Overview of Energy Storage Technologies for Space Applications

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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 over a range of mission scenarios, thermal environments, radiation fields, size /foot print, and 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 Table1. This paper gives an overview of the energy storage technologies that are being used in space applications.

Table 1 : A Chronological List of the 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

Primary Batteries

Primary batteries are electrochemical devices that convert chemical energy into electrical energy. Primary batteries are intended for single-use or "one shot" applications. Primary batteries have been used in sounding rockets, launch vehicles, planetary probes (Galileo, Cassini, Deep Impact) sample return capsules (Stardust, Genesis), Mars Landers (MER), and Mars Rovers (Sojourner). 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 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. Important characteristics of state-of-practice (SOP) primary batteries used in space science and other missions are provided in Table 2.

Table 2: State of Practice of Primary Batteries

Type	Cell Parameters and Battery Parameters by Mission Application	Nominal Voltage	Specific Energy, Wh/kg	Energy Density, Wh/l	Specific Power, W/kg	Operating Temp. Range, °C	Capacity Loss % Per Year	Mission Life (yrs)
Ag-Zn	Cell	1.61	200	550	1100	0 to +55	60	1
	Typical Launch Vehicle	28	119	280	120	5 to +40	60	1
Li-SO_2	Cell	2.9	238	375	680	-40 to +70	<1	
	Galileo Probe Battery	38	91	145	260	-15 to +60	<1	9
	Genesis Battery	24	142	125	400	-20 to +30	<1	6
	MER	30	136	**390**	390	0 to +60	<1	4
	Stardust	20	192	182	519	-26 to +50	<1	10
Li-$SOCl_2$	Cell	3.2	390	875	140	-30 to- 60	<2.5	
	Sojourner	9	245	515	100	-20 to 30	<2.5	4
	Deep Impact	33	221	380	105	-20 to +30	<2.5	4
	DS-2	14	128	340	65	-80 to +30	<2.5	4
	Centaur Launch batteries	30	200	515	85	-20 to +30	<2.5	6
Li- BCX	Cell	3.4	414	930	150	-40 to +70	<2	
	Astronaut Equipment	6	185	210	115	-40 to +72	<2	3
Li-CF_x	Cell	2.6	614	1050	15	-20 to 60	<1	
	Range Safety battery	39	167	150	15	-20 to 60	<1	

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.

Rechargeable Batteries

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 for load leveling and for providing electrical power during eclipse periods. 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 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

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. Important characteristics of SOP rechargeable batteries used in space science and other missions are provided in Table 3.

Silver-Zinc Batteries: Silver-zinc batteries have been used been used in space missions that require limited cycle life. Ag-Zn batteries 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. The major limitations of this battery are limited shelf life, limited operating temperature range and orientation sensitivity. Ag-Zn batteries are available from Yardney Technical Products, Eagle Picher Industries & BST Systems Inc.

Table 3. 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 to 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 to10	3		LMAC
	MGS	2/16	20/23	20	35	25	5 to 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 to 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

Ni-Cd Batteries: Ni-Cd batteries were the workhorses for space missions from the 1960s through the early 1990's. 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). Some of the important characteristics of SOP Ni-Cd batteries are given in Table 2.3-1. 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. Space Ni-Cd batteries are available in two versions: a) NASA standard Ni-Cd and b) super Ni-Cd. Ni-Cd batteries have demonstrated very long cycle life capability and reliability. These batteries have the capability to provide > 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 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.

Ni-H_2 batteries: 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 (Leo and GEO). 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. There are three versions of Ni-H_2 cells presently in use: a) Individual Pressure Vessel (IPV), containing one cell per pressure vessel, b) Common Pressure vessel (CPV), possessing two cells per pressure vessel, and c) Single Pressure Vessel (SPV), with 22 cells per pressure vessel (comprising a full battery in one pressure vessel). 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.

Li-Ion Batteries: 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-H_2 batteries. 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 the Beagle-2. 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. However, the limitations of SOP Li-Ion batteries are limited cycle life and safety under inadvertent abuse conditions. Nevertheless, the Li-Ion system has potential for further improvement in these characteristics.

Capacitors

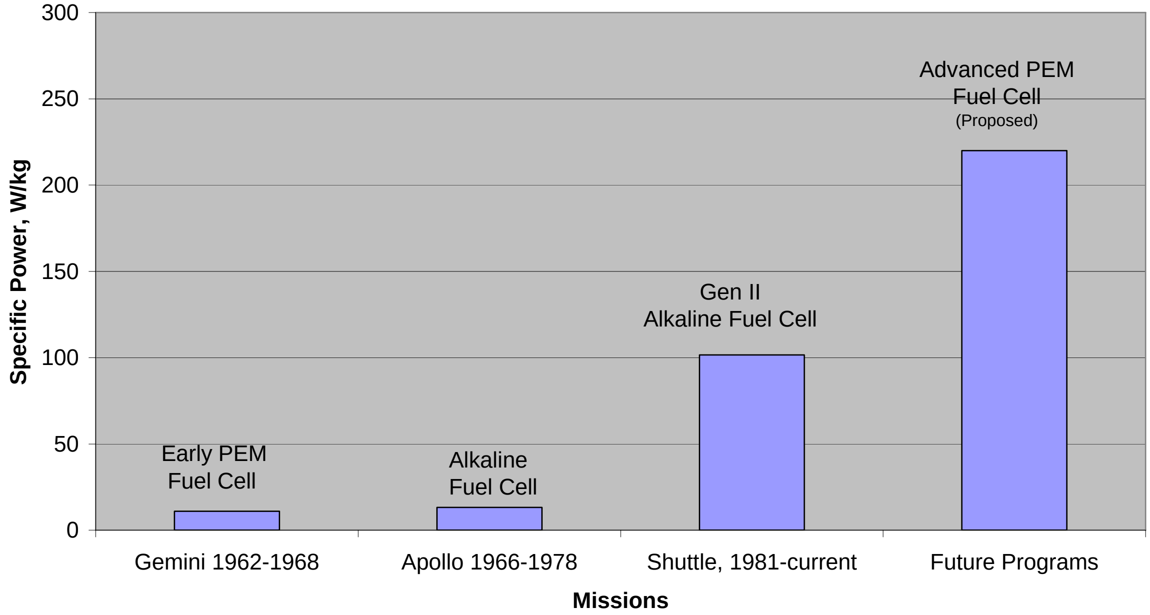
Capacitors are typically used on spacecraft as filtering elements for power management and distribution. However, on two occasions, capacitors have been used to store energy and supply short pulses of high power (Galileo and Cassini). The most important advantage of capacitors is the capability to supply high current 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 needs for further development of capacitors.

Fuel Cells

Fuel cells are particularly attractive for human space missions (such as for crew exploration vehicles, reusable launch vehicles or human lunar precursor missions that require multi-kilowatts of power for extended periods of up to 10 days. Conventional batteries are not suitable for such applications, due to much lower specific energy and scalability issues.

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^{o} C, and g) Regenerative Fuel Cells $80\text{-}175^{o}$ C

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 1). However, because of the low power density and relative low efficiency of the early PEM fuel cells, they were replaced with the alkaline fuel cells developed by United Technology Co (UTC) in the Apollo and Space Shuttle Programs. Since 1982, these AFC’s have performed very well in meeting the power needs for the Shuttle. The major draw back of these alkaline fuel cells is their limited operational life capability. However, there have been no major improvements in performance of the AFC since that time.



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