quantifying the benefits.

3.2.2 Outer Planet Probes

In the past, high energy density primary batteries were used to supply power to atmospheric probes. Such missions require primary batteries with mass and volume efficiency, long calendar storage life (> 10 years), radiation tolerance and minimal voltage delay. $Li-SO_2$ primary batteries have been utilized to power the payloads of the Galileo probe, and the Huygens Titan probe (currently on its way to Saturn as part of the Cassini-Huygens mission). Non-lithium-based primary batteries would have been impractically heavy. This would have impacted the mass and volume of the batteries, as well as the thermal shielding, due to their large mass fractions of the entry payload (30–50% of the entry mass). If the advanced primary batteries – more mass- and volume-efficient, and capable of operating at lower temperature and higher rate (e.g. $Li-SOCl_2$ or $Li-CF_x$) – had been available, substantial mass savings could have been achieved. The savings in probe mass could have reduced the spacecraft mass by as much as four times the battery mass savings.

Future atmospheric probes (such as those proposed for future Jupiter and Neptune missions) require advanced primary energy storage that can operate over a wide range of temperatures. This flexibility can reduce thermal protection mass and bulk, to enhance these missions by increasing the payload and extending the operating life. The operational temperature requirement varies from mission to mission and depends also on the thermal system design. The ability to withstand high g-loads (>100g) is required for the initial atmosphere entry phase. The aeroshells required for atmospheric probe missions are estimated at 30 to 50% or the total entry mass. This implies that each 1 kg savings in battery mass result in a corresponding 1.5 to 2 kg savings in probe mass, even without considering savings in structure and thermal protection mass. Energy storage systems with reduced mass and volume will make the difference between these missions being limited to one probe or having the capability to carry two or three probes, greatly increasing the science benefit from atmospheric probe missions.

3.2.3 Europa Icy Body Lander

Europa, the second Galilean satellite of Jupiter, has an icy surface shell that is believed to cover a global ocean. Placing a spacecraft on the surface of Europa could answer many questions about the nature of the ocean and the possibility of life or pre-biotic chemistry existing there. However, because of the challenging propulsion requirements for safe landing on an airless body, it is estimated that each kilogram of savings in landed mass would result in a 20 kilogram (or greater) savings in corresponding launch mass.

Europa lander concepts of varying sizes and lifetimes are being examined and a growing interest in the concept is likely in connection with the Jupiter Icy Moon mission. For very small landers with limited lifetime (radiation is also a major life limiting factor on Europa), primary batteries will be the preferred choice. Advanced primary batteries capable of operating at temperatures lower than –60°C would help extend the lifetime of these landers. As with Mars landers, a lower temperature operation will reduce the size of the thermal control system but that will be the subject of a detailed study.

Somewhat larger landers might use a miniature RPS (whose development is being contemplated) that could provide 10–20 watts of electrical power. In this case, rechargeable energy storage with very high mass and volume efficiency will be required to provide power for communications and instruments.

For a large lander, powered by one or two 100W class RPS units, in principle it is possible to implement the mission without batteries. However, studies performed by JPL's Advanced Products Development Team have indicated that batteries with specific energy >150 Wh/kg provided substantial performance benefits.

3.2.4 Titan Explorer

Delivering vehicles into the Titan environment is not as demanding as for the icy moons of Jupiter because the dense atmosphere of Titan can be exploited to decelerate the vehicle, and limit the amount of control needed during descent and landing. NASA is examining a number of alternatives for in situ exploration of Titan, including vehicles with either surface or aerial mobility. The power requirements for these missions will differ but many of the technical challenges are common. Here we examine the aerial missions.

A Titan Aerial Explorer or aerobot would exploit the dense atmosphere of Titan – 5 times that of Earth at sea level, which permits lighter-than-air vehicles of a size that can be delivered by a spacecraft designed to carry comparatively large payloads. Missions using vehicles with either vertical mobility (altitude) control or both vertical and horizontal mobility are being analyzed. In each case, they would be able to descend to the surface and take samples as well as performing remote sensing observations from several kilometers altitude in the atmosphere.

These aerial missions would use RTGs to provide primary power. However, secondary storage systems are being considered to provide load leveling and supplemental power for maneuvering and telecommunications. A companion study is currently underway in collaboration with NASA's Enabling Concepts and Technology (ECT) Program (recently reorganized into the Human and Robotics Technology (HRT) program to examine technologies needed in extreme environments such as that of Titan. The report detailing the results will be published during late calendar year 2004 and should be consulted for a more detailed analysis of the benefits of advanced low temperature energy storage systems.

3.3 Small Body Exploration – Comets and Asteroids

The exploration of comets and asteroids is a major focus of NASA's Solar System Exploration program since these objects contain a record of the very early history of the solar system. Here we will focus only on the energy storage needs of comet missions. Asteroid missions have broadly similar needs.

The Stardust NASA Discovery comet mission is currently in its operational phase. A second Discovery mission, Deep Impact, will be launched in late 2004 or 2005. An asteroid orbiter, DAWN, will be launched in 2006. And a Comet Surface Sample Return mission is the subject of a competitive selection in the New Frontier program. Each mission is different in character. Here we focus on how advances in energy storage have contributed to the past missions, and how they may have benefits for the sample return mission. However, since the sample return mission is in a competitive phase we rely on analyses that predate the competition.

Although asteroid missions have not been considered explicitly here, it is important to note that in general, many of the benefits to comet missions will carry over to asteroid missions.

3.3.1 Stardust Mission

Table 3.3-1. Stardust Comparison

Mission	Stardust Baseline Technology	Advanced Technology
Technology Used	Li-SO2	Li-CFX
Capacity (Ahr)	7	7
Specific Energy (whr/kg)	192	520
Energy Density (whr/l)	182	525
Volume (liter)		
Battery Mass (kg)	1.5	0.4
Sample Return Canister (SRC) Mass (kg)		
Sample Mass (kg)		

3.3.2 Deep Impact Mission

Several mission concepts are under study to explore comets and asteroids. The Deep Impact mission is now in Phase C/D and is scheduled for launch in 2004/2005. It will study the composition of the comet Temple 1 by firing an Impactor at the comet to open up the interior to remote sensing by spectroscopic instruments on the spacecraft. The Impactor is mechanically and electrically attached to the flyby spacecraft for all but the last 24 hours of the mission. Only during the last 24 hours does the Impactor run on internal (primary) battery power. This mission has baselined Li-$SOCl_2$ primary batteries because of the cell's highest specific energy (>245 Wh/kg) and energy density (515 Wh/l) compared with the other primary systems such as Li-SO_2. Table 3.3.2 illustrates this comparison.

Table 3.3-2. Deep Impact Impactor Comparison

Mission	Deep Impact (Impactor)	
Technology Used	Li-SO_2 primary (Reference)	Li-$SOCl_2$ primary (Selected)
Capacity (Whr)	2800	2800
Volume (liter)	7	5
Operating Temperature ©	0	-20
Specific Energy (whr/kg)	136	245
Energy Density(whr/liter)	390	515
Battery Mass (kg)	~65	~37
Total Impactor Mass	378	378
Total Payload Mass	~34	~62

3.3.3 DAWN Asteroid Rendezvous

A Discovery class mission (called (DAWN) is currently being developed to orbit two asteroids. This mission is using standard rechargeable energy storage, due to the long mission life. If Li-Ion technology with long cycle life was available, additional science payload could have planned, and mission mass (and potentially cost or risk) could have been reduced. Table 3.3-3 illustrates this comparison.

Table 3.3-3. DAWN Comparison

Mission	DAWN spacecraft	
Technology Used	Ni-H (selected)	Li-Ion
Capacity (Ahr)	35	35
Specific Energy (whr/kg)	34	110
Energy Density (whr/l)	32	200
Lifetime (cycles)	>5000	>5000[1]
Battery Mass (kg)	~27	~9
Total Mass (dry)	677	677
Science Payload (kg)	42	60

3.3.4 Comet Surface Sample Return

In contrast with both the Stardust and the Deep Impact missions where the spacecraft encountered the comet with a relative velocity of many kilometers per second, in a Comet Surface Sample Return mission, the spacecraft must rendezvous with the comet in order to accomplish the science objectives. The sample might be acquired from near the surface or it might involve penetration to a significant depth into the comet depending on the science requirements.

Comet sample return missions concepts include both Solar Electric Propulsion (SEP) and chemical propulsion variants. In either case, substantial secondary power systems are required for those missions designed to bring the spacecraft into close proximity of the selected body and where lengthy eclipse periods and/or dusty environments prevent use of the solar arrays.

In the event there is a requirement for deep drilling into the comet, this would substantially increase battery power requirements and infer a higher rate of discharge. Preliminary analysis indicates that mass savings of 50 to 100 kg by using a lithium-based system over a nickel-based system can be achieved for SEP missions and an impressive 500 kg or more savings for missions using chemical propulsion (due to the larger batteries required for load leveling with small solar arrays and the mass multiplier from the large amounts of propellant required.)

Since there is currently a competitive New Frontier solicitation for a Comet Sample Return Missions in the New Frontier program, a more detailed examination of the impact of energy storage technology on comet missions has not been conducted.

3.4 Venus Exploration Missions

Over the last four decades, the planet Venus, a near twin of the Earth, has been the explored by NASA using flyby, orbital, and atmospheric probe missions. The former Soviet Union had an even more extensive program of Venus exploration which included a series of short-lived landed missions and the Vega missions in which two balloons were floated in the high atmosphere of Venus for two days. The future exploration of Venus will include competitive missions through the Discovery and New Frontiers program. National Research Council's Decadal Survey of 2002 identified Venus Surface Sample Return as a long range goal for Venus exploration. The European Space Agency is currently developing an orbital mission called Venus Express.

3.4.1 Venus Environment

The Venus atmosphere contains mainly carbon dioxide, and the corrosive gas sulfur dioxide is a significant minor constituent. The conditions in the Venus atmosphere vary from about 460°C and 90 bars at the surface to about 0°C and 1 bar at an altitude of 55 km. The Soviet Vega balloons floated at about this altitude. The pressure varies with altitude as shown in Figure 4.4-1. The variation of temperature with altitude is shown in Figure 4.4-2.

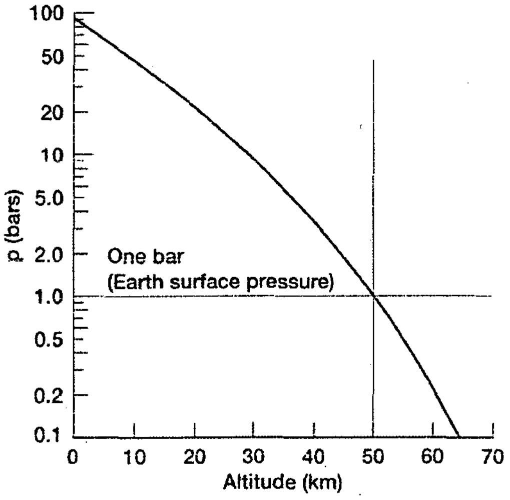


Figure 3.4-1. Pressure vs. Altitude on Venus

The relative solar intensity as a function of altitude is provided in Figure 3.4-2 for several wavelengths in the solar spectrum. A key point to be recognized is that very little solar energy actually reaches the surface of Venus. As a result of this fact and the high temperature at the surface making conventional solar arrays impractical, solar power is not feasible at the surface. Although radioisotopic power generation is feasible in principle, the high pressures and temperatures would require major redesign of these power sources. For these reasons, missions that land on the surface of Venus will require primary batteries in the foreseeable future.

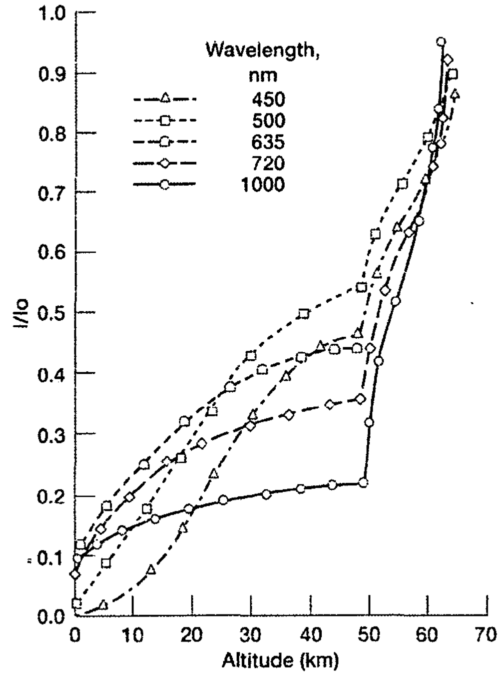
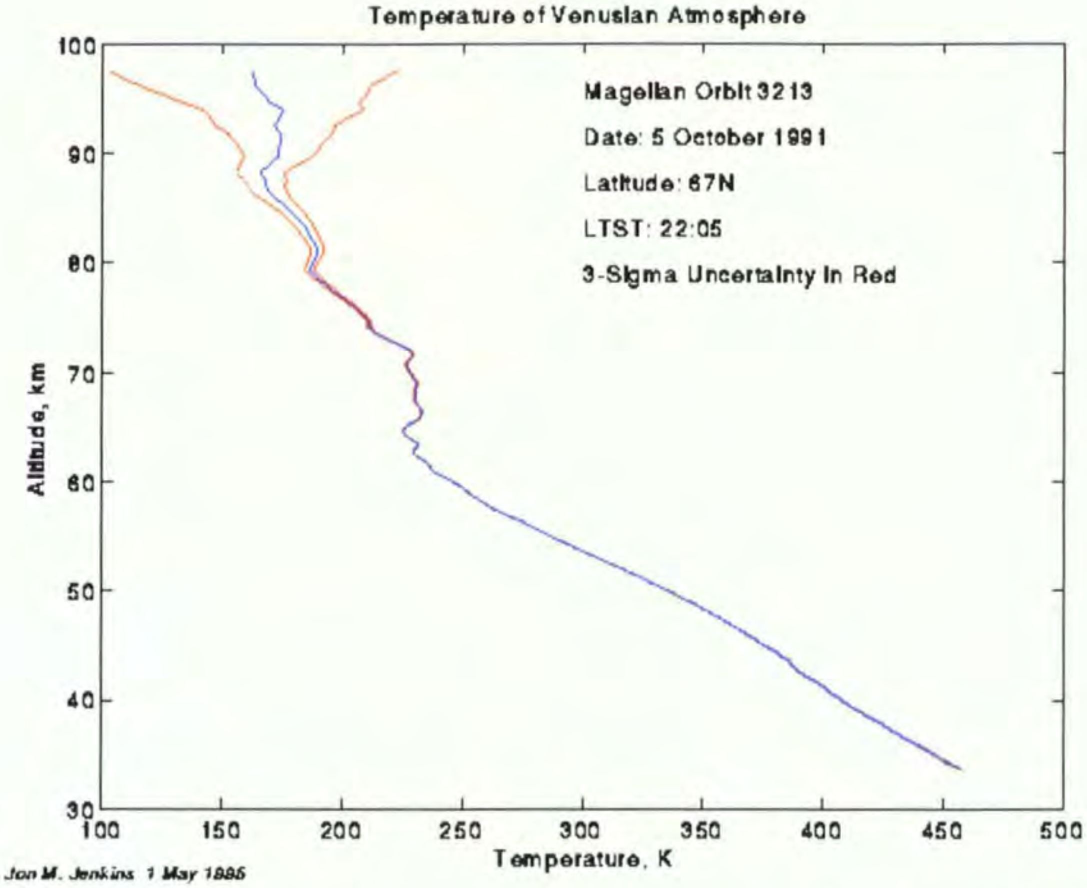


Figure 3.4-2. Relative Solar Intensity vs. Altitude on Venus (I/Io = solar intensity at altitude/extraterrestrial solar intensity). Note that Io = 2600 W/m^2, which is nearly double the solar intensity at Earth (1370 W/m^2).



Jon M. Jenkins 1 May 1995

Figure 3.4-3. Variation of temperature with altitude in the Venus atmosphere. The surface temperature is of the order of 460°C = 973 K.

3.4.2 Venus Lander Missions

All Venus atmospheric probe and lander missions to date have used a primary battery contained within the same pressure vessel and thermal containment system that protects the instrumentation. Batteries with improved specific energy can have major benefits to these missions, specifically to enable higher power communications for the duration of the mission or to enable a larger volume of the lander or entry probe to be set aside for instruments.

Power would be supplied to the Venus lander until the heat penetrates the enclosure and raises the interior temperature above the battery's operating limit. In this case, the life of the mission is not determined by the capacity of the battery, but rather by the time duration over which the thermal protection system maintains the battery within its operating temperature range. This is likely to be very short, measured in hours.

It is clear that a battery that could operate up to some intermediate temperature, say 250°C, would last longer than one restricted to lower temperatures (for the same amount of thermal isolation). However, it would still be limited by the life of the thermal protection system and by the maximum operating temperature of the avionics and other components inside the thermal enclosure. Thus, there may be no tangible advantage to a battery functioning in this way unless there were multiple temperature enclosures.

A primary battery that could operate at or above 460°C would not need thermal protection and could last as long as its energy storage capability meets the demands of the in situ spacecraft. Therefore, increasing the allowable operating temperature of primary batteries would have significant benefits for such Venus in situ missions, particularly if the allowable operating temperature exceeds 460°C. In this case, a variety of alternative mission scenarios would be enabled that would greatly enhance in situ exploration of Venus.

There are two approaches under study for long-lived Venus in situ missions. The simplest approach would be a lander that would rely on advanced thermal control materials to extend the lifetime of the lander. In this case, advanced low mass, high temperature batteries provide additional mission lifetime ranging from hours to days, depending on the payload supported and the approach used. In addition, batteries capable of running at surface ambient temperatures (460°C) allow for reduction in the size of the temperature controlled pressure vessel, resulting in mass savings that could be translated into additional thermal control system mass and provide additional lifetime. The Extreme Environments Program is currently studying a variety of advanced technologies, including energy storage systems that may benefit this type of mission by reducing the need for thermal control required to make such a mission practical. The results of their report will be published within the next six months, and should be consulted for a more detailed analysis of the benefits of advanced high temperature energy storage systems.

3.4.3 Venus Aerial Platforms

Lighter-than-air vehicles have already flown on Venus. In 1986, the helium-filled Soviet Vega balloons, which operated for approximately 48 hours in the upper atmosphere of Venus at about 56 km altitude, used primary batteries for power. For longer duration missions in this same region of the atmosphere, a combination of solar arrays and rechargeable batteries will be preferred. At these altitudes, the winds are such that a balloon will move between the dayside (illuminated side) of the planet and the night side on a roughly 6-day cycle. Accordingly, rechargeable batteries are needed in sizes to support science operations for the three-day periods of darkness. For some scientific objectives, it may be necessary to have balloons that operate at lower altitudes. In these cases, the temperatures will be higher, the illumination will be lower and the balloon will not travel as fast with the result that power will be have to be stored for a week or more.

Recent work in NASA's Revolutionary Aerospace Concepts program has examined the feasibility and application of solar powered heavier-than-air vehicles at Venus. In one concept (http://rasc.larc.nasa.gov/rasc_new/), a solar airplane station serves as a communication link with a vehicle on the surface. In this concept, the airplane does not enter the dark side of the slowly rotating planet, but requires considerable power to station keep in the high altitude winds. A rechargeable power system would be needed to support peak loads for communications.

3.4.4 Venus Surface Sample Missions

Sample return missions from Venus require acquisition of a sample on the surface and boosting the sample to orbit from a vantage point high in the atmosphere. In contrast with a Mars Sample Return mission, which involves several complex stages during entry, descent, and landing (including the use of multiple parachutes and a propulsion stage), the descent to the Venus surface is relatively simple. However, transferring the sample from the surface to orbit is more complex for Venus. The sample must first be lifted with by balloon to an altitude where the atmosphere is sufficiently thin and the atmospheric drag causes only minor reduction in the performance of the ascent vehicle. Several concepts have been examined for this. Advances in the specific energy of primary batteries will benefit this mission but are not believed to be enabling.

3.4.5 Long Duration Surface Missions

Long duration surface missions on Venus will require an advanced radioisotope power source. An alternative approach to carrying out detailed reconnaissance of a number of surface sites is to use a reversible fluid aerobot system, which would allow repeated excursions to the surface from a location high in the atmosphere where solar energy can be collected and where conventional electronics and power systems can operate. Using such a vehicle, solar energy could be stored in a rechargeable battery at the higher altitudes, and then used for excursions to lower altitudes with thermal protection. Repeated transits from high to low altitude and back would enable long missions on Venus. Considering the data in Figures 3.4-2 and 3.4-3, the minimum altitude that such an aerobot would have to reach in order to recharge the battery would depend primarily on the allowable temperature for the battery. A conventional battery, with an upper limit of perhaps 60°C, would require recharging above 50 km altitude. However, if an advanced battery could operate at 200°C, recharging could take place at around 30 km. If a high-temperature rechargeable battery could operate at 460°C, then the altitude needed for recharging would not be temperature-dependent and would be determined by the minimum solar flux needed by the photovoltaic cells. This could probably be as low as 10 km.

3.4.6 Summary

Several kinds of advanced forms of energy storage could have a significant impact on future Venus exploration missions. Primary and rechargeable systems that could operate within 50°C of Earth ambient could be useful for relative short duration surface missions. For missions that spend longer periods on the surface of Venus, primary and rechargeable energy storage systems that can function efficiently at higher temperatures will have major benefits.

3.5 Sun-Earth Connection Missions

With a few exceptions, Sun-Earth Connection missions are not a major driver of energy storage technology. Since they generally operate far from objects that occult the Sun, energy storage is not usually a major issue. Likewise frequent power cycling is not a requirement except for missions deep in the Earth and planetary magnetospheres.

For those missions that approach the Sun, high temperature batteries may have benefits. Near Sun missions will achieve mass savings from both increased mass efficiency of secondary energy storage and high temperature operations. The precise mass savings will depend on the mission, spacecraft design, and level of advanced technology applied. Additional analysis is required to quantify these benefits. The temperature behind the shield on an SEC near-Sun mission will determine the requirements for SEC batteries.

3.6 Origins and SEU Missions

Future Origins and SEU missions typically operate in regions of near-Earth space where they are not subject to the power cycling that has impeded adoption of lithium-based rechargeable batteries. These themes have not identified energy storage as a key enabling technology for future missions. Nevertheless it certainly has benefits on these missions.
"Where mature technologies exist that are still a critical component of space science missions, NASA must take active steps to ensure that the manufacturing and testing capabilities are preserved." Origins 2003 Roadmap.

"Continued advances in spacecraft technologies are crucial to SEU science goals. Several of the envisioned missions incorporate interferometric systems on multiple spacecraft that need precision pointing and/or formation flying systems. Thermal and mechanical stability tolerances are very tight, so new materials and mechanical designs must be studied." SEU 2003 Roadmap.

3.7 Mission Impact of Advances in Energy Storage Technology

There is a vital need to define the most productive investments in energy storage technology and to quantitatively compare the benefits of these investments with alternative investment choices. Earlier in this section, we compared the mass of a new technology energy storage system with the system used in past missions and drew some approximate conclusions on the impact on the ultimate science payload. However, these estimates did not consider how mass reductions in the new technology component ripple through other systems. A Cost and Mass Estimation Tool (CoMET) has been developed to make this kind of assessment.

Figure 3.7-1 provides the results of the analysis using CoMET to calculate total mission launch mass savings for both SEP, and chemical versions of a Comet Nucleus Sample Return (CNSR) and Asteroid Sample Return (VESTA) missions as a function of specific power of secondary energy systems. Included for comparison are a Venus, Neptune/Triton, Jupiter Orbiter with Probes, and a Titan mission. This analysis only applies to the main (orbiter) spacecraft. The Neptune and Jupiter atmospheric probes, Venus lander, and Titan Aerobot were treated as fixed masses for this analysis.

A more complete depiction of these impacts would compare the mass savings to the overall system mass. However, the analysis does illustrate the diminishing returns from increases in specific power as it exceeds 200 W/kg. It is important to note that this is for a specific design point. In the event that technology advances had been exploited to use more power, perhaps to gain greater data return, this point of diminishing returns would have occurred at higher power levels. Unfortunately, for the applications where the greatest leverage is achieved from performances advances – probes and landers and rovers – no adequate data set was available for new missions at this time. Compiling this data is the focus of an ongoing study of Technologies for Extreme Environments.

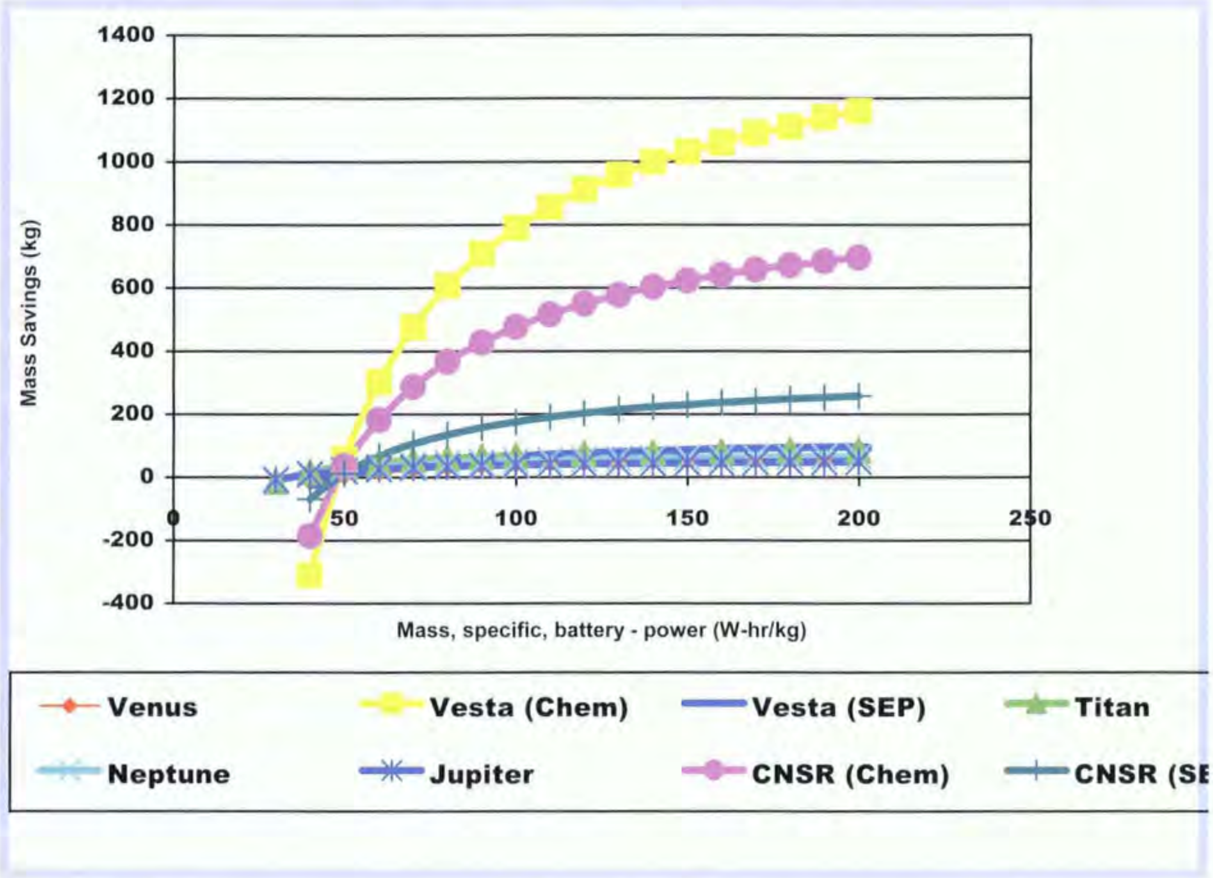


Figure 3.7-1. CoMET estimated mission launch mass reductions for Comet and Asteroid Sample Return Missions from use of advanced energy storage technology with higher specific energy than the baseline 50 W-hr/kg. Note that the X-axis is not cell specific energy, but packaged battery specific energy.

3.8 Summary

The findings in this section concerning the impact of advances in the technology and advances in primary and secondary energy storage area summarized in Table 3.8-1. This table focuses on Solar System Exploration missions, including Mars for which the most detailed analysis has been performed. For each application, the type of energy storage (primary or rechargeable) is identified. Then the impact of performance advantages achieved with new technology is characterized.

Table 3.8-1. Advances in Primary and Secondary Energy Storage

ENERGY SYSTEM PARAMETERS	Mission Category & Priority	Energy Storage Type		MISSION IMPACT (H=High, M=Medium)							
				Energy Parameters		Lifetime			Extreme Environments		
TARGET OF EXPLORATION/ Type of Mission	S-Strategic C-Competitive **Boldface = High Priority**	Primary	Rechargeable	Specific Energy (WH/Kg)	Energy Density (WH/l)	Long Cycle Life	Long Calendar Life	Low Self Discharge Rate	High Temperature	Low Temperature	High Radiation
MARS EXPLORATION											
Orbiters	**S,C**		Yes	H		H	H				
Landers	**C**		Yes		H		M			H	
Rovers	**S**		Yes		H		H			H	
Probes and low cost mission	**C**	Yes	Yes		H		M			H	
Sample Return	**S**		Yes	H	H		H			H	
OUTER PLANET EXPLORATION											
Orbiter - New Frontier Class	**C**		Yes	M	M		H				
Orbiters - JIMO Class	**S**		Yes	M	M		H				H
Atmospheric probe	**C (NF)**	Yes		H	H		H		H		M
Europa Icy Body Lander	**C or S**	Yes	Yes	H	H		H			H	H
Titan In Situ Exploration	**C or S**	Yes	Yes	H	H		H			H	
SMALL BODY EXPLORATION											
Fast Flyby /Sample Return	**C**		Yes	M	H		H			M	
Fast Flyby Impactor	**C**	Yes	Yes	M	M		H			M	
Comet Rend./Sample Return	**C (NF)**		Yes	H	H		H			H	
VENUS EXPLORATION											
Orbiters	C		Yes			H	M				M
Atmospheric Probe	C	Yes		H	H		M	H	M		M
Landers-Short Duration	**C (NF)**	Yes		H	H		M	H	M		M
Landers-Medium Duration	C		Yes	H	H		M		H		M
Aerial Platforms- Short Duration	C	Yes		H	H		M		M		M
Aerial Platforms- Long Duration	C		Yes	H	H		M		M		M
Surface Sample Return	**S**	Yes		H	H		M		H		M
Long Duration Exploration Systems	C		Yes	H	H		M		H		M
MOON & MERCURY EXPLORATION											
Orbiters	C		Yes	M	M	H	H				
Landers & Rovers	C		Yes	H	H	M	M		H	H	M
Surface Sample Return	**S (NF)**		yes	H	H	M	M				

The impact of gains in two energy-related parameters (specific energy and energy density) is considered first. Second are the parameters related to the lifetime related parameters (cycle life, calendar life and self discharge rate). Finally, the importance of a tolerance for various kinds of extreme environment (high temperatures, low temperatures, radiation) is tabulated. These desired attributes guide our discussion of new technologies in Section 4.

Both primary and rechargeable energy storage systems are important to the Space Science program. Primary batteries are the preferred solution for atmospheric probes, short-lived landed and aerial missions, and sample return missions where mass is at a premium.

Improvements in both specific energy and energy density are important. Energy density has emerged as a key factor in probe and landed missions where the volume of the vehicle is highly constrained. Any mission involving a hypervelocity entry, including aerocapture, is likely to have this characteristic.

Lifetime is also a key issue. Cycle life in excess of 10,000 cycles is important for relatively few types of planetary missions, basically science and communications orbiters to Mars and Venus. It will of course be a primary need for Earth Science missions and non-NASA applications. Calendar life on the other hand is vitally important for Space Science missions. Some outer Solar System Exploration missions have lasted decades and there is now an expectation that even some inner solar system exploration orbital missions (Mars, Venus) may require this capability.

Finally, tolerance for extreme environments is a key attribute. However, here the types of environmental tolerance required vary greatly with target and mission type. Even among Venus missions, some mission concepts will require high temperature tolerance and others can be implemented with conventional technologies.

4.0 Advanced Energy Storage Technologies

This section describes the status of advanced energy storage technologies that have the potential to provide the needs of future space science missions. In this report, advanced technologies are defined as those technologies that are not yet widely used in space science missions 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 flywheels.

4.1 Primary Batteries

Advanced lithium-primary systems under development include: improved Li-$SOCl_2$, Li-CF_X, Li-MnO_2, Li-air/oxygen, and Li-interhalogen compounds. These advanced primary batteries are projected to offer one or more of the following advantages: a) significantly higher specific energy and energy density with adequate specific power, b) minimal voltage delay, c) longer life, and d) improved low temperature performance compared to SOP Li-SO_2 batteries.

Among these advanced systems, Li-$SOCl_2$ and Li-CF_X are projected to be the most attractive candidates for future space science missions because they appear to have potential for improved performance characteristics, and have greater maturity.

4.1.1 Improved Lithium - Thionyl Chloride (Li-$SOCl_2$) Cells

Potential Benefits and Applications: Among the various primary batteries, this system possesses the highest potential for improved performance at low temperatures (perhaps as low as -100°C). Further, these batteries have moderate to high specific energy and energy density, coupled with demonstrated long life capability. Therefore, these batteries are attractive for future space science missions that require operation at low temperatures.

Chemistry: A detailed description of the Li-$SOCl_2$ system and its capabilities is given in Section 3.2.4 and is not repeated here. The improved low temperature cell chemistries will employ electrolytes that possess high conductivity and low freezing points and will likely consist of catholyte blends.

Status: Under the New Millenium DS-2 program in the late 1990's, JPL developed a unique battery that functioned at temperatures as low as –60°C for a Mars microprobe mission. The cell developed under this program was designed to withstand impact shock levels as high as 80,000g. JPL (in collaboration with Yardney) modified the Li-$SOCl_2$ chemistry by using an alternate electrolyte salt ($LiGaCl_4$) and optimizing the salt concentration. The resultant cells showed improved power and energy density at –60°C compared to SOP Li-$SOCl_2$ cells. However, the performance of these cells dropped off significantly below –60°C and displayed a severe voltage delay at low temperatures.

No work is currently in progress within NASA, industry, or DoD laboratories to resolve the issues of low temperature performance and voltage delay.

Key Issues: The SOP Li-$SOCl_2$ cell exhibits moderately high specific energy (>250 Wh/kg) and energy density (>400 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.

Technical Directions: 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 lithium-ion conduction across the lithium chloride film, and c) poor reduction kinetics of $SOCl_2$. The low temperature performance of these batteries can likely be improved with the use of alternative electrolytes and improved cell designs. Addition of suitable solvent additives, investigation of alternate electrolyte salts, and controlling the purity of the electrolyte are anticipated to minimize voltage delay and improve 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 times mass and volume savings relative to SOP $Li-SO_2$ and $Li-SOCl_2$ batteries, b) wider operating temperature range (-60–60°C), c) minimal voltage delay, and d) improved life characteristics. This cell system is very attractive for planetary probes and surface missions that require high energy density primary batteries and low temperature operations.

Chemistry: A detailed description of the $Li-CF_x$ system is given in Section 2.2.5. The chemistry of the $Li-CF_x$ cell is described by the following reactions:

a. $xLi + CF_x \Rightarrow xLiCF_x$

b. $xLiCF_x \Rightarrow xLiF + C$

----

c. $xLi + CF_x \Rightarrow xLiF + C$

Status: SOP batteries have very low rate capability and poor performance at low temperatures. These issues were discussed in Section 2.2.5. There are no major research and development efforts by the industry in this area at this time. Some minimal efforts are underway at DoD laboratories (Army-CECOM) and these are focused on improving the rate capability of this system. NASA has no activities in this area.

Key Issues: The low rate capability of $Li-CF_x$ cells is due to three factors, consisting of: a) low conductivity of the cathode material, CF_x, (this is the dominant limitation), b) low conductivity of the solvent-electrolyte at the very low temperatures, and c) low surface area of existing cells with thick electrodes. The rate capability at low temperatures can be improved by the use of alternate solvent-electrolytes-that include linear and cyclic ethers in conjunction with $LiAsF_6$ or other salts such as $LiBF_4$. The rate capability can also be increased simply by using thin electrodes with higher surface area. The thin electrode design will diminish specific energy content to some extent due its larger percentage of inert (but electrically conducting) grid material. Nevertheless, the thin electrode design will enable the higher rate capability-that is desired in various Code-S missions. Additional improvements that are desirable for future space missions include: radiation tolerance and the ability to withstand high shock levels. Use of alternate cathode binder materials, and seal designs are promising approaches to increasing radiation tolerance. The shock sensitivity of the cells can be greatly enhanced through modifications in electrode/cell design.

Technical Directions: In order to provide Code-S with Li-CF_x primary batteries that have high specific energy (~800 Wh/kg), long life (10–15 years) with adequate specific power, and the ability to operate in harsh temperature environments (to –80°C), developments should focus on the following areas:

a) New electrolytes and salts (and combinations thereof) that enhance the ionic conduction, which, in turn, leads to higher specific energy and extends the operational temperature limits.
b) Modified electrode designs and electrolytes to lower the operating temperature and increase rate capability.
c) Evaluation of alternate cathode and binder materials and seals to improve the radiation tolerance.
d) Development of robust cell designs to withstand high shock levels.

4.2 Rechargeable Cells and Batteries

Advanced rechargeable lithium systems presently under development include: Li-Ion, Li-Polymer Electrolyte, and Li-Solid Inorganic Electrolyte, and Li-S. These cells are projected to offer one or more of the following advantages: a) higher specific energy and energy density, b) long cycle life and calendar life, c) improved low temperature performance, d) low self-discharge, e) high charge/discharge efficiency, and f) lower cost compared to SOP rechargeable batteries. Among these systems, the Li-Ion system has the highest potential to meet the near-to mid-term needs of Space Science missions in view of its high level of technical maturity, and potential for improved cycle life and low temperature performance capabilities. The lithium solid polymer electrolyte (SPE) system offers packaging advantages compared to the lithium ion system, however, it is in the early stages of development (TRL ~2). This technology is projected to be available for missions beyond 2015. The Li-solid inorganic electrolyte system has the intrinsic capability of providing very long shelf and operational life compared to the other lithium systems, but it is also in very early stages of development (TRL 1-2). Among the advanced rechargeable systems, Li-S batteries have highest theoretical specific energy, but this technology is in a very early research stage (TRL ~1). Some of the important potential capabilities of these systems and their technology development status are given in Table 4.2-1.

Table 4.2-1. Comparison of SOP Batteries with various Li-batteries

Characteristic	SOP Ni-H_2	Li-Ion with liquid electrolyte	Li-Solid Polymer Electrolyte*	Li-Solid Inorganic Electrolyte*
Technology Readiness Level	10	5-9	3	1-2
Specific energy (Wh/kg)	30-40	100-150	>200	> 200
Energy density (Wh/l)	40-50	200-300	300-450	> 300
Cycle life	60, 000	1500	1500	>10,000
	(at 30% DOD)	(at 100% DOD)	(at 100% DOD)	at 100% DOD
Operating temperature	-5-30 C	-60 to 80 C	0-80 C	0-80 C
Self discharge rate		1% / month	0.25% / month	0.1% month
Shape factor /packing eff	Poor	Good	Excellent	Excellent

* Projected values based on analysis (not data)

4.2.1 Lithium-Ion Batteries (Liquid Electrolyte)

The present work in Li-Ion batteries is primarily focused on adopting/modifying commercially available Li-Ion technology for specialized applications. The U. S. Army is focusing its efforts to improve and adopt this technology for Army communication equipment. Most of the Army work is in the areas of safety, manufacturing, cost reduction, packaging and field-testing. AFRL's programs are directed towards development of high-rate cells and batteries for aircraft and weapons applications. DOE efforts are focused on developing high-rate and low cost batteries for electric hybrid vehicles. None of these applications are aimed at specific NASA Space Science needs. Two types of Li-Ion batteries are under development for space applications: a) long life Li-Ion batteries, and b) improved low temperature Li-Ion batteries. However, NASA support for such work is minimal. This section describes the status of the development of these two types of batteries for space applications.

4.2.1.1 Long-Life Li-Ion Batteries

Potential Benefits and Applications: Rechargeable Li-Ion batteries with liquid electrolytes are very attractive for planetary and Earth (LEO and GEO satellites) orbiters, since they offer significant mass and volume savings as well as cost advantages over SOP Ni-Cd and Ni-H_2 batteries. These advantages are mainly due to higher specific energy, energy density, cell operating voltage, coulombic and energy efficiency, and lower self-discharge rates of Li-Ion cells relative to SOP cells. Since Li-Ion cells have much higher voltages than other SOP cells, Li-Ion batteries require fewer cells per battery and also fewer interconnections. As a consequence Li-Ion batteries utilize a simpler design than the other SOP batteries. This simpler design of the Li-Ion battery improves its innate reliability relative to the other SOP batteries.

Status: Development of long life Li-Ion batteries for aerospace applications is being pursued in the United States, Japan and Europe. In the United States, the principal players are NRO/DoD, NASA and AFRL. In Japan, the efforts are being led by the Japanese Space Agency and Japan Storage Battery Company. In Europe, the efforts are primarily led by the European Space Agency and SAFT Battery Company in France.

The NRO/DoD program is focused on developing Li-Ion cells/batteries required for low Earth orbital (LEO) applications, and the program is aimed at developing 10–50 Ah prismatic cells with > 30,000 cycles @ 30% DOD. The chemistry of this cell is similar to that used by the Sony Corporation (Sec. 2.3.5). The technical approaches being pursued to improve the cycle life performance include: a) establishment of stringent process controls, b) optimization of operational regimes (depth of discharge, charge voltage selection and temperature of operation), c) minor modifications in cell chemistry in terms of electrolytes and electrode additives, and d) the use of light weight cell components and Ziegler terminal seals. Experimental cells have been fabricated and the cycle life performance assessment of these cells is in progress at a number of institutions. The performance characteristics of SOA cells are summarized in Table 4.2-2.

Table 4.2-2. Performance Characteristics of Li-Ion Cells from Various Sources

	Yardney	EPI	SAFT-USA	MSA	JSB	COMDEV
Chemistry	MCMB, LiNiCoO2	MCMB, LiCoO2	C(?), LiNiCoO2	MCMB, LiCoO2	C, LiCoO2	MCMB, LiCoO2
Amp-Hrs	10,25,55	6,25	4,8,44,115	10,50	50,100,175	
Cycle Life (GEO)						1350
Cycle Life (LEO) (DOD %)	14,000 (30%)	8000 (30%)	14,000 (30%)	>10,000 (40%)	> 10,000	11,000 (30%)
Cycle Life (100%DOD)	>1000	>1000	>1000		>1000	>1000
Sp Energy (Wh/kg) Cell or Battery	130-145 (C) 110 (B)	110-130	130-150 (C)	98-123	136-146	104 (B)
En. Density (Wh/l)	260-300	240-260	277-315	256-315	254-300	

The AFRL program is focused on developing Li-Ion batteries required for both aircraft and space (GEO/LEO) applications. NASA/JPL and NASA/GRC were initially involved in this program with AFRL to develop Li-Ion batteries required for future space applications. However, NASA is no longer working with AFRL on this program due to funding issues. Yardney Technical Products, Inc. (Lithion, Inc.) and SAFT America, Inc. are involved in the manufacturing of these cells/batteries under AFRL-sponsored programs. The cell chemistries of Yardney and SAFT are similar in that both employ mixed metal oxides as cathodes and graphitic carbon anodes. The configuration of SAFT cells is cylindrical, while that of Yardney cells is prismatic. Cells of 10 to 200 Ah are currently being fabricated and tested. The technical approaches being pursued to improve the cycle life performance include: a) establishment of stringent process controls, b) optimization of operational regime (depth of discharge, charge voltage and temperature), and c) minor modifications in cell chemistry, in terms of electrolytes and electrode additives.

NASA/JPL and NASA/GRC are not presently involved in the technology development of long-life lithium-ion cells. NASA/JPL had significant development efforts in lithium-ion batteries prior to 1998, but this work has been on hold due to lack of funding. The present efforts at JPL and GRC are mainly focused on testing and evaluation of cells developed under the AFRL program. NASA/JSC is evaluating commercial Li-Ion cells for astronaut equipment. NASA/GSFC is evaluating AEA batteries (employing small 1.3 Ah cells manufactured by Sony Corp.) for ST6 application, which requires a limited operational life of one to two years.

Japan Storage Battery (JSB) Company is developing cells of 50-190 Ah capacity for Earth orbital applications (GEO and LEO) and has distributed several cells to U.S. aerospace companies for evaluation. SAFT has developed forty 100 Ah cells for Earth orbital applications (GEO and LEO) and has distributed several cells to European Space Agency (ESA) and U.S. aerospace companies for evaluation.

NASA/JPL, NASA/GRC, NASA/GSFC, AFRL, TRW, Boeing, and LMA are currently evaluating some of the cells developed under the above programs for their cycle life performance capabilities and on-board battery management methods. Aerospace companies are also evaluating the suitability of commercially available, small-capacity (1-3 Ah) cells for space applications.

Long-life Li-Ion batteries currently under development have a specific energy of ~ 100 Wh/kg and ~ 250 Wh/l at the battery level and a charge-discharge efficiency of over 95%. The specific energy and energy density at the cell level are much higher compared to the battery level (~ 30-50% greater). Furthermore, these cells have the capability of delivering 10,000 to 15,000 cycles at 30% DOD and have an operational life in excess of 5 years (Figure 4.2-1). However, these capabilities still fall short of meeting the requirements of advanced space science missions, in the areas of long cycle life capability (>30,000 cycles @ 30% DOD), and operational life > 20 years). The performance characteristics of the above developmental cells are shown in Table 4.2.2. The major life limiting failure modes observed on cycling Li-Ion cells are: loss of capacity, increase of cell impedance and shorting of cells. The failure mode depends on the cell chemistry and operating conditions.

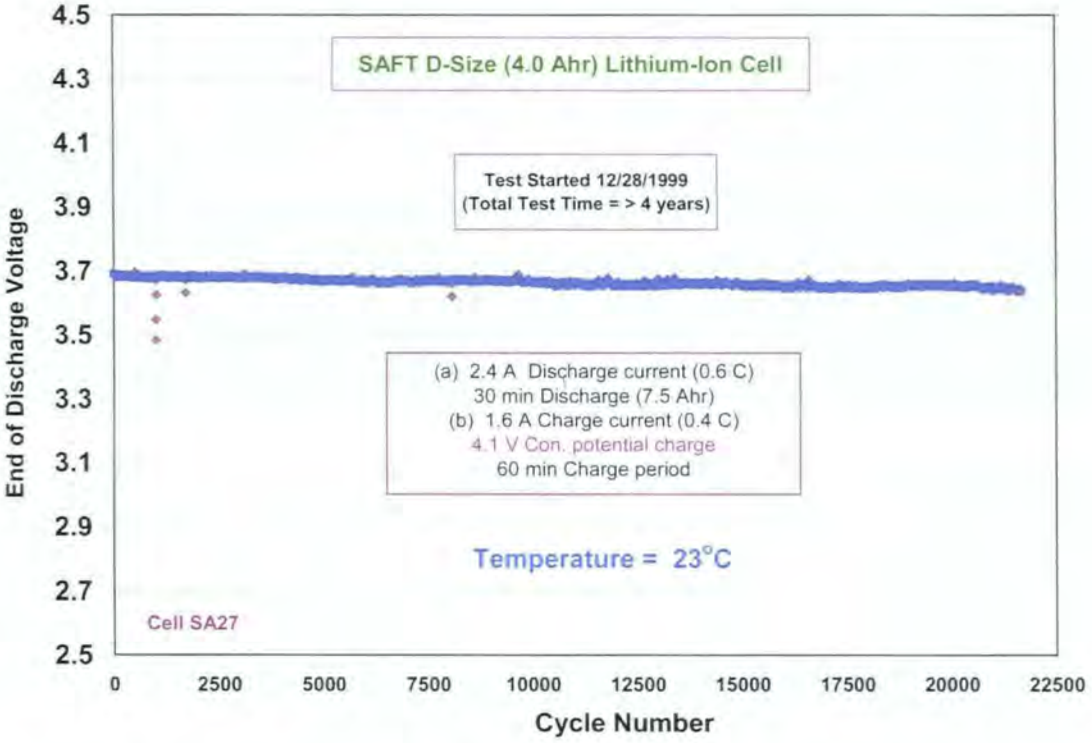


Figure 4.2-1. Cycle life performance of a prototype Li-Ion cell at 30% DOD (23°C).

Key Issues: The major issues that are limiting the use of Li-Ion batteries in planetary orbiters and Earth orbital missions are: a) limited demonstrated cycle life (<15,000 cycles compared to the 30,000 cycles @ 30% DOD required), b) limited demonstrated calendar life (5–7 years compared to the 15/20 years required), and c) lack of data on the radiation effects of mature cells.

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 recyclable lithium due to electrode passivation processes, c) structural degradation of the cathode, and d) increased interfacial impedance at the electrodes due to the passivation processes. Potential approaches to resolve these issues include: a) use of electrolytes with improved chemical and electrochemical stability, b) examination of new cathode materials with improved stability, c) the use of selective electrode surface coatings (e.g., MgO, Al_2O_3 for cathodes and coke-based coatings for graphitic anodes), d) optimization of electrochemical cell design (electrode capacity ratio), and e) optimization of cell operating parameters.

Detailed experimental studies were conducted by JPL on the radiation tolerance of Li-Ion batteries up to radiation doses as high as 18–25 Mrad on fresh cells. The results obtained to-date indicate that Li-Ion cells are fairly tolerant to radiation and exhibit a capacity loss of less than 10% upon radiation exposure. However, the effects of the radiation on performance need further study for cells that are stored a long time, as in missions to outer planets.

4.2.1.2 Low-Temperature Li-Ion Batteries

Potential Benefits and Applications: Li-Ion batteries are very attractive for near-term and mid-term solar powered planetary surface missions in view of their superior low temperature characteristics (compared to SOP rechargeable batteries or other advanced lithium battery systems) and relatively advanced stage of development.

Status: Prior to 2000, JPL had developed a Li-Ion cell that can function at –20°C, and this technology was transferred to Yardney and SAFT for manufacturing. These batteries are presently in use on the MER rovers (Spirit and Opportunity) and they have the best low-temperature performance of any SOP rechargeable battery.

Recently, under a DoD sponsored program, JPL identified a new electrolyte that permits the operation of Li-Ion cells effectively at temperatures as low as –40°C. Experimental cells fabricated by Lithion and SAFT using this electrolyte showed more than 20–30% higher capacity at –40°C compared to SOP Li-Ion cells (Figure 4.2-2). These cells are presently under evaluation at JPL. AFRL is considering use of cells containing this electrolyte for several aircraft applications. The U.S. Army (Army CECOM) has interest in low temperature lithium-ion batteries and has funded research and development efforts in this area in the past. However, the Army currently has no funded activities in this area.

JPL has also identified several promising approaches to further improve the low temperature conductivity of Li-Ion battery electrolytes and for additional improvements in cell performance at low temperatures. However, this work is not currently being pursued due to funding limitations.

The consumer electronics industry has little interest in low temperature batteries and, hence, is not pursuing any work in this area.

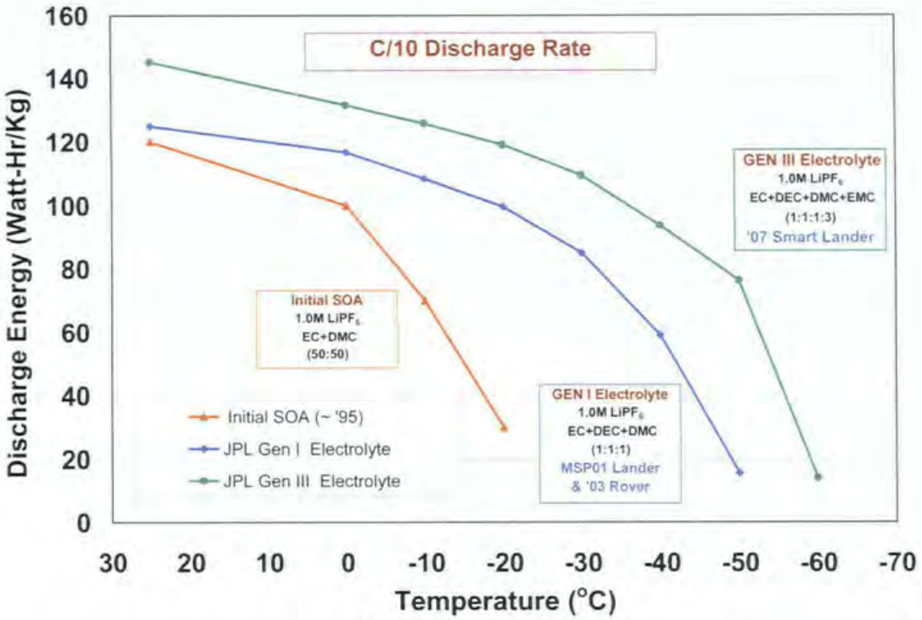


Figure 4.2-2. Improvements made in the low-temperature performance of Li-Ion Cells using advanced electrolytes developed at JPL.

Key Issues: Significant improvements have taken place over the last several years to improve the performance of prototype Li-Ion cells from –20°C to –40°C. However, the power and energy capabilities of SOA Li-Ion cells are still inadequate at –40°C and require further improvement for future planetary surface applications. The parameters that affect the low temperature performance of Li-Ion cells are described in Figure 4.2-3. Of these factors, the electrolyte properties have the most dramatic impact on low temperature performance. (i.e., if the electrolyte is frozen, the cell/battery will not operate). The second key factor limiting low temperature cell operation is poor kinetics of lithium transport at the electrode interface. The third factor limiting performance is poor lithium diffusivity within the bulk of the electrode material. The approach to solving the first two issues involves development of electrolytes that are ionically conducting and form stable and kinetically-favorable surface films on the electrodes at the low temperatures. The third aspect requires development of new electrode materials that enhance kinetics for lithium intercalation and also Li^+ diffusion.

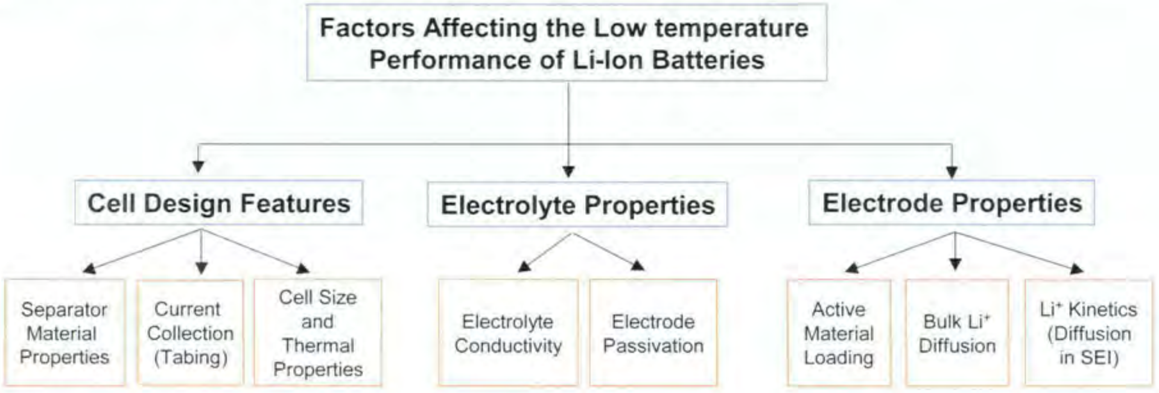


Figure 4.2-3. Factors Affecting Low-Temperature Performance of Li-Ion Batteries

4.2.1.3 Future Directions for Advanced Li-Ion Battery Development

In order to facilitate introduction of Li-Ion batteries into various future Code S missions, the following efforts are recommended:

- Develop Li-Ion batteries that possess long cycle life and calendar life for the benefit of planetary orbiters, and LEO and Geo satellites.
- Develop improved low temperature Li-Ion batteries to enhance, or in some case even enable future planetary Landers and Rovers.
- Optimize charge-discharge control methodologies and develop robust control hardware to enhance the performance of multi-cell battery configurations and ensure safety and reliability in all missions.
- Improve the specific energy and energy densities of Li-Ion cells further to enable increased payloads in future missions.
- Carry out a test program to establish a performance database on Li-Ion batteries. The testing effort should include life cycle assessment, storage effects, low temperature capabilities, and radiation tolerance.
- Collaborate with AFRL to establish a source capable of manufacturing high reliability cells using a consistent process that is protected and controlled by government oversight.

4.2.2 Lithium Polymer Electrolyte Batteries

Two types of batteries are currently under development: 1) Lithium-Ion Gel Polymer Electrolyte (Li-Ion GPE) batteries, 2) Lithium Solid Polymer Electrolyte (Li-SPE) batteries. Lithium gel polymer electrolyte battery technology is in a relatively advanced stage of development and small capacity cells are being manufactured for several consumer electronics applications. The performance capabilities of these batteries are very similar to those of Li-Ion batteries with liquid electrolytes, except for improved specific energy resulting from their "pouch" design, and packaging efficiency. However, Li-solid polymer electrolyte technology is in the very early stages of development and may only be available for far term missions (>2015). The following sections describe the status of development of these types of lithium polymer batteries.

4.2.2.1 Li-Ion Gel Polymer Batteries

Potential Benefits and Applications: Li-Ion Gel Polymer batteries employ a unique technology wherein the electrolyte is intimately associated with the electrode structures. This technology avoids the need for external preloads usually provided by a rigid and heavy cell case and battery end plates and tie rods. The Li-Ion Gel cells then employ a lightweight laminated case and the battery does not need support. As a result, the Li-Ion Gel Polymer batteries offer slightly higher (10–20%) specific energy and energy density compared to Li-Ion batteries with liquid electrolytes. This technology was initially considered for the Mars 2001 Lander application. However, it was not selected finally for this mission in view of its poor low temperature performance and cycle life performance (circa 1998). Since that time, the performance capabilities of the system have been improved considerably and the system may be attractive for future Mars surface missions.

Chemistry: In Li-Ion GPE batteries, carbon is used as the anode material, lithiated transition metal oxides ($LiCoO_2$, $LiNiCoO_2$, $LiMnO_2$) are used as cathodes, and a gel polymer containing a lithium salt is used as the electrolyte. The gel polymer electrolyte is prepared by incorporating a liquid plasticizer and/or solvent (ethylene carbonate, diethyl carbonate, diethyl carbonate) containing a lithium electrolyte salt (Li PF_6) into a polymer matrix (PVDF, PAN, and other acrylic polymers) capable of forming a stable gel. Initial versions of these batteries used metallic lithium as the anode material. The behavior of gel polymer is much like a liquid electrolyte in terms of ionic conduction mechanism, transport characteristics and even performance. Several polymers have been successfully used as gels, including PVDF, PAN, PMMA, etc. To date, academic discussions still remain regarding the extent of the chemical interaction of the polymeric separator ("inert matrix") with the impregnated liquid electrolyte.

Development Status: This technology is in the relatively advanced stage of development, and the small to moderate sized cells are being manufactured in the U.S. (Ultra-life, Valence, Compact Power, Alliant Tech Systems) for use in several consumer electronics and Army applications. The cycle life capability and low temperature performance of Compact Power cells, activated with JPL low temperature electrolytes, are given in Figures 4.2-4 and 4.2-5.

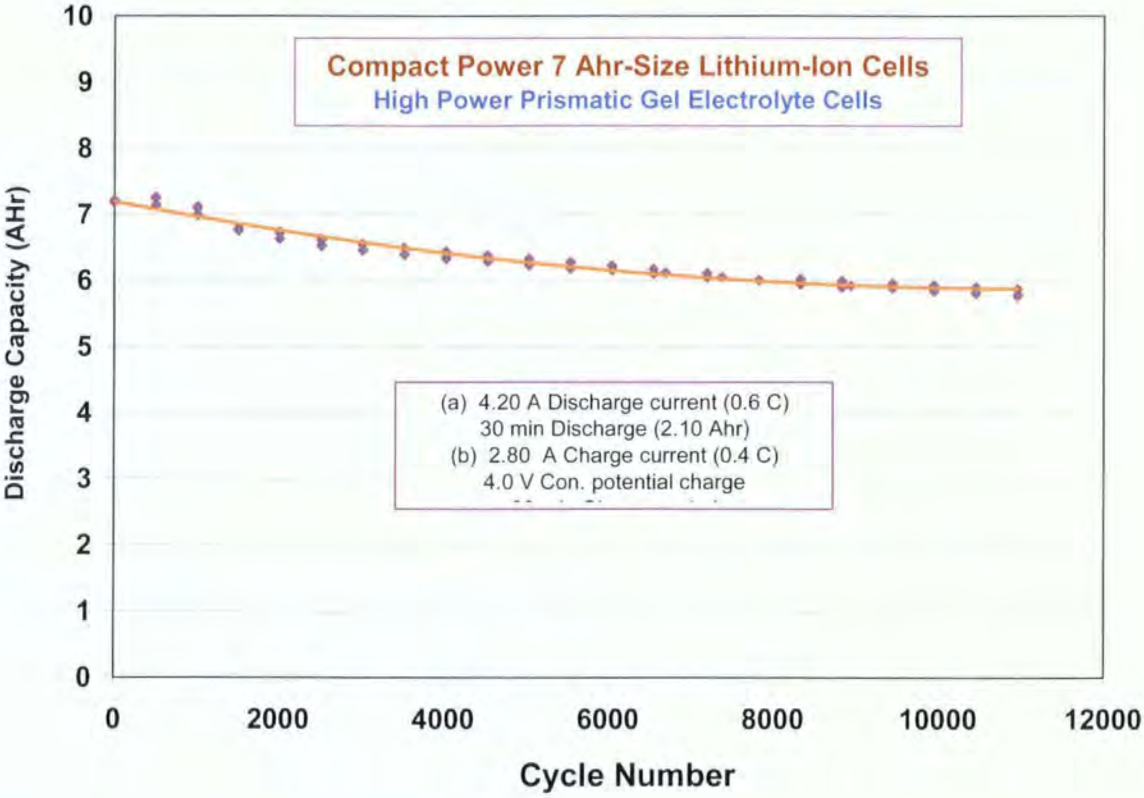


Figure 4.2-4. Cycle life performance of gel polymer electrolyte Li-Ion cells using advanced electrolytes developed at JPL.

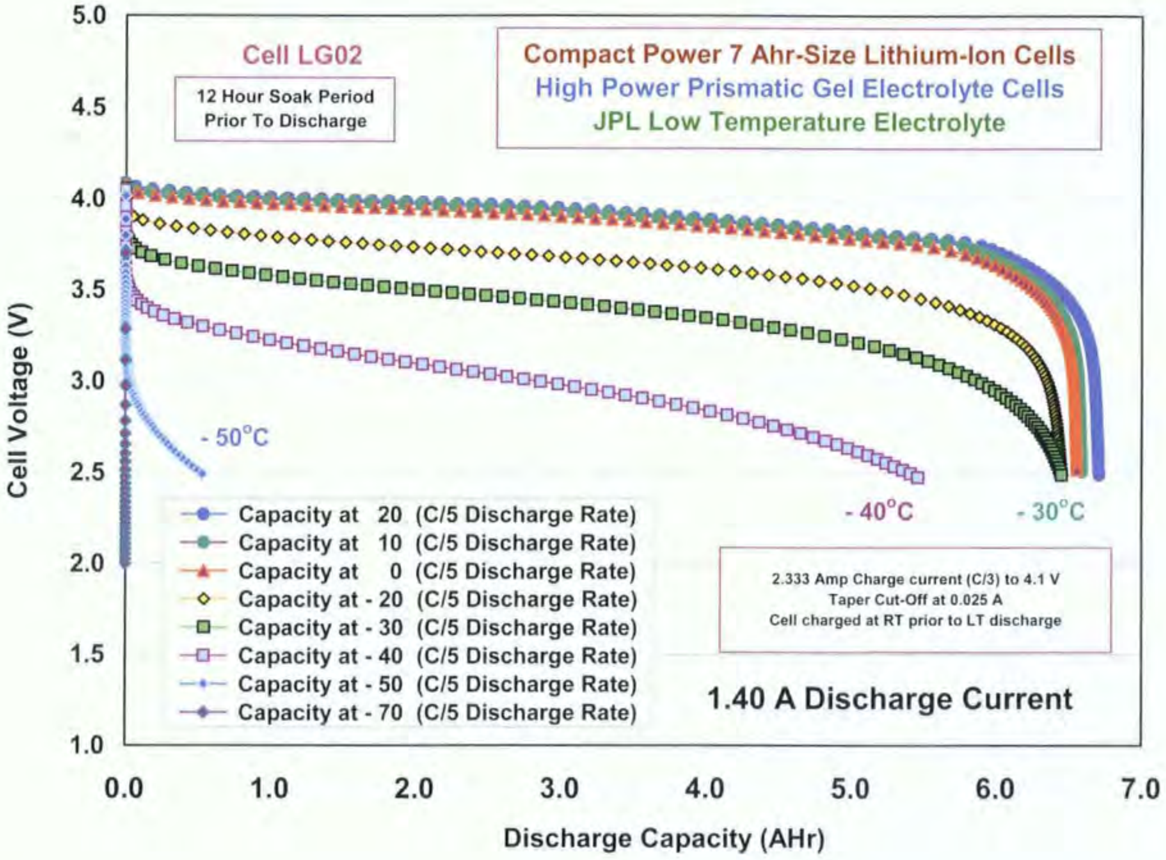


Figure 4.2-5. Low temperature performance of gel polymer electrolyte Li-Ion cells using advanced electrolytes developed at JPL

Key Issues: The performance limitations of Li gel polymer cells are very similar to those of liquid electrolyte-based cells and are of: a) limited cycle life, b) typically poor low temperature performance, and c) poor integrity of the cell seals (that can lead to venting). Furthermore, due to the nature of the packaging, the cells may need to be incorporated into a hermetically sealed battery housing in order to be applicable for use in deep space vacuum.

4.2.2.2 Lithium Solid Polymer Electrolyte Batteries

Lithium solid polymer electrolyte batteries offer potential performance and cost advantages over rechargeable lithium-based cells with liquid electrolytes. The potential performance advantages include: higher specific energy and energy density, longer cycle life, and lower self-discharge rates. Since the polymer systems are solvent-free, lithium metal can be used as the anode material in place of carbon-based materials used in lithium-ion systems. The use of lithium translates into higher cell specific energy and energy density due to the much higher theoretical electrode potential of metallic Li. In addition, due to the lack of volatile components, solid polymer electrolyte-based cells have the potential to dramatically decrease internal pressure, enabling the use of lighter aluminum/resin-laminated films (~100 μm in thickness) as casings instead of much heavier stainless steel or aluminum. Thus, some investigators have projected true solid polymer electrolyte-based systems may yield up to 50% better cell specific energy (e.g., > 200 Wh/kg) compared with lithium-ion systems (although this has yet to be demonstrated). The technology has also been projected to possess improved cycle life, shelf life, and self-discharge characteristics due to the absence of reactive solvents (that are primarily responsible for impedance build-up and capacity loss). Another potential advantage of cells with polymer-based electrolytes is that they are expected to be available in conformable configurations with a flexible shape factor that will allow for integration into spacecraft structures with greater packaging efficiency.

Chemistry: In breadboard Li-SPE batteries, lithium metal is used as the anode material, transition metal oxides/chalocogenides (V_6O_{13}, V_2O_5, TiS_2, MnO_2, $LiCoO_2$) are used as cathodes, and solid polymers containing lithium salts are employed as the electrolytes. A true solid polymer electrolyte, unlike a gel polymer electrolyte, is entirely solvent-free. The polymer electrolyte consists of a lithium electrolyte salt ionically complexed with a polymer possessing solvating characteristics.

The technical challenges involved in developing practical Li-SPE cells and batteries include development of:

- Appropriate solid polymer electrolytes with ionic conductivity in the range near 1×10^{-3} S/cm at ambient temperatures.
- Suitable anodes and cathodes that interface with the SPE to transfer electrons to and from the electrolyte.
- Large-scale membrane fabrication processes which yield large, uniform films with predictable performance.
- Cell fabrication techniques and appropriate cell designs which will result in aerospace quality cells (5-50 Ah size).

Status: Lithium solid polymer electrolyte battery technology is still in an early stage of development. The major barrier to successful development of this technology is unavailability of lithium solid polymer electrolyte with adequate conductivity ($>10^{-3}$ mS/cm) in the desired temperature range.

In 1960, Wright and co-workers discovered that polyethylene oxide (PEO) and polypropylene oxide (PPO) complexed with alkaline metal salts exhibit high ionic conductivity at warm temperatures. Later in 1978, Armand and co-workers recognized the potential of these polymer electrolytes for use as separators in solid-state batteries, especially for use in rechargeable lithium batteries. Since that time, considerable effort has been directed toward the development of polymer electrolytes for use in rechargeable lithium batteries. The major players involved in the development of solid polymer electrolytes are: HydroQubec, 3M, University of Rome, NASA/JPL, EIC, NASA/GRC, LBL, University of Minnesota, University of Pennsylvania, North Western University, SRI, and Covalent Associate. Most of the work in the U.S. was carried out under the sponsorship of DOE, DoD and NASA. The approaches investigated included: a) modification of PEO polymer structures, b) examination of alternate polymers (polyoxymethylene, polysiloxanes, poly-phosphozenes, etc.), c) use of alternate salts (lithium triflate, $LiAsF_6$, $LiPF_6$, lithium imides, and lithium superacid salts) and d) addition of inorganic fillers (alumina, silica, titania, etc.). Although the ionic conductivity of PEO solid polymer electrolytes is acceptable at high temperatures (60–110°C), conductivity is low (10^{-6} to 10^{-8} S/cm) at ambient temperatures. The highest reported conductivity to date for polymer electrolytes is about 10^{-4} S/cm at 60°C and above and 10^{-5} S/cm at 25°C. The desired room temperature conductivity is at least 10^{-3} S/cm for polymer electrolytes to function at moderate power densities in batteries. No commercial cells have been made so far with solid polymer electrolytes. Experimental batteries have been fabricated by 3 M and Hydroqubec for electric vehicle (EV) applications under a DOE sponsored program. The work is presently on hold by DOE, as their focus has shifted from pure EVs to hybrids that require high power batteries.

PERS Program: In FY2000, NASA/GRC established a program to develop lithium-based, polymer electrolyte batteries for aerospace applications. The overall objective of this development program, which is referred to as PERS (Polymer Energy Rechargeable System), is to establish a world-class technology capability and a U.S.-based manufacturing resource that will ensure U.S. leadership in polymer-based battery technology for aerospace applications. Once developed, this technology is expected to be superior to other conventional battery technologies.

The PERS program is addressing both near- and far-term R&D issues and technical challenges that are critical for successful development of the polymer-based battery technology. The initial phases of the program will focus on the development of critical cell components in order to achieve necessary levels of performance. This initial work includes the development of solid polymer electrolytes, the development of anode and cathode materials that are compatible with the electrolyte, and the achievement of desired electrode/electrolyte interfacial properties. The programmatic approach to be taken for this critical component development is to support as many novel R&D concepts and technical approaches as are viable. Some examples of far-term issues and needs are component/cell scale-up, cell/battery designs to address specific applications, thin-film fabrication technologies, and the establishment of appropriate manufacturing processes.

A NASA Research Announcement (NRA) was released in FY2000 to solicit efforts to address the development of the polymer electrolytes, cathodes and anodes for PERS batteries (with emphasis upon electrolyte development). The initial goals of this program are to develop and validate the fundamental building blocks of a Li-SPE cell: the electrodes and the electrolyte. The primary near-term objective of the program is to support the development of a solid polymer electrolyte that satisfies the critical performance levels necessary for successful cell operation, including:

- A polymer electrolyte material with an ionic conductivity of ~10^{-3} S/cm over a wide temperature range (-40 to +65°C)

- A polymer electrolyte material with high a lithium-ion transport number (approaching unity) to prevent concentration gradients in the cells.
- Low interfacial impedance between the electrolyte and the electrodes
- Adequate chemical compatibility with electrode materials
- A large window of electrochemical stability
- Low electronic ionic conductivity
- Good dimensional and thermal stability
- Mechanical properties that allow scale-up of the manufacturing process.

To explore viable approaches for accomplishing these goals, multiple contract and grant efforts were funded at various organizations to address these aspects of component level development required for the PERS batteries. In addition to the external contracts and grants, research and development activities have been supported at JPL, AFRL and GRC. Electrolyte chemistries and concepts under consideration include: (1) polymer electrolytes based on "solvent-free" binary salt complexes, (2) cation-conducting polyelectrolytes, (3) polymer-ceramic composites, (4) inorganic-organic hybrids and (5) hybrid/gelled systems. The mechanisms for ionic conduction in these various materials tend to be complex. The key to developing better electrolytes appears to lie in developing a better understanding of how ions propagate down polymer chains.

Table 4.2-3 lists the requirements of this initial phase of the PERS Program, and the progress that has been made so far.

Table 4.2-3. Requirements for Initial Phase of PERS Program

Property	Requirement for PERS	Value at start of PERS	Current value under PERS
Electrolyte ionic conductivity (S/cm)	10^{-3}	10^{-6}	10^{-4}
Transference number	> 0.5	~ 0.2 – 0.3	NA
Electrochemical and chemical stability	0-4 V	0-3 V	0-3 V

Under this program, researchers have reported room temperature ionic conductivities of the polymer electrolytes under development in the range of 10^{-4} S/cm. This represents an increase of nearly two orders of magnitude over ionic conductivities exhibited by the previous state-of-the art solid polymer electrolytes at room temperature. The progress to date has been encouraging, and several current concepts offer the promise of meeting the program goals. A further increase in electrolyte ionic conductivity is required to make this a viable technology to meet NASA's energy storage needs. In addition, this electrolyte needs to be demonstrated to be compatible with the appropriate electrodes and be capable of being produced in mechanically stable films.

If these fundamental problems can be solved, the cell chemistry and architecture will be defined, and prototype cells will be produced and tested. Based on these tests, cell designs will be modified, and optimized. Eventually, batteries will be produced, and manufacturing processes will be defined. A commercial infrastructure to produce these batteries will be needed.

Key Issues: Lithium solid polymer electrolyte battery technology is in the very early stages of development. The state-of-the-art (SOA) cells have power densities of at least one to two orders of magnitude lower than that desired for most applications. Further, the cycle life of the SOA cells is also very limited. Significant advances are need at the materials level (particularly with respect to the electrolyte) before this technology can be considered for future space applications. The SOA polymer electrolytes still have very low conductivity and require two to three orders of improvement before they can be considered for evaluation at the cell level.

4.2.2.3 Future Directions for Lithium Polymer Battery Development

The following efforts are required to advance lithium polymer battery technology to future space missions.

- Continue to monitor the Li-Ion gel polymer electrolyte development being carried out by the industry.
- Initiate a test program to assess their performance and viability of commercially available Li-Ion gel polymer cells for future space science missions.
- Conduct research efforts to develop solid polymer electrolytes with improved room temperature conductivity and work with the industry to demonstrate technology feasibility.
- Conduct research on advanced electrode materials and composite electrode electrolyte structures.

4.2.3 Lithium Solid-State Inorganic Electrolyte Batteries

Potential Benefits and Applications: NASA has an anticipated the need for miniature power sources for micro/nano-spacecraft. Lithium solid-state inorganic batteries have the potential to satisfy this need. In addition, these batteries have the potential to fulfill the NASA need for power sources for outer planetary missions with calendar life of more than 12 years and tolerance to radiation. Co-location of micro solid-state batteries with devices and sensors on silicon chips is made possible by the compatible fabrication techniques of integrated circuits. This co-location can 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.

Solid-state inorganic lithium rechargeable batteries are projected to deliver high specific energy (>200 Wh/kg) and energy density (300 Wh/l) over a wide operational temperature range (0 to 80°C), while providing tens of thousands of cycles. These solid-state batteries offer enhanced safety compared to other Li-Ion liquid electrolyte-based systems or gel polymer electrolyte (GPE) batteries. However this technology is still at a very early stage of development.

Chemistry: Solid-state inorganic lithium rechargeable batteries are similar in some ways to the Li-based SPE 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 are employed as the electrolytes. The electrode materials used in these batteries are not 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 microns.

Development Status: The technology is in the very early stages of development (TRL ~2). Current efforts are focused on the development of inorganic solid-state electrolytes, with the goal of fabricating experimental cells to demonstrate conceptual feasibility. The conductivities of the state-of-the-art solid-state electrolytes are low (10^{-7} to 10^{-4} S/cm); hence, very thin electrolyte layers, free from any pinholes, must be used to minimize resistive losses. For this reason, the electrolyte must be utilized as a thin film, with a thickness of no more than about 10 μm. Several classes of lithium-ion conductors, including borate or phosphate glasses and various NASICON-type ceramic materials, have been studied as candidate electrolytes for these batteries. Notable among these is the lithium phosphorous oxynitride (LiPON) glassy material that emerged from the studies at Oak Ridge National Laboratory. LiPON has an ionic conductivity of the order 10^{-6} S/cm and possesses a wide electrochemical window that enables the use of high voltage cathodes, such as lithium cobalt oxide, lithium nickel oxide, or lithium manganese oxide. Although the conductivity of LiPON is three orders of magnitude lower than for liquid electrolytes, its ability to be deposited in thin (1-2 microns) layers permits rapid discharging of cells at high rates.

The cells employing this technology are fabricated by means of RF sputter deposition to lay down thin layers of current collector, cathode, electrolyte, and lithium on a suitable substrate material. This substrate can be any of several materials, such as alumina, mica, fibers, silicon, or plastic, or any smooth surface that can survive the rigors of cell fabrication (i.e. a 300°C to 700°C anneal step). The cathode current collector is located on top of the substrate and is comprised of a thin layer of metal (Ti or Pt). The active cathode material can be any of several oxides, such as $LiCoO_2$, $LiNiCoO_2$, $LiMn_2O_4$. The anode is located on top of the electrolyte and is comprised of a layer of lithium metal and a layer of copper that serves as current collector. The batteries can potentially be packaged in a bipolar configuration by stacking one on top of another. In this case, the metallic anode collector (Cu) of a cell contacts the metallic cathode collector (Pt or Ti) of the cell above. Similarly, the metallic cathode current collector of this cell contacts the anode current collector of the cell below. A major issue involved with producing these batteries is development of a suitable packaging process. The combination of a non-liquid chemistry with a metallic lithium anode creates an environment where any moisture can cause cell failure. Extreme care must then be taken to create a truly hermetic package that will last the desired lifetime.

The organizations presently active in this technology are: DOE-Oak Ridge Laboratories, NASA/JPL, NASA/GRC, NASA/GSFC, AFRL and Chemmat. Some limited work is also in progress in Korea and Japan. Only very small capacity (<1 mAh) experimental batteries have been fabricated and tested by these organizations. Researchers at the ONRL have demonstrated a cycle life of over 80,000 deep discharge cycles and a calendar life of about 10 years. One major deficiency of today's lithium thin-film battery technology is the low area-specific capacity. This deficiency is due to the inability to use thicker electrodes, because of de-lamination issues or conductivity problems. This deficiency, in turn, results in low specific power capability in terms of W/l or W/cm2, almost an order of magnitude lower than desired by sensors or other such devices.

Key Issues: The technology is in a very early stage of development. Current breadboard cells have extremely low capacity (a few micro-mAh) and the power densities are at least an order magnitude lower than desired for most applications. Significant advances are needed at the materials level before this technology can be considered for future space applications.

Future Directions for Lithium Solid Inorganic Electrolyte Battery Development: This technology may not be available for major applications until perhaps 2015, due to the current problems evident at the materials level. The following research efforts are required to advance lithium solid inorganic electrolyte battery technology to become applicable for future space missions:

- Develop new electrolyte materials with higher conductivities, improved interfacial stability, and improved processing capability.
- Develop thicker composite cathodes with improved electronic and ionic conductivity for enhancing the area-specific capacity and hence power densities.
- Develop fabrication methods to construct high capacity cells and batteries.
- Develop methods for cell sealing or enclosure.

4.2.4 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 presently at an early stage of development (TRL 1). Small capacity cells (2 Ah) have been made and tested. The system is being developed primarily by universities and research start-up companies, such as Moltech, Polyplus, SION Power, and Tadiran.

Chemistry: Li-S batteries are based on the lithium metal anodes and sulfur or polysulfide cathodes. The following cell reactions are relevant.

$2\,Li + S \Rightarrow Li_2S$

$2x\,Li + S_x \Rightarrow xLi_2S$

$2x\,Li + R_2S_x \text{ --> } xLi_2S + R\text{-}R$

Development Status: This technology is in a very early stage of development (TRL 1). The work is focused on developing suitable sulfur cathode materials and electrolytes (liquid organic, solid polymer and solid inorganic).

Sulfur has long been of interest as a cathode reactant because of its low equivalent weight and high reduction potential. Sulfur is an insulator, which makes it difficult to discharge efficiently. Also, sulfur forms polysulfides by direct reaction with sulfide ions. When used with liquid electrolytes, Li-S cells produce polysulfides that provide a "shuttle" mechanism during the overcharge process. This “shuttle” provides an electrochemical overcharge protection mechanism at the expense of the round-trip efficiency. Polysulfides, such as dithiadiazole and 1,3,5-trithiazine polysulfides, discharge at 2.7–3.0 Volts. The U. of Tokyo has synthesized derivatives with many polysulfide links containing up to 60% sulfur. In these, the S_8 bonds are already broken, and this enhances the discharge efficiency.

Glass electrolytes, such as the Thio-LiSi-CON family and LiPON and other solid electrolytes, offer promise of higher cell efficiency and elimination of the polysulfide "shuttle." Materials of construction present significant challenges. Anodes are of Li (metal) on substrates such as Cu or

Ni. Electrolytes are glasses or other solid electrolytes as noted above. Alternatively, both liquid and polymer electrolytes would be useful in conjunction with a thin glass or solid electrolyte layer for anode interface control and to block polysulfide diffusion. Very thin layers of active materials and perhaps dispersion over high-surface-area nanomaterial positive current collectors will help decrease the limitations of electron transport. Case, lid, insulator, and Ziegler feed-through materials could be the same as those used for Li-Ion cells. "Shutdown" separators could be used with the liquid or liquid/polymer combinations, but not with the solid electrolytes or glasses alone.

Experimental cells with a specific energy of 400 Wh/kg have been developed and are under evaluation. The cells have limited cycle life (only 200 cycles to-date) and low rate capability.

Key Issues and Resolution Strategies: The present experimental Li-S cells with solid state inorganic electrolytes cells have a demonstrated specific energy of 420 Wh/kg and 520 Wh/l. However, these batteries have limited life capabilities and poor specific power. Experimental cells have exhibited more than 200 cycles at 100% DOD. Many technical challenges remain. The development of this system will require the following activities:

- Characterize new glass and/or solid electrolytes that can minimize the polysulfide shuttle.
- Synthesize and study organic polysulfides.
- Select cell materials, such as current collectors, separators, containers and seals compatible with the chemistry.
- Demonstrate electrochemical performance in small, thin-film cells and scale up to suitable sizes.

Future Directions: Recognizing the exceptionally high specific energy and energy density of this system, the assessment team recommends a limited research effort of this. However, a development program is premature until the materials issues are resolved.

4.3 High-Temperature Batteries

A challenge for energy storage is the development of a battery that can operate at the surface of Venus where temperatures are near 460°C. If operating time is relatively short, the requirement may be met by insulating an existing battery such that it delivers the required energy before temperature exceeds the battery limits (about 50–70°C for primary batteries and 40–60°C for secondary batteries). Existing batteries will not work for longer operating times unless their operating range can be extended. For very long operating times at the surface of Venus, it is essential to have a battery that can withstand and operate at this high temperature of 460°C.

Several such high temperature batteries were developed and demonstrated by DOE some time ago. These batteries are: a) LiAl-FeS_2, b) Na-S, and c) Na-metal chloride.

Potential Benefits and Applications: LiAl-FeS_2, Na-S, and Na-metal chloride batteries can operate near 460°C. These batteries offer relatively high specific energy compared to aqueous rechargeable batteries and also good specific power outputs. On this basis the batteries are well suited for long term Venus surface missions.

Types of High Temperature Batteries: Significant work was carried out in the 1970s and 1980s on development of high temperature (300 to 600°C) rechargeable high temperature batteries. DOE and several contractors have examined high temperature rechargeable batteries for over 30 years for electric vehicle and load leveling applications. These systems-include: a) LiAl-FeS_2, b) Na-S, and c) Na-metal chloride. Several functional and full-scale electric vehicle (EV) demonstration units were developed and tested. These systems may be perceived as being at mid TRL (3-4). Although these batteries were designed as rechargeable versions, they can function in the primary battery mode as well. In addition to the above three systems described, there are some additional rechargeable battery systems that can also function at high temperatures and these include: a) Li-Ci_2, b) Li-CoS_2, and c) Li-CO_2. However, these latter battery systems are in early stages of development and their TRL levels are 1-2.

Table 4.3-1. Summary of High-Temperature Battery Concepts

Battery System	Predicted Maximum T (°C)	Estimated TRL for Venus	Comments
LiAl-FeS_2	600	3-4	
Na-S	450	3-4	Upper limit of 450°C may be extendable. Fragility is a big problem
Na-MCl_2 (M=Ni or Fe)	500	3-4	Demonstrated excellent performance, reliability and safety
LiSi-FeS_2		3-4	Same basic chemistry as thermal batteries.
LiSi-CuO		2	
LiSi-CF_x		1	
Li-CO_2		1<	Very high theoretical performance. CO2 available on Venus.
Li-Cl_2	>430	1<	

4.3.1 Mid-TRL High Temperature Batteries

In the mid-TRL range (4-5), there exist three systems that have received research emphasis for terrestrial EV and load leveling applications: a) LiAl-FeS_2, b) Na-S, and c) Na-metal chloride. 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.

LiAl-FeS_2 Battery: 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 to 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 plus some electrolyte. The cathode is made of pressed FeS_2 plus more electrolyte. The separator is made from pressed MgO powder.

Sodium-Sulfur (Na-S) Battery: This system was the first among the high temperature batteries widely studied and well developed, following the observation that sodium beta alumina ceramic permits rapid mobility for sodium ions. This battery employs a molten sodium anode, a molten sulfur cathode, and a sodium beta alumina ceramic electrolyte/separator. The electrolytic property of the beta-alumina is again due to its conductivity of sodium ions and its insulating property is due to its inability to conduct electrons. Beta-alumina 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 300–450°C. The overall cell reaction is:

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

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 inner can and also a metal rod serve as anode current collector. 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-$NiCl_2$) Battery: This system is an offshoot of sodium-sulfur, with the sulfur cathode replaced with transition metal chlorides in contact with sodium tetrachloroaluminate melt for improved safety. This battery, pioneered in the 1980's 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 to 500°C. 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 $NiCl_2$ cathode is located inside the electrolyte tube. 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 as the positive current collector.

Characteristics of High-Temperature Battery Concepts: The general characteristics of the three high temperature battery systems described above are given in the Table 4.3-2. This table establishes the following major conclusions:

- The Na-nickel chloride system yields the highest open circuit and operating voltages.
- The LiAl-FeS_2 system has the highest operating temperature range.
- Energy and power characteristics of all three are significantly higher than those of aqueous systems and all fall within a reasonably narrow range. Some differences do exist

with the Na-S and $LiAl-FeS_2$ systems, however, offering somewhat higher energy and power than the Na-nickel chloride system

- 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 appears to be promising, however, the amount of testing has been quite limited. The best cycle life demonstrated to-date is 1000 to 2000 cycles.

Table 4.3-2. Characteristics of High-Temperature Batteries

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

Key Issues: The major unresolved issues include: a) adapting cell and battery designs for space applications, b) insuring the stability of seals and terminals, c) minimize the corrosion of current collectors at high temperatures, and d) determine the effects of zero gravity upon performance.

4.3.2 Low-TRL High Temperature Batteries

Lithium-cobalt disulfide, lithium–chlorine, and lithium-carbon dioxide cells are some of the advanced conceptual high temperature electrochemical cells that may operate at temperatures as high as 425°C. They have potential for much higher specific energy and energy density than existing cells or adaptations of present thermal batteries. These electrochemical cells would utilize low specific-weight cathodes in combination with Li or Li alloy anodes and molten salt or solid electrolytes. The $Li-CoS_2$ couple has been used in thermal batteries with a molten salt electrolyte such as LiCl:KCl eutectic. The $Li-Cl_2$ couple is used commercially in an electrolysis process to produce Li from molten salt LiCl. The Navy has also investigated this couple in high energy density primary cells using molten salt electrolytes. The thermal batteries operated for a few minutes to a few hours. Cells can be stored indefinitely and only operate when heated. Their projected performance characteristics are given in Table 4.3-3.

Table 4.3-3. Potential performance of low-TRL high-temperature batteries

Couple	Equivalent weight	Voltage	Sp. Energy (Wh/kg)	Projected Cell Performance*
Li-Cl_2	42.4 g	4.54	2870	860 Wh/kg
Li-CoS_2	37.7 g	2.2	1564	470 Wh/kg
Li-CO_2			10,800	3240 Wh/kg

* at 30% packing efficiency

4.3.3 Technical Directions

It is recommended that an ongoing system analysis be completed that deals with 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 leading to a single battery chemistry, if that is appropriate.

4.4 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 of Code M and Code T) that require multi kilowatts of power for extended periods of up to 10 days. Conventional batteries are not suitable for such applications due to much lower specific energy and scalability issues. Space science missions require between a few watts to hundreds of watts for durations of fractions of an hour to few hours. For these conditions, SOP fuel cells are not attractive due to miniaturization difficulties and system complexity. However, when operating time for space science missions is extended beyond tens of hours, fuel cells offer appreciable mass volume savings over batteries. (See Appendix II)

Several types of fuel cells have been under development for a number of commercial, and military applications. These are listed below with their typical operating temperatures:

a) Proton Exchange Membrane, 80°C
b) Alkaline, 175°C
c) Phosphoric Acid, 175°C
d) Molten Carbonate, 650°C
e) Solid Oxide, 900-1000°C
f) Direct Methanol Fuel Cells 80° C
g) Regenerative Fuel Cells 80–175° C

Among these systems, H_2-O_2 PEM fuel cells and regenerative fuel cells are most promising for future space missions, and are described below.

4.4.1 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) and can significantly enhance future Shuttle Orbiter Missions by reducing power system mass and increasing payload. In addition, PEM fuel cells can further enhance the shuttle missions for other reasons, including extension of time between servicing that would extend missions and reduce maintenance costs. PEM fuel cells are also attractive not only for the Shuttle Orbiter, but for other Code T applications as well (including Lunar/ Mars Base Station power and Lunar/ Mars Surface Exploration Vehicles). PEM fuel cells can be considered for space science missions in place of primary batteries in missions such sample return capsules that require energy storage devices 5kWh or higher (~ 100 watts for 50 hours).

Development Status: PEM fuel cell technology is in the advanced stage of development (TRL 4-5). Historically, PEM fuel cells were developed by General Electric and were the first fuel cells to be deployed in several of the Gemini missions starting in 1962 (Figure 4.4-1). However, because of the low power density and relative low efficiency of the early PEM fuel cells, they were replaced with the AFC from United Technology Co (UTC) in the Apollo and Space Shuttle Programs. Since 1982, these AFC's have performed very well in meeting power needs for the Shuttle. However, there have been no major improvements in performance of the AFC since that time. The PEM fuel cells have seen rapid advances in performance over the last fifteen years.

The advances in the PEM system have resulted primarily from a number of PEM development efforts sponsored by Department of Energy, commercial organizations, and NASA. Most of these development efforts have been focused on terrestrial applications of the PEM for electric vehicles and stationary power applications. Leading companies include Ballard Power Systems, Plug Power Systems, and Siemens.

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 have led to an increase in power density from 40 mW/cm^2 in the late 1960s to 1500 mW/cm^2 in the late 1990s. 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 in 1999. 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. Projected specific power of the PEM is now 250 W/kg or 2.5 times the specific power of the existing alkaline fuel cells100 w/kg as shown in Figure 4.4.1.

For some time NASA/JSC has recognized the potential of the PEM fuel cell and it's potential advantages over the AFC for the Shuttle. NASA development programs have resulted in many of the advances in power density and life of the system.

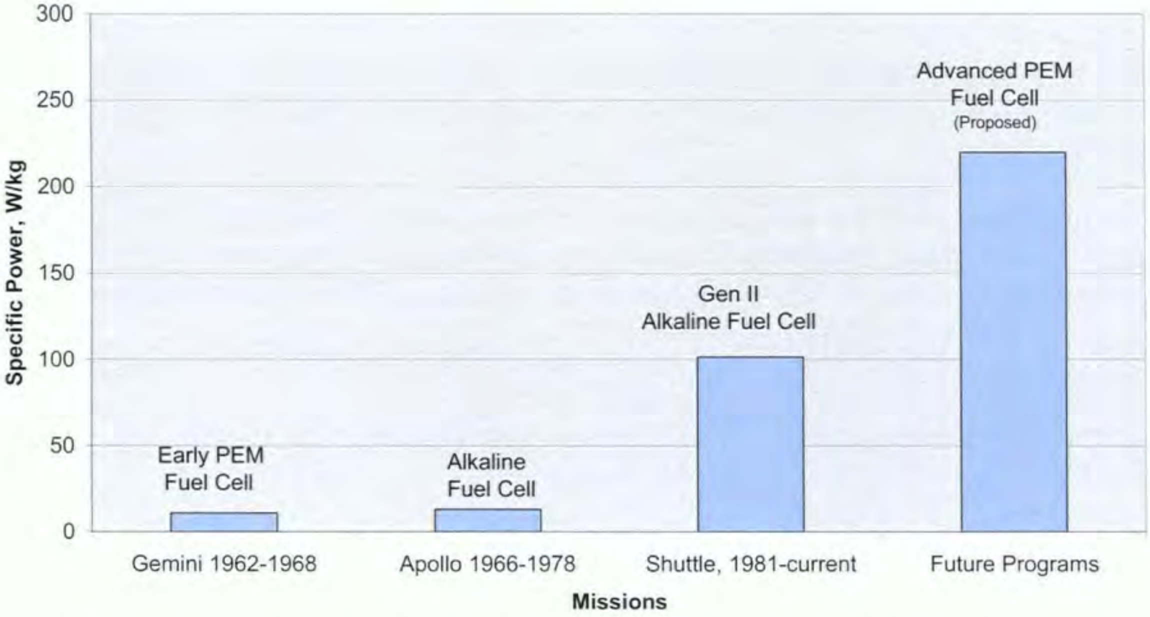


Figure 4.4-1. Specific Power of Fuel Cell Technologies for Manned Missions

The projected advantages of the PEM over the AFC system are summarized in Table 4.4-1. 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 4.4-1. Comparison of Alkaline and PEM Fuel Cell Technologies for Space Missions.

Characteristic	Alkaline Fuel Cell	PEM Fuel Cell
Specific Power, Watts/kg Power Density, Watts/liter	90 155	200 300
Efficiency	70%	70%
Maintenance frequency	Every 2600 h	Predicted to be >5,000 hours
Differential Pressure Limit	41 kPa	300 kPa
Operating Temperature	90°C	80°C
Failure Mechanisms	Attack of epoxy frames and Noryl insulator plates by KOH.	Not known.

Key issues: The key issues that need to be addressed for transitioning the PEM fuel cell technology to space missions are: a) optimization of the balance of plant design, especially water removal, b) validation of system performance, c) Life demonstration at system level, and d) resolve miniaturization issues with for small fuel cell systems for space science applications.

4.4.2 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 Mars surface missions. Potentially this type of system can offer as high as five to ten times 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 forty years under the NASA/DoD sponsored programs.

In 1995 under a NASA/GRC 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 has been demonstrated by Giner Inc. This electrolyzer operates at about 1000 mA/cm^2 at a cell voltage of 1.72 V operating at 80^{o}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 weight reduction because a single stack is used. Also, common gas and fluid handling subsystems will lead to further reduction in 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.

4.4.3 Technical Directions

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

- 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 space 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.

4.5 Capacitors

Capacitors are typically utilized 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.

Supercapacitors and ultracapacitors, especially the most recent versions, have some of the character of batteries because their electrodes emulate a battery electrode. 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 super capacitor has specific energy up to 10 Wh/kg, more than twice the values of other capacitor designs. Its essential features are typically asymmetric construction and use of an aqueous electrolyte.

Third-generation capacitors should achieve 20 Wh/kg in the next several years using material systems presently identified. And because of perceived cost advantages for this aqueous electrolyte product, products at this performance level will likely become commercially available. 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.

Generation IV capacitors, which are distinguished by the combination of asymmetric electrodes and organic electrolyte capacitors, are only now starting to appear. This design operates exactly like a Generation III device but with a non-aqueous electrolyte. Thus, the operating voltage can be much higher. Work has only recently started on Generation IV electrochemical capacitors. Many battery-type electrodes are under investigation as to their suitability for this application. The state of the art is expected to progress to 25 Wh/g for energy-optimized devices.

4.6 Flywheels

4.6.1 Introduction

Flywheels store energy as kinetic energy of rotation of high-speed rotors. A form of flywheel is presently used on many spacecraft for attitude control ("reaction wheels"). To act as an energy storage medium, flywheels need to operate at higher speeds where the challenge is to maintain its structural integrity as centrifugal forces tend to tear it apart. Flywheels are used in terrestrial applications where mass is not critical. However, in space, mass is critical, and flywheel technology is very challenging. Some approaches combine the two functions of acting as an energy reservoir and also attitude control. All of these are still at a low TRL for space science applications.

Flywheels are interesting because they have the potential for very long cycle life at > 75% DOD, and they may be operable over fairly wide temperature ranges. Magnetic bearings and rotors have been demonstrated up to 60,000 RPM. There is no taper charge and there are fewer thermal constraints than for batteries. Accelerated life testing may be credible. High discharge rates are attractive for pulse power applications. Flywheels in large sizes are under development for various terrestrial applications. However, for space science missions, it is unclear that these devices can compete favorably with batteries.

One area where flywheels might eventually out-perform batteries is in high-cycle LEO orbiters. Such flywheels for spacecraft could be implemented in two possible modes:

- Fixed-Axis Energy Only System (Flywheels arranged in counter rotating pairs to achieve energy storage with net zero momentum
- Fixed-Axis Energy/Momentum System (Flywheels replace reaction wheels and batteries. Minimum of four flywheels required to achieve energy/ momentum storage as required by EPS/ACS)

Some analyses indicate a significantly greater benefit from the combined energy/ momentum storage system.

The combined Energy/Momentum System has been identified by the name IPACS (Integrated Power and Control System), and an active program is in place to build a breadboard demonstration unit of this combined technology, called "COMET" for Combined Momentum and Energy Transfer.

4.6.2 Description

Flywheels provide an alternative to batteries for energy storage. A flywheel is a device that stores energy mechanically in a rotating mass. Energy is added to the system by applying torque to the spinning mass so as to accelerate it to faster speeds. Energy is taken out of the system by having the rotating mass generate torque that decelerates the spinning mass to slower speeds. The torque that accelerates or decelerates the flywheel is generated electro magnetically with a motor/generator unit.

The kinetic energy stored in a flywheel is proportional to the flywheel's moment of inertia, and the square of its rotational speed. To store more energy in a flywheel, one can increase its inertia or its speed. Increasing the inertia increases the weight, so increasing the speed is the preferred method. Doubling the top speed of a flywheel quadruples its stored energy, and therefore its energy density.

The critical elements of a flywheel system include:
- Rotor
- Magnetic bearings
- Motor/generator
- Touchdown bearing
- Housing
- Controller
- AC/DC power processing

The NASA flywheel technology program was originated in 1995 and concentrated initially on developing improved rotors capable of higher rotational speeds, and low-loss magnetic bearings. In this connection, rotors were built and tested to destruction at spin speeds of 43,000 and 60,000 rpm. Work has also been done on improved low loss magnetic bearings. Algorithms for integrated energy storage and attitude control have been developed.

4.6.3 Advantages and Disadvantages

Potential advantages of flywheels over other energy storage devices include:
- Capability for many cycles at high depth of discharge (significant benefit for LEO applications)
- Well defined state of charge
- Temperature-independent state of charge
- Wider operating temperature range
- Probable radiation tolerance
- Overall system benefits from combining energy storage and attitude control

The energy level or state-of-charge of the flywheel can be determined quite accurately and quickly with a single measurement. The energy depends on the moment of inertia and speed and moment of inertia of the rotor is known when the system is built and tested, and doesn't change over the life of the system. The state-of-charge is then given directly from the rotor speed. By comparison, the state-of-charge of batteries cannot be determined so readily and accurately as it depends on various design and operational characteristics.

Another advantage of the flywheel is its capability to operate consistently over its temperature regime. While batteries are driven by chemical reactions with rates that change with temperature, a flywheel's energy capacity is essentially independent of temperature. The limit on high temperature operation is due to the materials used to construct the rim, specifically the epoxy. The best epoxies today are rated for temperatures up to around 250°C. At the low temperature end, the limit for current rotor designs is the point where the preload is lost at the hub/rim interface. This is because the different coefficients of thermal expansion cause the hub to shrink faster than the rim at cold temperatures. The operational temperature of the electronics that run the system is limited to approximately -55°C to +125°C.

Given that flywheels require torque to charge and discharge, and that multiple flywheels are required at a system level to negate unwanted torque from single flywheels, technologists have developed concepts that use flywheels to simultaneously store energy and generate controllable torques in multi-axes. When the torque capability of the flywheels is used for attitude control of a satellite in planetary orbit, the weight of the combined flywheel energy storage/attitude control subsystem is predicted to be much less than the sum of separate battery and ACS subsystems.

4.6.4 Flywheel Applicability

Although the inherent energy storage capabilities of flywheels and batteries may be comparable, flywheels can operate at much higher "depths of discharge" than batteries especially for extended cycling. Therefore, the delivered energy of flywheels can be higher and their mass lower than batteries for applications with extended cycling requirements.

LEO applications require extended cycling and are currently met with batteries that operate at only 25-35% DOD so as to meet the requirements. Flywheels have the capability to meet these extensive cycle requirements with lower mass than batteries in that they can operate at much higher DOD's on the order of 85-90%. Flywheels may then be more attractive than batteries for such GEO applications.

A combined flywheel energy storage/attitude control subsystem would generate the greatest mass benefits because it would replace the heavy, slow rotors of conventional ACS with fast, lightweight rotors. It would operate over a wider temperature range than batteries, thus reducing the complexity, weight and cost of the relevant thermal control system. Array power requirements would also be reduced. Several studies, both by government and by industry, predict these system benefits to produce significant weight savings. (See Appendix III).

Because of the potential advantages of flywheels in LEO, this technology is likely to match well with missions of Codes Y and M. In Code S deep space applications, where batteries can be operated at depths of discharge around 70%, the potential mass advantages of flywheels over batteries are reduced compared to LEO. Nevertheless, flywheels still offer other advantages previously cited and might possibly be useful in some Code S orbiter missions.

4.6.5 Technical Directions

Technology advances that are needed include increasing speed, reducing weight, reducing complexity, reducing fixed losses, and demonstration of an end-to-end functioning system. NASA-GRC is working on each of the above technology elements. In addition, NASA-GRC is developing a flywheel breadboard system to demonstrate the feasibility of simultaneous energy storage and ACS with a single system. The *Coordinated Momentum and Energy Transfer* (COMET) demonstration system is now under construction and is expected to be tested in 2003-2004. However, COMET does not utilize a modern state of the art rotor.

4.7 Adequacy of Energy Storage Technology Programs

The DOD and the DOE have invested and continue to invest a considerable amount of funds into energy storage technology. However most of this work is not directly applicable to NASA needs for space science missions.

The DOE is presently investing in fuel cell and Li-Ion and lithium polymer battery technologies. However, this work is driven primarily by the goals of high rate power delivery at low depths of discharge and cost reduction. Many of the NASA needs (long life, operation at low and high temperatures) are not relevant.

The DOD has several sub-agencies that invest in energy storage technology. The Army needs low-cost, portable, short-life batteries or fuel cells for field communications. The air force requires large batteries for high power levels for aircraft. The Navy has a program in Li-Ion batteries with polymer electrolytes that might someday be applicable to NASA missions but this appears to be a long-term development. In addition, the CIA has a program in long cycle-life Li-Ion batteries, but this is not available to NASA.

Within NASA, Code S has no funded technology programs in energy storage technology. Code R (now Code T) has several technology programs including:

- A small program to test Li-Ion batteries
- A significant program in Li-Ion batteries with polymer electrolytes
- A moderate program in fuel cell development
- A significant program in flywheel development

Neither the fuel cell nor the flywheel programs apply to space science missions. The Li-Ion work does apply, but is not of a magnitude or direction to fulfill space science mission needs.

There are no programs in high-temperature battery development, and it is clear that ongoing energy storage technology programs will not meet the needs of future space science missions.

4.8 Summary of Advanced Energy Storage Devices

Primary Batteries

- Advanced lithium-primary systems under development include advanced Li-MnO2, Li-CFx, advanced Li-SOCl2 and Li-O2.
- Among these systems, Li-CFx and Li-SOCl2 are the most promising for future space science missions, in view of their higher specific energy, long shelf life, and potential for improved performance at ultra-low temperatures.
- NASA has no current technology development programs for primary batteries.

Rechargeable Batteries

- Advanced rechargeable battery systems under development include Long Life Li-Ion, Low temperature Li-Ion, Li/Li-Ion polymer electrolyte, Li-inorganic solid electrolyte and Li-S. These advanced Li batteries are projected to offer one or more of the following advantages: a) higher specific energy and energy density (3-6 X compared SOP Ni-Cd/Ni-H2 batteries, b) long cycle life and calendar life, c) improved low temperature performance, d) low self-discharge, e) high charge/discharge efficiency, and f) lower cost compared to SOP rechargeable batteries.

- Among these systems, the Li-Ion system has the highest potential to meet the near- to mid-term needs of space science missions in view of its high level of technical maturity, improved cycle life, and low temperature performance capabilities. Current NASA funding of Li-Ion battery technology is inadequate to produce products in a few years.
- In the longer run, advanced Li batteries with polymer or inorganic electrolytes may provide advantages over Li-Ion batteries with liquid electrolytes. NASA/GRC is implementing a program on the development of lithium polymer electrolytes.

High Temperature Batteries

- High temperature battery systems that are attractive for near term Venus surface mission applications are: a) LiAl-FeS_2, b) Na-S, and c) Na-Metal Chloride. These systems were brought to fairly advanced stage of development (TRL3-4) under prior DOE sponsored programs for electric vehicles.
- There are some other promising high temperature batteries that are in early stages of development and they are: 1): Li-Cl_2, 2) Li-CoS_2, and 3) Li-Co2.
- 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 if that is appropriate.

Fuel Cells

- Fuel cells are attractive for human space missions that require multikilowatts 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.
- Advanced fuel cell systems under development include: Polymer electrolyte membrane (PEM) fuel cells, Direct Methanol fuel cells , solid oxide fuel cells and regenerative fuel cells.
- Among these systems H2-O2 PEM fuel cells and regenerative fuel cells are most promising for future human space missions, in view of their performance advantages and advanced stage of development. Small PEM fuel cells are attractive for space science missions that require power of 100 watts and above for 20–30 hours.

Capacitors

Advanced capacitor technologies under development include ultra capacitors and super capacitors. These capacitors have 2–3 times higher specific energy compared to the SOP double layer capacitors. They can deliver thousands of cycles with minimal degradation in performance and are attractive for applications that require repeated short high discharge pulses.

Flywheels

Two types of fly wheels are under development: a) Fixed-axis energy-only system, and b) Fixed-axis energy/momentum system.

- The fixed axis energy only system is attractive for energy storage applications and the second technology is for energy storage and attitude control applications.

- The potential benefits of flywheels include the capability for many cycles at high depth of discharge, wider operating temperature range, and radiation tolerance. The major issues of flywheels are system size and system complexity. They are attractive for low earth orbital missions that require a usable energy storage capability of 5KWh or more. TRL level of this technology is at 3-4.

5.0 Recommendations

This section provides the recommendations of the assessment team on energy storage technologies required for future space science missions. These recommendations are based on a review of the needs of the next decadal space science missions, the capabilities of SOP technologies, and the potential of advanced technologies to fill the gaps between needs and SOP capabilities.

Overall Recommendation:
The assessment team recommends that Code S establish a program to develop advanced energy storage technologies that will enable and enhance the capabilities for next generation space science missions. The team also recommends that Code S establish and maintain partnerships with other NASA enterprises and/or government agencies wherever appropriate.

Specific Recommendations:

- The assessment team recommends the development of advanced primary, rechargeable, and high-temperature battery technologies to meet mission needs. Emphasis should be placed on technologies that offer significant mass and volume savings, can function in extreme environments, and have long-life. These technologies will provide significant benefits to future missions for the Solar System Exploration and Mars Exploration Programs (e.g. landers, rovers, orbiters and probes). Sun-Earth Connection and Origins Theme missions will also benefit from mass and volume savings. Development of high-temperature batteries may also be a worthwhile pursuit, pending system engineering studies of alternatives for exploring Venus in situ.
- The recommended battery technology areas are:
  a) Low-Temperature Primary Batteries,
  b) Long-Life Rechargeable Batteries,
  c) Low-Temperature Rechargeable Batteries,
  d) High-Temperature Batteries (subject to recommendation of ongoing system studies).

  The assessment team reviewed the status of advanced primary battery technologies presently under development and concluded that:
  - Advanced CFx and Li-$SOCl_2$ primary battery technologies are recommended for further development to achieve high specific energy and possibly lower temperature operation at appropriate power levels.
  - Advanced Li-Ion and Li-Polymer/Li-solid state rechargeable battery technologies are recommended for further development to achieve long life with high specific energy.
  - Advanced Li-Ion rechargeable battery technology is recommended for further development to achieve lower temperature capability.
- It is recommended that a system analysis be completed to evaluate alternatives for high-temperature rechargeable and primary batteries be conducted for their applicability to Venus (surface and atmospheric) missions.

- Wherever there are competing technologies for the same end result, the team recommends establishing technology readiness gates to monitor the progress and down-select to the most promising technology as soon as possible.
- It is recommended that Code S establish a test and validation program to demonstrate the electrical performance, life capabilities, and identify problems of advanced energy storage technologies. In this connection, it is recommended that Code S augment and modernize the existing infrastructure at various NASA centers as needed to support missions.
- It is recommended that Code S work with AFRL and other DoD agencies to transition advanced energy storage technologies to industry for technology maturation and mission insertion.
- It is recommended that Code S monitor the technical developments funded by other NASA Codes in the areas of fuel cells, capacitors, and flywheel technologies and evaluate their relevance to future Space Science missions. Furthermore, it is recommended that Code S provide encouragement to Codes T and M to advance fuel cells, capacitors, and flywheel technologies, in proportion to their relevance to Code M missions.

5.1 Program Description

The assessment team recommends the development of an Advanced Energy Storage Technology Program that includes Low Temperature Primary Batteries, Long Life Rechargeable Batteries, Low Temperature Rechargeable Batteries, and possibly High Temperature Batteries, depending on the outcome of ongoing system studies.

5.1.1 Low Temperature Primary Batteries

Objective:
Develop low temperature and long-life lithium primary batteries that are mass- and volume-efficient, and radiation tolerant to enable/enhance the capabilities of *in-situ* missions projected for the next decade (Solar System and Mars Exploration Programs). The suggested performance targets are shown in Table 5.1-1.

Table 5.1-1. Primary Energy Storage Performance Goals

Primary Energy Storage Characteristics	Present State of Practice	Goal (5 years)	Goal (10 years)
Specific Energy at 0C (Wh/kg)	250	400	600
Specific Energy at –40 C (Wh/kg)	100	200	300
Specific energy at –80 C (Wh/kg)	50	100	200
Discharge rate (hrs)	> 20	> 20	> 20

Benefits:

The classes of missions that will significantly benefit from advanced low-temperature primary battery technologies are planetary probes, landers, sample return capsules, and distributed sensor networks. The mission impact/benefits of these technologies are: a) operation at temperatures as low as than –80°C, b) increased payload mass (from 2-3 times mass and volume savings compared to SOP primary batteries), c) longer operational life (> 10 years), and d) improved radiation tolerance.

Approach:

The approach to develop advanced primary batteries will consist of an initial parallel development effort on the two most promising systems: Li-CFx and Li-$SOCl_2$ (Li-interhalogens). The challenges in these systems are different. Li-CFx already has high specific energy but only at exceedingly low rates, whereas Li-SOCl2 requires an increase in specific energy. Both systems will benefit from new electrolytes that perform well at low temperatures. Subsequent efforts will require down-selection to the most promising technology for maturation to TRL 6.

The initial phase of the effort will focus on advancing both technologies to TRL 4, utilizing the following activities:

1) Identify electrolytes that have good lithium ion conductivity at these low temperatures
2) Improve the Li electrode/electrolyte interfacial properties for enhanced charge transfer
3) Improve the ionic and electronic conductivity of cathode material (CF_x)
4) Demonstrate technology feasibility with experimental cells at appropriate rates of charge and discharge.

The second phase of the effort will focus on advancing the down-selected technology to TRL 6 and will consist of the following activities: a) cell design and fabrication, b) battery design and fabrication, c) electrical and life performance, and d) performance validation at the prototype cell and battery levels. The assessment team also recommends fostering partnerships with various universities and industries for the initial phase of the development (TRL 2-4) and developing partnerships with the relevant industries for advancing the technology to TRL 6.

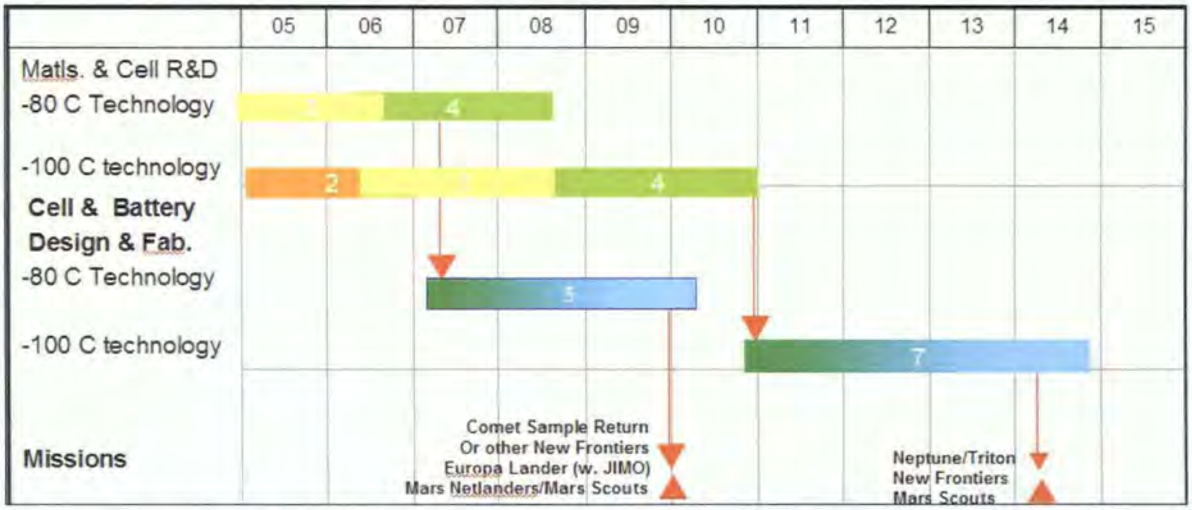


Figure 5.1-1. Low Temperature Primary Battery Technology Roadmap

Technology Roadmap and Resource Requirements:

The proposed technology roadmap for the development of low temperature primary batteries is given above in Figure 5.1-1. A rough estimate of the developmental costs for the effort is given in Table 5.1-2. The cost estimates for these efforts are based on a comparison with costs incurred in the past in developing similar technologies. Manufacturing infrastructure already exists for the manufacturing of primary lithium batteries, and hence no costs were included for establishing manufacturing facilities. The low temperature primary batteries are not of interest to DOD and hence NASA cannot expect any cost sharing from DoD.

Table 5.1-2. Rough Estimated Cost for the Development Low Temperature Primary Batteries.

Task	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
Materials & Cell R&D (TRL 1-3)											
Li Technology-1	0.6	0.6	0.6								1.8
Li Technology-2	0.6	0.6	0.6	0.6	0.6	0.6					3.6
Tech Maturaration TRL(4 to 6)			1	1	1	1	1	1	1	1	8
Total Cost	1.2	1.2	2.2	1.6	1.6	1.6	1	1	1	1	13.4

5.1.2 Long-Life Rechargeable Batteries

Objective:

Develop long-life rechargeable batteries that are mass and volume efficient to enhance the capabilities of: a) next decadal Mars orbital missions (high cycle life), b) outer planet orbital missions (long shelf life) c) Earth orbital missions (high cycle life), d) Mars surface exploration missions (moderate cycle life at low temperatures) and e) Sun-Earth Connection and Origins missions (long shelf life). The suggested performance targets for this technology are listed in Table 5.1-3. Separate batteries may be developed for long shelf life and high cycle life; the two characteristics may not necessarily be needed in the same battery.

Table 5.1-3. Rechargeable Energy Storage Performance Goals

	Ni-Hydrogen	Lithium Technology		
Rechargeable Energy Storage Characteristics	Present State of Practice	Present State of Practice	Goal 5 years	Goal 10 years
Specific Energy (Wh/kg)	30	100	120	200
Energy Density (Wh/liter)	10	200	200	400
Cycle Life at 30% DOD *	50,000	10-15,000	30,000	50,000
Calendar Life (years)	15	3	10	15

* DOD = Depth-of-discharge

Benefits:

The classes of missions that will significantly benefit from these technologies are: a) solar-powered Mars orbiters, b) RPS-powered outer planetary orbiters that require batteries for load-leveling, c) solar-powered Earth orbiters (LEO, GEO & MEO), and d) solar or RPS-powered long-life planetary landers and rovers. The mission impact/benefits of these technologies are: a) reduced power subsystem mass, b) smaller solar arrays, c) longer operational life, and d) survivability in radiation environments. These advantages are mainly due to the higher specific energy, energy density, cell operating voltage, efficiency, and lower self-discharge rates compared to currently used battery technologies. Furthermore, these advanced batteries can also provide significant cost savings for future missions.

Approach:
It is recommended that long-life lithium-ion batteries be developed to meet the near-term (5 year) goals in Table 5.1-3, and lithium polymer and solid-state batteries be developed with the goal of meeting the long-term (10 year) goals. Lithium-ion technology has been identified for the near-term goals in view of its relatively advanced stage of development (TRL 9 for short-life applications, TRL 3 for long-life applications). Lithium polymer and solid-state battery technologies have theoretical potential to provide higher mass and volume savings than Li-Ion batteries, but they currently are at a low TRL level (1-2). Consequently, they will require more time to be developed. In addition, the Li-S cell is worthy of exploration because it has some attractive features, but it is still at an early emergent stage of development.

The initial phase of the effort to develop advanced Li-Ion batteries will focus on advancing long storage and cycle life Li-Ion technology from TRL 3 to TRL 4, and will consist of the following activities: a) development of stable electrolytes, b) identification of suitable additives to stabilize cathode/anode material structures, c) determination of optimum operating conditions to enhance life, d) establishment of a performance database, and e) elucidation of failure modes and mechanisms and project life performance. The initial phase of the Li-polymer/Li solid-state battery efforts will focus on advancing the technology from the present TRL 1-2 to TRL 4, and will consist of the following activities: a) development of improved polymer/solid-state electrolytes with high conductivity and stability, b) development of composite electrodes with high ionic and electronic conductivity, c) identification of electrodes with high specific capacity and reversibility, and d) demonstration of the technology feasibility in experimental cells. In both cases (Li-Ion and Li-polymer/solid state), if the first phase is successful, the second phase of the effort will focus on advancing the technology to TRL 6 and will consist of the following activities: a) cell design and fabrication, b) battery design and fabrication, c) electrical and life performance, and d) performance validation at the prototype cell and battery levels. (See Figure 5.1-2.)

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.

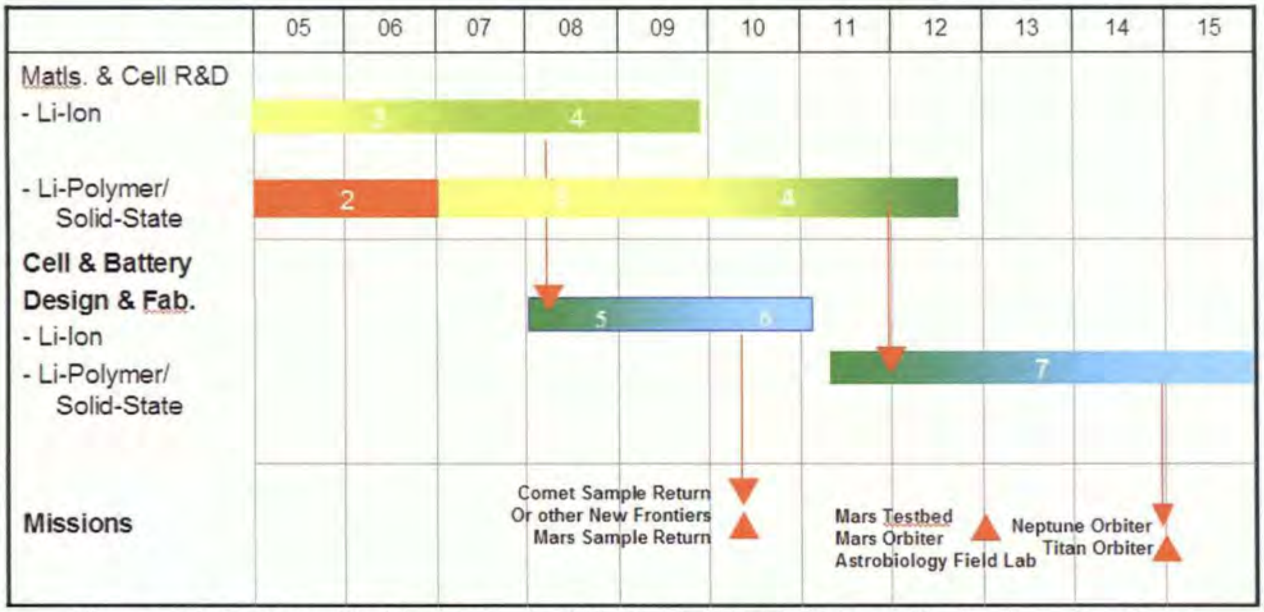


Figure 5.1-2. Long Shelf- and Cycle-Life Rechargeable Battery Technology Roadmap

Technology Roadmap and Resource Requirements:

The proposed technology roadmap for the development of long life rechargeable batteries is given Figure 5.1-2. A rough estimate of the developmental costs for the effort is given in Table 5.1-4. The cost estimates for the effort are based on costs incurred in the past in developing similar technologies. These batteries are of much interest to DoD and hence NASA and DoD need to work together and share the cost of this technology development effort.

Table 5.1-4. Rough Estimated Cost for the Development Long Life Rechargeable Batteries

Task	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Total
Materials & Cell R&D (TRL 1-3)												
Li Ion Technology-1	1	1	1	1	1							5
Li Polymer/SolidstateTechnology-2	2	2	2	2	2	2	2	1				15
Tech Maturaration TRL(4 to 6)			2	2	2	2	2	2	2	2	2	18
Total Development Cost	3	3	5	5	5	4	4	3	2	2	2	38
DOD Cost Share for Tech Maturation			1	1	1	1	1	1	1	1	1	9
NASA Cost Share	3	3	4	4	4	3	3	2	1	1	1	29

5.1.3 Low Temperature Rechargeable Batteries

Objective:

To develop rechargeable batteries that retain a significant fraction of their room temperature mass and volume efficiency at temperatures as low as -80°C, and thus enhance the performance capabilities of solar powered *in-situ* exploration missions on Mars and cold outer planets and their moons. The suggested performance targets for this technology are given Table 5.1-5.

Table 5.1-5. Rechargeable low temperature batteries – performance goals

	Lithium Ion Technology		
	Present State-of-Practice	5 years	10 years
Specific energy at 0°C (Wh/kg)	100	120	200
Life Time (yrs)	5 yrs	10yrs	15 yrs
Cycle Life (# of cycles) (80%DOD)	> 500	> 500	> 500
Low Temperature Performance			
Specific Energy at –20°C	70	100	160
Specific Energy at –40°C	40	80	140
Specific Energy at –60°C	0	65	120
Specific Energy at –80°C	0	40	80
Discharge rate (hours)	>10	> 10	> 10

Benefits:
The missions that will significantly benefit from the advanced low temperature rechargeable battery technologies are: a) solar-powered Mars Landers, b) Mars Rovers, c) Lunar Landers, and d) Lunar Rovers. The mission impact/benefits of these technologies are: a) operation at temperatures lower than –60°C, b) increased payload mass (up to 4-5 times mass and volume savings compared to SOP primary batteries), and c) long operational life (>5 years). These advantages are primarily due to higher specific energy, energy density, cell operating voltage, efficiency, and lower self-discharge rates of these batteries. Furthermore, these batteries will also provide significant cost savings for future missions.

Approach:
It is recommended that efforts be focused primarily on the development of Li-Ion and Li-$CuCl_2$ batteries for this application because this technology has the highest potential for further advancement in the near term. The initial phase of the effort will focus on advancing this technology to TRL 4 and will consist of the following activities: a) the identification of electrolytes with improved lithium-ion conductivity at low temperatures, b) the development of improved electrode materials with enhanced kinetics for lithium intercalation and diffusion,and c) the demonstration of the technological feasibility with experimental cells. The second phase of the effort will focus on advancing the technology to TRL 6 and will consist of the following activities: a) cell design and fabrication, b) battery design and fabrication, and c) performance validation at the prototype cell and battery levels.

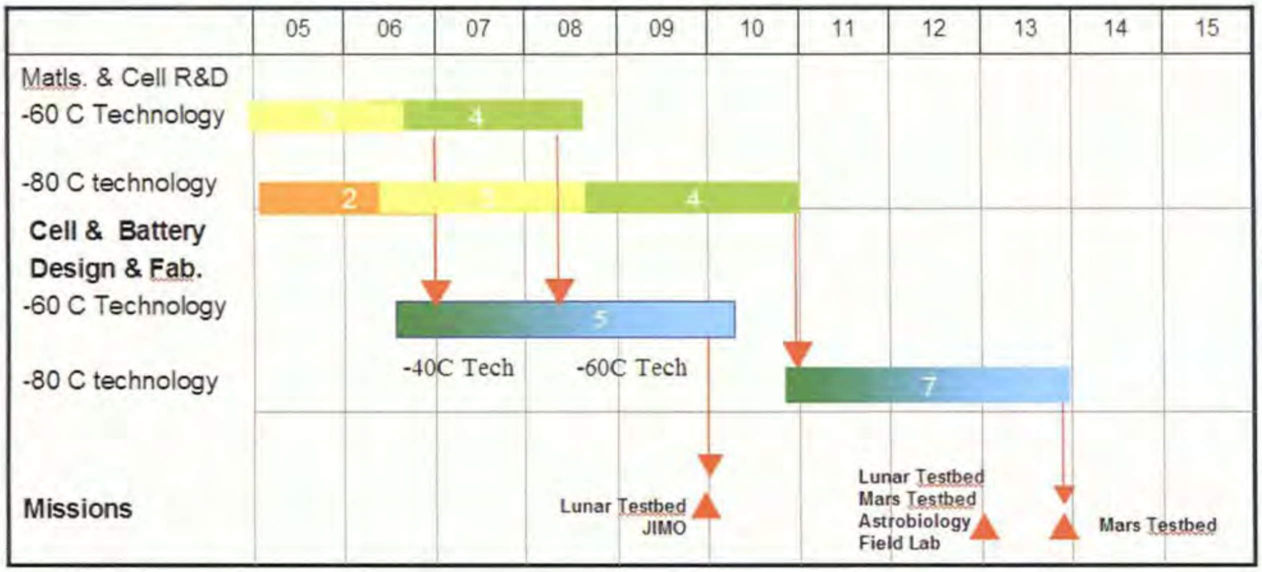


Figure 5.1-3. Low Temperature Rechargeable Battery Technology Roadmap

Partnerships are recommended with various universities and industries for the initial phase of the development (TRL 3–4) and forming partnerships with the industry for maturing the technology to TRL 6.

Technology Roadmap and Resource Requirements:

The proposed technology roadmap for the development of low temperature rechargeable batteries is given in Figure 5.1-3. A rough estimate of the developmental costs for the effort are given in Table 5.1-6. The cost estimates for the effort have been arrived on the basis of costs incurred in the past in developing similar technologies. These batteries are of little interest to DoD, and hence DoD is unlikely to share the cost of the effort.

Table 5.1-6. Rough Estimated Cost for the Development of Low Temperature Rechargeable Batteries

Task	2005	2006	2007	2008	2009	2010	2011	2012	2013	Total
Materials & Cell R&D (TRL 1-3)										
Li Technology-1	0.6	0.6	0.6	0.6						2.4
Li Technology-2	0.8	0.8	0.8	1.2	1.2	1.2				6
Tech Maturaration TRL(4 to 6)			1	1	1	1.5	1.5	1.5	1.5	9
Total Cost	1.4	1.4	2.4	2.8	2.2	2.7	1.5	1.5	1.5	17.4

5.1.4 High-Temperature Batteries

The team recommends completion of an ongoing system analysis to evaluate competing high-temperature rechargeable and primary battery technologies to determine their value in enabling high-performance future missions (surface and atmospheric) to Venus. If this study concludes that development of high-temperature batteries is needed, a detailed development roadmap should be developed for one or two of the most promising battery concepts, complete with milestones and eventual "down-selects" to a single high-temperature battery technology.

5.2 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 Space 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 AFRL 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, 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. It is estimated that the facility upgrade may cost about $4 M.

6.0 Abbreviations and Acronyms

AFRL – Air Force Research Laboratory
AM0 – Air Mass Zero (solar spectrum in space)
AM1.5 – Air Mass 1.5 (solar spectrum at the earth's surface)
AR - antireflection
ARPS – Advanced Radioisotope Power Source
ASO - Astronomical Search for Origins
AU – Astronomical Unit (distance from Earth to Sun is 1 AU)
BMDO - Ballistic Missile Defense Organization
BOL – Beginning of Life
C&DH – Command and Data Handling
CIS – Copper Indium Diselenide
CNOFS – Communication/Navigation Outage Forecasting System
CNSR - Comet Nucleus Sample Return
COI – Composite Optics Inc.
CVD – Chemical Vapor Deposition
DOD – Department of Defense
DUS&T – Dual Use Science and Technology
EDL - Entry, descent and landing
EOL – End of Life
ESS - Explore the solar system
EUV – Extreme Ultra Violet
GEO – Geosynchronous Earth Orbit
GRC – Glenn Research Center
GSFC – Goddard Space Flight Center
Isc – short circuit current
ITO – Indium tin oxide
JPL – Jet Propulsion Laboratory
LEO – Low Earth Orbit
LILT – Low Intensity Low Temperature
LMSC – Lockheed Missiles and Space Co.
MEP - Mars Exploration Program
MJ - Multi-junction
MSL - Mars Science Laboratory (MSL) mission
MSR - Mars Sample Return (MSR) mission
MOCVD – Metal Organic Chemical Vapor Deposition
NREL – National Renewable Energy Laboratory
OAI – Ohio Aerospace Institute
PDR – Preliminary Design Review
PMAD –Power Management and Distribution
PV- Photovoltaics

RPS – Radioisotope Power Source
RTG – Radioisotope Thermal Generator
SAVANT - Solar Array Verification and Analysis Tool
SEC – Sun Earth Connection
SEP – Solar Electric Propulsion
SEU - Structure and Evolution of the Universe
SOP - State of the art
SS - Stainless steel
TFC - Thin film cells
TRL – Technology Readiness Level
TRMM - Tropical Rainfall Measuring Mission
UV - Ultraviolet
Voc – Open Circuit Voltage
XTE – X-ray Timing Explorer

Appendix I - Infrastructure

Overview

Spacecraft power systems depend on the capability of the energy storage system to provide the power necessary to meet mission objectives. Batteries, fuel cells and capacitors have been the basic components of energy storage systems since the beginning of the space program. The ability to produce space-qualified hardware has been limited (and remains so) to a few contractors who maintain a continuing relationship with NASA Centers and aerospace contractors. This is a common situation for many highly reliable qualified components unique to NASA, DOD and commercial aerospace applications. Contractors are typically available only from a limited number of companies and then only at high cost. The NASA and Defense Community Labs (including the National Labs) support the leading edge of the U.S. capability for aerospace energy storage systems.

Relatively few companies, especially those in the high volume commercial business, get involved in the complexities involved in producing an aerospace quality product. There are four basic reasons for this:

a) The difficulty in assuring available sources of high quality chemicals and materials from acceptable manufacturers
b) The difficulty in maintaining equipment, standards and approved manufacturing processes required to reproduce the product
c) The high cost of oversight, and record-keeping and maintaining a quality control and reliability staff, and
d) The extensive testing required to verify a qualified product.

Therefore the availability of sources for space-qualified battery cells, fuel cells and capacitors is limited to a very few companies, often a single source. Even when a sole source is designated, there is competition with others in the procurement queue.

The Nickel–Cadmium Cell Story

The "legacy" aerospace Ni-Cd cell provides an example of the problems involved with maintaining a supply of an aerospace quality product. At the onset of the space program, multiple suppliers vied for the Ni-Cd cell business. Eventually, the General Electric (G.E.) - derived SAFT (France) technology proved superior and became a NASA standard design. G.E. (Gainesville, FL) was the commercial manufacturer that assembled commercial grade plates into aerospace cells in a controlled "aerospace" facility. The manufacturing process was defined in a NASA-controlled Manufacturing Control Document (MCD), which had taken a number of years to establish. The aerospace facility used extensive cell tests defined in the MCD to assure a high degree of reproducibility and reliability. Ultimately, the cells were defined as "NASA Standard Cells." The G.E./NASA (standard) cell design became the dominant aerospace cell design through the 1980s.

Cell performance and deliveries peaked in 1978. Because of the limited amount of business in aerospace cells, G.E. sold the cell operations to Gates Rubber Co. Gates attempted to streamline the process and reduce process waste. However, in 1983 their cell test results showed unusual behavior. This resulted in a decision by the separator manufacturer to terminate production of the product used for more than 20 years and to substitute it with a product that they thought would be an improvement. The changes made by the industry were discussed and documented in the 1986 Gates Problem Workshop. The only resolution was to produce additional test cells, forcing them essentially to requalify the product with the new separator. Gates eventually sold the Gainesville operation to SAFT, who discontinued the G.E./NASA (standard) cell design in favor of the one originally developed in France. This design is still produced today but has had limited acceptance because of implementation of superior Super Ni-Cd and Ni-H_2 cells since then.

Throughout the 1970s and 1980s, NASA sponsored numerous R&D programs to gain the knowledge of the intricacies of battery manufacturing technology. Many companies and research labs were involved in bringing the technology to a consistent high quality product. Among the organizations were Aerospace Corp., Air Force, JPL, NASA GRC and GSFC, Tyco Labs, G.E. Research, Hughes, Boeing, TRW, Yardney, Gulton Industries, and a number of small companies (usually through SBIR and IR&D programs).

NASA aerospace cells were assembled into batteries at NASA prime contractor facilities (e.g., McDonnell Douglas, TRW, G.E. Aerospace, Ball Aerospace, Boeing, etc.) for specific NASA contracted missions. Each battery design was tailored to a particular spacecraft design and therefore each battery design was unique for each mission. However, in the 1970s, NASA developed the idea of a Multi-Mission Modular Spacecraft (MMS) to include a Standard Modular Power Subsystem (MPS), and Standard Batteries and Cells. This approach also included a Standard Attitude Control Subsystem and Data Handling Subsystem. Standard Subsystems were manufactured by McDonnell-Douglas for a line of NASA spacecraft including the Solar Max and Landsat missions. These missions were very successful, lasting over 8 years in LEO at 20% depth of discharge (DOD) and exceeded 10 years in GEO at 70% DOD. However, each aerospace prime contractor continued to produce its own spacecraft design including battery hardware for their contracted programs. Thus, the successful NASA-sponsored McDonnell-Douglas standard hardware was used only by McDonnell-Douglas for their NASA and DoD missions.

Based on work at Hughes that removed one of the major Nickel/Cadmium degradation mechanisms, Hughes developed the "Super Nicad," and established the process to produce these cells at Eagle-Picher (E-P), Colorado Springs, CO. NASA and their defense counterparts worked with Hughes and E-P/Colorado Springs, to verify the performance and qualify the Super Nicads for missions. JPL had found the Super Nicads especially robust with respect to radiation tolerance. This was a lengthy process, even though aerospace Ni-Cds were state of art. The "Super Ni-Cd" has been quite successful in NASA LEO missions since 1992 when SAMPEX was launched. They have also been successful in commercial GEO missions operating at 70% DOD.

In another disappointing move, E-P made the decision to close the Colorado Springs plant in January 2002. This was unfortunate for "legacy" space programs faced with cost and schedule impacts that exceeded the $2M/year needed to keep the plant in operation. The defense programs found the means to keep the plant in operation for another year making Super Ni-Cds and aircraft cells while potential buyers negotiated with E-P. This switch produced a number of quality problems that led to situations where at least 5 major space programs would have switched to Super Nicads had there been no availability problems. To date, a number of Super Ni-Cds have been made for flight programs and have been successful. However, despite their advantages only a few thousand Super Nicads have been made for flight programs. There was also an attempt to develop an improved NASA/(standard) design at E-P/Joplin. In summary, despite having a flight-qualified product, changes in economics, corporate positions and funding led to considerable shuffling to find an alternate source of space cells. Subsequently, these improvements to Super Nicads were overtaken by other events.

The Nickel-Hydrogen Cell Story

The Ni-H_2 cell promised a 50% weight reduction and much greater cycle and calendar life than the Ni-Cd cell. It could deliver 50 Wh/kg (nameplate) and support 5-10 year LEO @ 40% DOD and 15-20 year GEO @ 70 % DOD. As with Ni-Cd, at first there were many competitive manufacturers and competing designs. The AFRL team at Wright-Patterson AFB, working with Hughes, developed the "pineapple slice" design, later referred to as the MANTECH design. This design came from the DOD program to have Hughes transfer the technology to suppliers including E-P, Gates, and Yardney Technical Products (YTP), Pawcatuck, CT. SAFT did their own design, but export controls precluded their being involved in a scale-up of the USAF design It soon became clear that the MANTECH design was superior, and that E-P was becoming the dominant producer. Verification testing was a major program at Martin/Denver. First results were mixed, but improved. A joint NASA/USAF LEO Life Test at NWSC/Crane verified that the E-P battery was clearly superior. YTP's Ni-H_2 plant went into mothballs. NASA/GRC made major contributions to the technologies of electrolyte concentration, wall-wicks, and standardization of manufacturing processes. Problems with the baseline Ni-Cd eased the difficulties in infusing Ni-H_2 technology. The Ni-H_2 cell was better in most ways, but a few of its characteristics (self-discharge, internal impedance, round-trip efficiency, radiation resistance) remained inferior to Ni-Cd. This left a niche for Super Ni-Cd batteries.

After the 1/28/1986 Challenger disaster, a joint-services team dedicated itself to applying Ni-H_2 technology to the Hubble Space Telescope, roughly paralleling defense community efforts for other programs. Co-operation and collaboration were superb, and a "win-win" resulted. Testing at MSFC was a major factor in this success and provided the data to convince NASA top management to make the change from Ni-Cd. The original 5 batteries manufactured in 1990 are still supporting the mission. The impact of this government-wide acceptance was huge, easily amortizing the investment made in NASA Labs before and since. Obviating the need for 4 or 5 maintenance and replacement flights had impacts in the $B. Ni-$H_2$ technology also made (and continues to make) a major contribution to national defense. The Ni-H_2 business in the U.S. peaked at something like 6,000 cells/year, (or $90 M/year) normalized to 50 Ah, with HST, ISS, and Defense programs accounting for the bulk of this. The 1990's were the Ni-H_2 decade, with most flight systems baselining this echnology. However, the promise of commercial communications relays (LEO, GEO, and MAO) led to an overcapacity situation with Ni-H_2. Realizing this, programs moved procurements forward to preclude availability problems.

The Lithium-Ion Cell Story

In 1991, SONY introduced the Li-Ion cell for camcorders and personal communications. As with Li-CFx and Li-MnO_2, work had begun in the U.S. much earlier (ARL/Ft. Monmouth began work on CFx in 1968 and George Methlie has a 1968 patent including Li-MnO_2) but it wasn't possible to move forward due to U.S. management resistance to investment in new technology. Dr. Jim Auborn, during USN summer duty at Bell Labs., also proposed Li-Ion technology far ahead of commercialization in Japan. Soon after introduction, it became clear that Li-Ion technology was "the wave of the future" for most, if not all rechargeable energy storage applications. Dr. Rao Surumpudi/JPL was one of the first to recognize this, and has been a leader in implementing this technology. 1991 SONY (HC) Li-Ion cells were tested and their advantages and disadvantages were quickly determined. The NASA goal was to evaluate a cell capable of supporting 5 year LEO @ 40% DOD and 15 year GEO @ 70% DOD. E-P and YTP were envisioned as suppliers. From the outset, there were major differences in approach: cobalt vs. nickel/cobalt cathodes; small cells vs. large cells; cylindrical vs. prismatic cells; and cell level vs. module level charge control.

Nine years later, the same questions prevail. All have made real progress, to the point that it looks like most of the permutations and combinations may have use for various missions. The downside of this is that the U.S. market of ~ 6000 50-Ah Ni-H_2 cells/year will gradually be replaced by 2000 Li-Ion cells/year. These Li-Ion cells are inherently less expensive, so a \$90M/year market will become a \$6-15M/year market. That will be split 4-6 ways if the current developers remain viable. Introduction of a second generation will lead to further fractionation. There just isn't enough revenue per year to support even 1-2 suppliers worldwide for Li-Ion aerospace cells. Li-Ion technology also requires much deeper technical expertise than did Ni-H_2 and Ni-Cd. Our traditional suppliers do not have the R&D depth to do this on their own. None of them will become naturally predominant as E-P did in Ni-H_2 technology. Without more R&D support from the NASA and U.S. Government labs, they will fall farther behind the Japanese and the French, whose governments continue to heavily subsidize their programs. Recent projections are that only 1-2 primes worldwide will survive the present over-capacity situation driven by scaling up for a huge commercial satellite business that never materialized. Although the time has passed to create a first generation LEO life test program, NASA and Defense Community collaborators have yet to procure the resources to do so.

Summary

Each battery technology has a 15-20 year product cycle; new technology insertions occur about every 22 years. The energy stored on the largest LEO and GEO missions doubles about every 5.5 years, but 2002 levels were already around 15-KWh, far larger than Code S programs require. Code S-specific requirements for Li-Ion technology are typically far more stringent than those for other space missions, including high radiation, high and low temperatures, and perhaps higher shock resistance and reactive chemical environments.

Lessons-learned during the past 35 years can guide us toward what works:

a) Government or government-sponsored R&D leading to robust and well-documented designs;

b) Thorough verification and qualification testing keyed to MCDs;
c) Technology transfers to manufacturers or manufacturing in U.S. Government Labs;
d) Oversight by the system primes and the U.S. Government sponsor's technical personnel.

To do as well for the next 10-20 years of Code S missions will need:

a) Succession planning and "mentoring" of the next generation of experts in the NASA Centers;
b) A healthy infrastructure and physical plant in the Centers;
c) A healthy infrastructure in one or two suppliers;
d) Stable testing capability at GRC, JPL, NWSC/Crane and other Centers;
e) Resources at the prime contractors to apply the new technology to Code S missions;
f) Resources at NASA Centers for safety and abuse testing and launch support;
g) Support enough Super Nicad production to buy down risk.

Appendix I - Infrastructure

Appendix II - Fuel Cell Analysis

Introduction

In this section, a hypothetical fuel cell system on a space science spacecraft is analyzed, and the performance characteristics are estimated as a function of several key parameters. The purpose is to determine if, within certain applications, fuel cells could compete effectively with batteries on space science missions. Both primary and rechargeable (regenerative) fuel cell systems are considered.

We consider a system to be composed of a PEM fuel cell stack, plus high-pressure hydrogen and oxygen storage tanks. In the case of regenerative fuel cells, a water storage tank and an electrolyzer are also included. It is assumed here that the fuel cell stack itself acts as the electrolyzer, but this assumption is not critical. Other ancillary flow elements (such as pumps, filters, separators, etc.), are not included. However, the masses of these elements are expected to be negligible for systems with moderately long discharge times, that are dominated by fuel and tankage mass. These are the only conditions for which fuel cells are likely to compete. The main object is to understand how the energy stored (and power delivered) per unit mass (or volume) varies with discharge time. The main feature that makes fuel cells attractive is their potentially high stored energy content per unit mass. Another highly relevant parameter is the power that can be drawn from the fuel cell per unit mass. Needless to say, the power, times the discharge time, is the recoverable stored energy.

Overview of the Calculation

The sequence of calculations is given below.

We start by assuming a fixed amount of H_2 and O_2 mixture, kg, to be stored (in an assumed stoichiometric ratio of 2H2-O2). We also, assume a fixed pressure of 3000 psi for both H_2 and O_2 in their storage tanks.

The masses of the H_2 and O_2 storage tanks can be determined quite readily from existing pressure vessel design data with known amounts of H_2, and O_2, temperature, and properties of the advanced tank materials. The corresponding volumes of these tanks are determined from the same design data.

The mass of the stack is determined by the following sequence of computations:

a) Compute total energy stored, kWh. Total energy stored: kWh = wt of reactants (kg) times energy content of reactants (3661 Wh/kg) times conversion efficiency (note: the value 3661 wH/kg is the normalized theoretical energy of a stoichiometric mixture of H_2 and O_2).
b) Compute average power, P (watts) as a function of discharge time in hours (h). Average power P = total energy [Wh,/discharge time (h)].
c) Compute average current, I (amps) for each discharge time. Average current I = [Average power (W)/Voltage (V)]. The voltage, V is taken as the assumed constant operating voltage.

d) Compute the required area of the stack, A, (cm^2) for each discharge time. Required area, A = [Average current/ operating current density, (mA/cm^2)]. (note: the operating current density is specified for the PEM stack)
e) Compute the required mass of stack (kg) for each discharge time. Mass of stack = Required area, A, times weight of stack per unit area. (note: the weight of stack per unit area is the characteristic number known for the PEM type stack.)
f) Compute the required volume of the stack, L (m^3) for each discharge time. The required volume = required mass (kg)/ density of the stack (kg/L). (note: the density of the stack is again a characteristic number known for the PEM type stack.)
g) Compute the total system mass for each discharge time. Total system mass = mass of tanks + mass of stack.
h) Compute the total system volume for each discharge time. Total system volume = volume of tanks + volume of stack.
i) Compute overall system specific energy and specific power for each discharge time. The specific energy = total energy/total system mass and specific power = system power/total system mass.
j) Compute overall system energy and power densities and for each discharge time. The energy density = total energy/ total system volume and power density = system power/total system volume.

Parametric Computations

Incremental operating times are selected in the range of 0.1 to 100 hours. The following parameters are then computed for each time and for the assumed tank pressures of 3000 psi:

- Overall system specific energy
- Overall system specific power
- Overall system energy density
- Overall system power density

The complete set of computations is then repeated for assumed tank pressures of 5,000 and 10,000 psi.

Tank and Fuel Mass and Volume

The following analysis is a modification of the analysis provided by Ken Burke of NASA-GRC. First, a primary system is modeled. Then, a rechargeable system is modeled. The only differences between the two are that in a rechargeable system, the round-trip efficiency is lower, and the mass of a water storage tank must be included.

We consider a system of two tanks, one containing hydrogen at high pressure, and the other containing oxygen at high pressure. The amounts of each gas are in stoichiometric proportion. Since the reaction is

$$2H_2 + O_2 \Rightarrow 2H_2O$$

there will be 8 kg of oxygen for every kg of hydrogen. Since the volume of each tank is proportional to the number of moles stored, the volume of the hydrogen tank will be twice that of the oxygen tank if both gases are stored at the same pressure (assuming ideal gases).
Let the total mass of fuel (oxygen plus hydrogen) be m_f (kg). This implies that there are (8/9) m_f kg of oxygen and (1/9) m_f kg of oxygen.

The power density of the primary fuel cell system is
Power density = (Power generated)/(stack mass + tankage mass + fuel mass)
$D_{pp} = P/\{M_{st} + M_{Tk} + m_f\}$
By definition we set the fuel mass = m_f kg.

The data in Table A2-1 were provided by Joe Lewis of JPL. The ultra-light tank technology utilized in the table is already at TRL 4 and has a good chance of being advanced to TRL 6 over the next several years. By the time that fuel cells would be employed on spacecraft, ultra-light tank technology should be available. We will therefore estimate the tank masses from the simple rules:

Tank Mass/Gas Mass (hydrogen) = 5
Tank Mass/Gas Mass (oxygen) = 0.5

Tank volumes will depend on pressure. For purposes of estimating the specific energy and specific power, we will estimate the tank volumes based on a pressure of 5000 psi. For estimating the volumetric energy density and power density, we will treat the pressure as a parameter to estimate the tank volumes.

Table A2-1. Effect of Storage Pressure at 20°C (293°K) on Composite Tank Mass for GH_2 and GO_2

Gas and Quantity	Volume (liters)	Storage Pressure (psia)	Tank Diameter and Length (in)	Ultra-light Tanks		Chandra-Type Tanks	
				Tank Mass (kg) (Note 2)	Tank Mass/ Gas Mass (Note 4)	Tank Mass (kg) (Note 3)	Tank Mass/ Gas Mass (Note 4)
GH_2 (0.0625 kg)	4.13	3,000	7.4	0.31	4.96	0.52	8.32
	2.67	5,000	6.4	0.32	5.12	0.46	7.36
	1.59	10,000	5.4	0.41	6.56	0.40	6.40
GO_2 (0.5 kg)	1.73	3,000	5.5	0.24	0.48	0.62	1.24
	1.12	5,000	4.8	0.22	0.44	0.50	1.00
	0.74	10,000	4.2	0.27	0.54	0.44	0.88

Notes:
1. Composite tanks consist of a metallic liner overwrapped with composite. Liner is 6061-T62 aluminum alloy for GH_2 and annealed Inconel 625 nickel alloy for GO_2. Composite-skirt mounting was assumed for all tanks in this study. All tanks assume a single 0.250 inch-inch diameter outlet boss.
2. Ultra-light tanks have a 0.005-inch minimum thickness line and are based on JPL-developed technology.
3. Chandra-type tanks have a 0.030-inch minimum thickness liner.
4. Tank mass efficiency will increase with increasing tank size.

$m_H = (m_f/9)$ kg = mass of hydrogen gas
$n_H = (m_f/18)$ kg-moles of H_2
$m_O = (8\ m_f/9)$ kg = mass of oxygen gas
$n_O = (m_f/36)$ kg-moles of O_2
$M_H = 5\ (m_H) = (5/9)\ (m_f)$ = mass of hydrogen tank
$M_O = 0.5\ (m_O) = (4/9)\ (m_f)$ = mass of oxygen tank
$M_{Tk} = (m_f)$ = total mass of both tanks
\

Stack Mass

The energy contained in the fuel is

$E = (3661)\,(m_f)\,(W\text{-}h)$

The power generated by the stack (W) is:

$P = (3661)\,(m_f)\,(e_p)/t\ (W)$

where t is the discharge time in hours, and (e_p) is the conversion efficiency of a primary fuel cell.

The stack mass is estimated as follows:

A_m = active area/kg of stack

$(V_d)\,(I_d)$ = power generated (W) per unit active area of stack

$(V_d)\,(I_d)\,(A_m)$ = power generated per kg of stack (W/kg)

If the power generated is divided by the power per kg of stack, we obtain the stack mass as

$M_{st} = \{(3661)\,(m_f)\,(e_p)/t\}/\{(V_d)\,(I_d)\,(A_m)\} = \{(3661)\,(m_f)\,(e_p)\}/\{t\,(V_d)\,(I_d)\,(A_m)\}$

Power Density and Energy Density for Primary Fuel Cells

$D_{pp} = P/\{M_{st} + M_{Tk} + m_f\}$ (W/kg)

$D_{pp} = \{(3661)\,(m_f)\,(e_p)/t\}/\{[(3661)\,(m_f)\,(e_p)]/[t\,(V_d)\,(I_d)\,(A_m)] + [m_f] + [m_f]\}$

$D_{pp} = 1/\{[(V_d)\,(I_d)\,(A_m)]^{-1} + [5.46\text{x}10^{-4}\,(t)/(e_p)]\}$

The energy density is just

$D_{pe} = (t)\,(D_p)$ (W-hr/kg)

$D_{pe} = 1/\{[(t)\,(V_d)\,(I_d)\,(A_m)]^{-1} + [5.46\text{x}10^{-4}\,/(e_p)]\}$

Power Density and Energy Density for Rechargeable Fuel Cells

To convert from primary to rechargeable fuel cells, we replace e_p by e_s and we add the mass of the water tank to the total mass. The power density of a rechargeable fuel cell is

$D_{sp} = P/\{M_{st} + M_{Tk} + m_f + M_w\}$ (W/kg)

where M_w is the mass of the water tank. When all of the hydrogen and oxygen is converted to water, the mass of water is m_f (kg). This tank has a volume of m_f (liters), assuming a density d_w = 1 kg/liter under pressure. We will assume that the mass of the water tank is the same as that of the mass of a hypothetical gas tank with the same volume. According to Table 1, the mass of an oxygen tank of volume 1.12 liters at 5000 psi is 0.44 x 0.5 = 0.22 kg. A water tank of volume 0.5625 (liters) therefore has an estimated mass of 0.11 kg. Thus to this approximation, the water tank mass is about half of the oxygen tank mass. But:

$M_O = 0.5\,(m_O) = (4/9)\,(m_f)$

so that

$M_w = (2/9)\,(m_f)$

The power and energy densities for rechargeable fuel cells are then:

$D_{sp} = 1/\{[(V_d)\,(I_d)\,(A_m)]^{-1} + [6.67\text{x}10^{-4}\,(t)/(e_p)]\}$

$D_{se} = 1/\{[(t)\,(V_d)\,(I_d)\,(A_m)]^{-1} + [6.67\text{x}10^{-4}\,/(e_p)]\}$

Volumetric Densities

The volumes of tanks are given in Table 1 for one specific value of m_f, namely $m_f = 0.5625$ kg. For any arbitrary value of (m_f) the scaled values of the tank volumes are

$V_H = (m_f/0.5625)$ x (v_h = hydrogen volume in the table in liters)
$V_O = (m_f/0.5625)$ x (v_o = oxygen volume in the table in liters)
$V_w = (2/9)(m_f)$

The total volume of tankage is

$V_{tk} = (m_f/0.5625)\{v_h + v_o + 0.125\}$

The volume of the stack is found from

A_v = active area/liter of stack
$(V_d)(I_d)$ = power generated (W) per unit active area of stack
$(V_d)(I_d)(A_v)$ = power generated per liter of stack (W/liter)

If the power generated is divided by the power per liter of stack, we obtain the stack volume as

$V_{st} = \{(3661)(m_f)(e_p)/t\}/\{(V_d)(I_d)(A_v)\} = \{(3661)(m_f)(e_p)\}/\{t(V_d)(I_d)(A_v)\}$

For a primary fuel cell the energy and power densities on a volumetric basis are then estimated as:

$C_{pp} = P/\{V_{tk} + V_{st}\}$
$C_{pp} = 1/\{[4.86x10^{-4}(v_h + v_o)(t)/(e_p)] + [(V_d)(I_d)(A_v)]^{-1}\}$
$C_{pe} = 1/\{[4.86x10^{-4}(v_h + v_o)/(e_p)] + [(t)(V_d)(I_d)(A_v)]^{-1}\}$

For a rechargeable fuel cell, we need to add in the volume of the water tank.

$C_{sp} = P/\{V_{tk} + V_{st} + V_w\}$

Therefore

$C_{sp} = 1/\{[4.86x10^{-4}(v_h + v_o + 0.125)(t)/(e_p)] + [(V_d)(I_d)(A_v)]^{-1}\}$
$C_{se} = 1/\{[4.86x10^{-4}(v_h + v_o + 0.125)/(e_p)] + [(t)(V_d)(I_d)(A_v)]^{-1}\}$

In the equations for C_{ij}, or D_{ij} the first index I is p for primary and s for rechargeable, and the second index is p for power density and e for energy density. The primary term C or D refers to volumetric or mass density.

Nominal Parameters

$e_p = 0.5$ for primary
$e_s = 0.44$ for rechargeable
$V_d = 0.75$ volt
$I_d = 1000$ ma/cm^2
$A_m = 1540$ cm^2/kg
$A_v = 715$ cm^2/liter

T = 300 K (<u>note</u>: for rechargeable fuel cells, where the system can be launched with the water tank full and the gas tanks empty, we can operate well below 300 K in space and therefore utilize smaller gas tanks. For a primary fuel cell, the system must be launched with the gas tanks full, and therefore we are pretty much restricted to ~ 300 K for primary systems. We will use T = 300 K for both primary and secondary systems)

Results

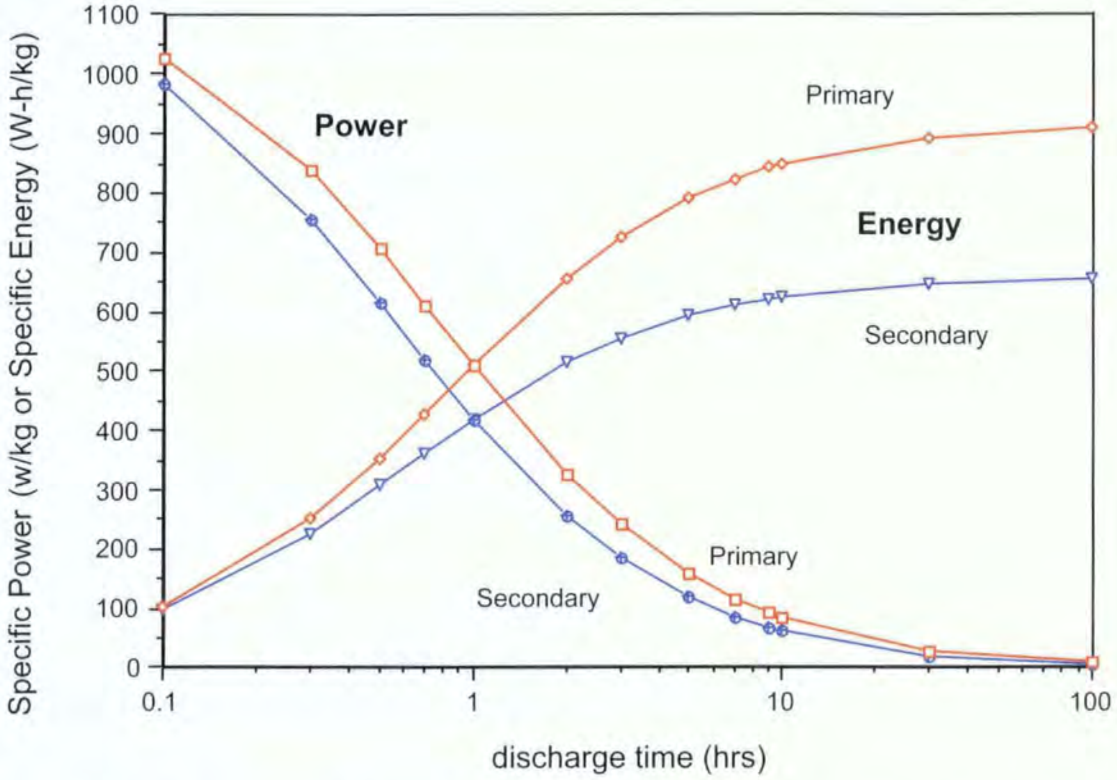


Figure A2-1. Comparison of primary and rechargeable storage for nominal conditions (300 K, 5000 psi)

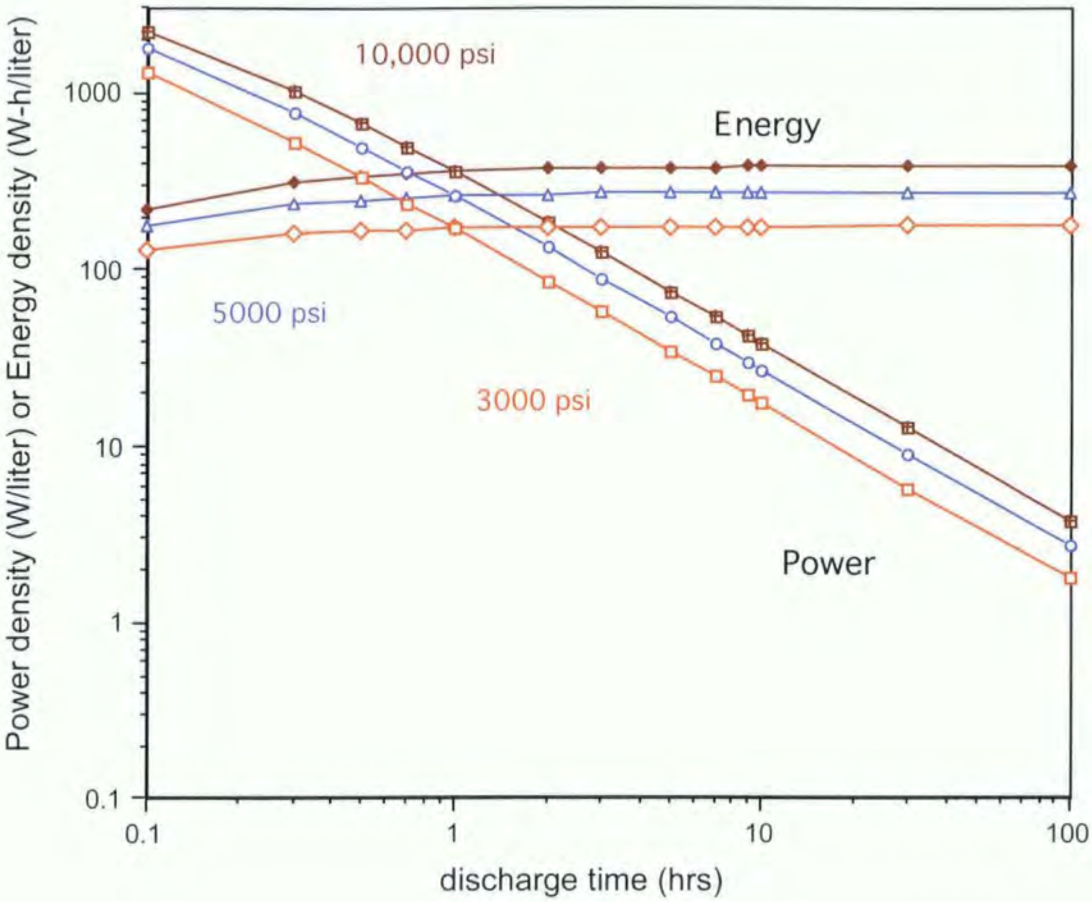


Figure A2-2. Volumetric densities for primary fuel cells at 300 K

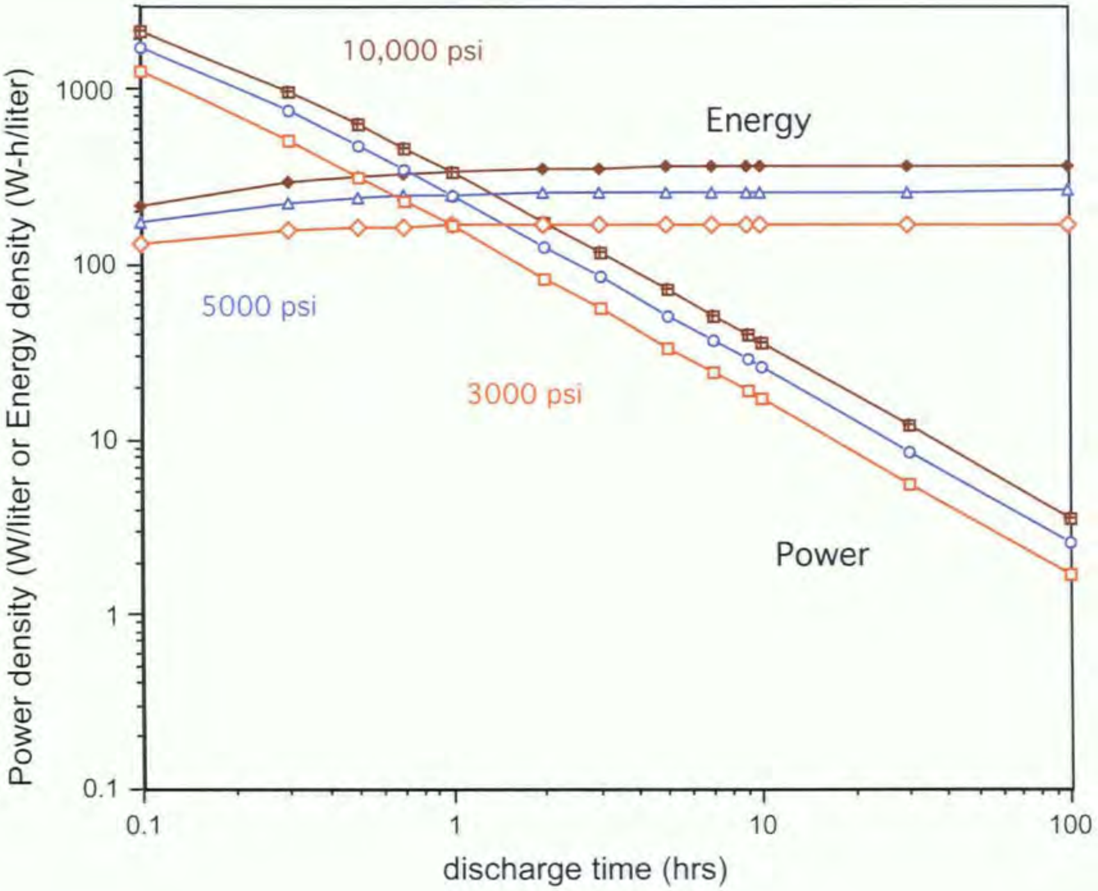


Figure A2-3. Volumetric densities for rechargeable fuel cells at 300 K

Appendix III - Flywheel Analysis

Flywheels for orbiting spacecraft could be implemented in two alternative modes:

Fixed-Axis Energy-Only System

- Flywheels arranged in counter-rotating pairs to achieve energy storage with net zero momentum for use as an Energy Storage System.

Fixed-Axis Energy/Momentum System

- Flywheels replace reaction wheels and batteries.
- Minimum of four flywheels required to achieve energy/momentum storage for use as a combined Energy Storage System/Attitude Control System.

The combined Energy Storage System/Attitude Control System provides the greatest benefits and is the principal thrust of current technology efforts.

The predicted performance of future flywheels depends upon the assumed value for the specific energy of the future flywheel system. Based on the observation that an estimated specific energy of ~ 25-30 Wh/kg has already been achieved with a rather crude rotor, flywheel, technologists have projected mid-term achievable specific energies ranging from 44 to 70 Wh/kg using composite rotors and other mass-saving innovations.

The most advantageous way to employ flywheels on spacecraft is to use an integrated set of wheels to provide both energy storage and momentum for the attitude control system (ACS). The predicted benefits of the combined system are much greater than for an energy-only flywheel system. The reason for this is that conventional attitude control systems (ACS) utilize rather heavy, slow rotors that are far less efficient than the rotors used in combined flywheel systems. When the predicted mass of the combined flywheel system is compared to the sum of masses of conventional energy storage systems and ACS for a LEO mission, the combined flywheel system looks very attractive. Presumably, flywheels would not be put into service for another ten years. Therefore, the comparison should be among batteries that are likely to be available in ten years. In the present report, the comparison of flywheels with batteries includes a comparison with Li-Ion batteries (both the current capability and that projected for ten years hence), and the results are shown in Table A3-1. While Li-Ion batteries have not yet demonstrated the cycle life needed for LEO applications, it is presumed that cycle life of Li-Ion batteries will be demonstrated by the time that flywheels are put into service.

Table A3-1. Comparison of Energy-Only Flywheel with Battery for LEO (5 kW 100 min orbit, 35 min eclipse)

	Current Values			Post-2013	
Parameter	NiH_2	Li ion	Flywheels (6)	Li-Ion	Flywheels
energy density	35	35	44	150	70
orbit time	100	100	100	100	100
eclipse time	35	35	35	35	35
DOD	0.35	0.35	0.89	0.35	0.89
RT efficiency	0.8	0.8	0.95	0.93	0.95
charge/discharge efficiency	0.9	0.9	0.95	0.9	0.95
delivered energy	2900	2900	2900	2900	2900
stored energy	9206	9206	3430	9206	3430
required energy	4475	4475	3382	3850	3382
spacecraft power	5524	5524	5233	5524	5233
battery replenish	4131	4131	3122	3554	3122
% energy before taper		70	N/A	70	N/A
% insolation time before taper		55	N/A	55	N/A
P1		4674		4523	
P2		223		215	
Total Array Power	9655	9655	8355	10047	8355
storage mass (1)	263.0	263.0	78.0	61.4	49.0
electronics mass (2)	27.6	27.6	included	27.6	included
Subtotal	290.7	119.7	78.0	89.0	49.0
array mass (4)	50.8	50.8	44.0	52.9	44.0
Subtotal	341.5	173.4	122.0	141.9	93.0
attitude control sys mass (3	47.4	47.4	N/A	47.4	N/A
Total System Mass	388.9	388.9	122.0	189.3	93.0
array power density (5)	190				
battery electronics density	200				

(1) stored energy/energy density
(2) bi-directional converter
(3) using Honeywell design momentum wheel
(4) array power/array power density
(5) 3-junction GaAs Ultraflex arrays
(6) 1 kW-hr class flywheel module (projected based on paper studies)

The data in Table A3-1 were assembled by means of the following steps:

(1) The delivered energy is the amount of energy that must be delivered to the spacecraft from the battery or flywheel per discharge cycle. This is set by the mission, and for our purposes is assumed to be 2.9 kWh for LEO.

(2) RT efficiency is the (round-trip) efficiency inherent to the energy storage device and refers to the power that can be retrieved at the output terminals per unit power at the input terminals of the storage device. It is assumed that this is 80% for Ni-H_2 batteries, 90% for Li-Ion batteries and 95% for flywheels.

(3) Charge/discharge efficiency refers to the losses in the cabling and power management system between the energy storage device and the power source (usually a PV array) or the spacecraft. It refers to the power that can be delivered to the input terminals of the storage device per unit power generated at the array, or the power that can be delivered to the spacecraft from unit power at the output terminals of the storage device. These two efficiencies are assumed to be equal. For batteries, these efficiencies are taken as 90%, and for flywheels, 95%.

(4) DOD = depth of discharge = percentage of stored energy that can be withdrawn from storage device in a discharge cycle. This is assumed to be 35% for batteries in LEO, and 89% for flywheels.

(5) The stored energy is the amount of energy that must be stored in the storage device at the onset of the discharge cycle in order to provide the delivered energy during eclipse.
stored energy = (delivered energy)/(DOD x discharge efficiency)

(6) The required energy is the amount of energy that must be supplied by the array to replenish energy storage for each discharge cycle.

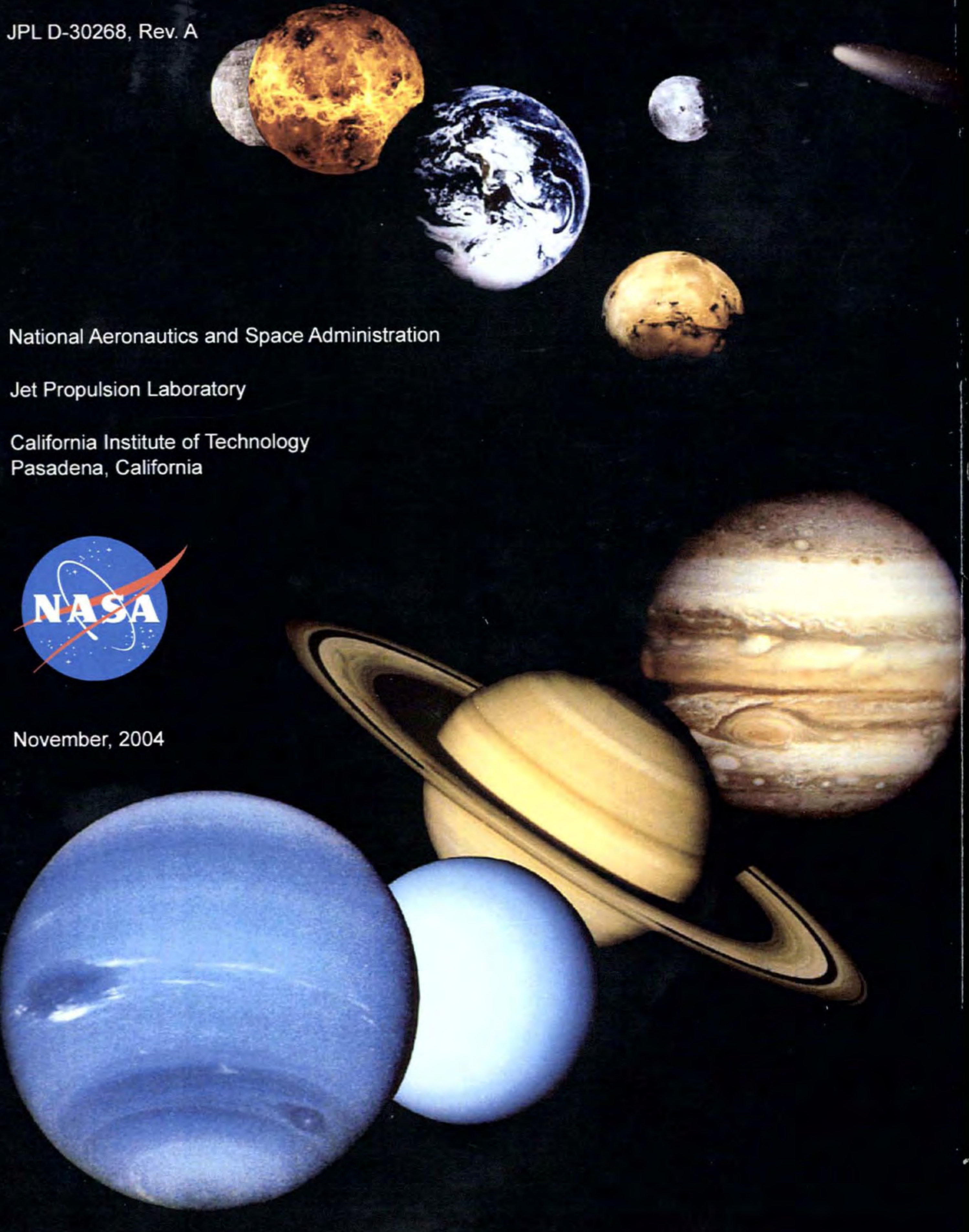
required energy = delivered energy/{(charge efficiency)(discharge efficiency)(RT efficiency)}
(7) % energy before taper and % insolation time before taper are inputs that set the taper charge regimen for batteries. The taper charge is required by the batteries because the electrochemical conversion is less efficient as battery reaches full charge.
(8) P1 and P2 are the calculated powers from the array to accommodate taper charge of the batteries. Taper charging is not required for flywheels.
(9) Array power is calculated as follows:
spacecraft power = delivered energy/{(charge efficiency)(eclipse time)}
battery replenishment power = required energy/(orbit time - eclipse time)
Total Array power = spacecraft power + battery replenishment power ; for flywheels
= spacecraft power + P1 ; for batteries to allow for taper charge
(10) The storage mass is
storage mass = stored energy/(nominal storage specific energy)
(11) Battery Electronics Mass = spacecraft power/battery electronics density ; electronics for flywheels is included in the storage energy density estimate
(12) Attitude Control System Mass is an estimate for a medium sized spacecraft using masses for a Honeywell design momentum wheel (Model HM 4520)
(13) Array Mass = total array power/array power density
(14) Total System Mass is the sum of array mass plus battery or flywheel mass plus attitude control system mass (for batteries) plus electronics mass. This gives the true, “complete system” mass comparison.

The current measured specific energies are 35 Wh/kg for Ni-H_2, and 100 Wh/kg for Li-Ion batteries. Since Ni-H_2 batteries are a mature technology, it is unlikely that this specific energy will change in the future. The specific energy of Li-Ion batteries ten years hence is estimated to be 150 Wh/kg. Since no representative end-to-end flywheel systems have been built and tested, the specific energy for flywheels can only be roughly estimated. Flywheel technologists believe that if a representative end-to-end flywheel system were built today (including the entire system with control electronics), it would achieve a specific energy of about 44 W/kg. Similarly, they estimate that if a representative end-to-end flywheel system were built ten years from now, its specific energy is likely to increase to the range 70-75 Wh/kg.

These calculations predict that if a representative end-to-end flywheel system can achieve the performance figures given in Table A3-1, such a flywheel system would have a huge advantage over current SOP NiH_2 batteries, and a significant advantage over current SOP Li-Ion batteries in LEO. Even if the specific energy of Li-Ion batteries ten years from now rises to 150 Wh/kg, flywheels would still outperform these advanced Li-Ion batteries.

Appendix III - Flywheel Analysis

JPL D-30268, Rev. A



National Aeronautics and Space Administration

Jet Propulsion Laboratory

California Institute of Technology
Pasadena, California

November, 2004