Batteries and Fuel Cells in Space

by Gerald Halpert, Harvey Frank, and Subbarao Surampudi

The year 2000 will mark the 44th anniversary of the space program that began with the launch of the first Sputnik on October 4, 1956. Tremendous progress has been made in the exploration of space since the late 50s. Thanks to the flexibility and capability of batteries and fuel cells, NASA and the U.S. Air Force (USAF) have been able to accomplish a wide range of challenging space missions. Batteries and fuel cells are used in a wide variety of space applications such as launch vehicles, earth-orbiting spacecraft, space shuttle, crew return vehicles, astronaut equipment, planetary spacecraft, landers, rovers, and penetrators. In these missions, batteries and fuel cells are used as a primary source of electrical power or as an electrical energy storage device.

Space missions impose several critical performance requirements on batteries and fuel cells. Batteries required for space applications must be capable of operating in a hard vacuum and withstand severe launch environments (vibration, shock, and acceleration). Space applications also require batteries that can provide maximum electrical energy in minimum weight and volume. Long cycle life (> 30,000 cycles) is the critical driver for orbiting spacecraft, and long active shelf life is the driver for planetary probes (> 7-10 years). Radiation resistance and operation at temperatures as low as -80°C is essential for some planetary missions. No single battery system can meet all these complex requirements. A number of different battery systems, such as silver-zinc, nickel-cadmium, nickel-hydrogen, and lithium, have been used to meet the complex requirements of various missions. In general, the specific energy of batteries in space has grown (see Fig. 1). Generally, batteries for space applications are custom designed and fabricated to meet the mission requirements. Some of the important space applications for batteries and fuel cells are discussed below.

A History of Space Batteries

The Ag-Zn battery was the first choice in the early days of space missions. The Ni-Cd battery became the major energy storage device over the next 20 years because of its long cycle life. The $Ni\text{-}H_2$ battery started to play a role in the 80s. Recently, there has been considerable interest in the use of lithium-ion batteries because of their high specific energy and energy density. A chronological history of battery firsts in space appears in Table I.

Silver-Zinc Batteries—The earliest use of a battery in an orbital spacecraft was the primary Ag-Zn battery used in the Russian spacecraft, Sputnik, launched October 4, 1956. This primary battery was used to provide power for communication and spacecraft operation. There were no solar cells available for charging, and thus when the energy was depleted, communication was terminated. The Ag-Zn primary was intended to provide power to the 84 kG spacecraft for three weeks. The spacecraft actually remained in orbit for three months. The second Sputnik, launched a month later, carried the dog known as Laika. The second Sputnik was six times larger than first one and lasted five months. It also utilized a much larger Ag-Zn battery. Silver-zinc batteries have been used in several U.S. spacecraft. Ranger 3 (1961 launch), utilized two, 14 cell 50 Ah, Ag-Zn batteries for its main power, and two, 50 Ah, 22 cell batteries for its TV camera power. Ranger 3 was placed into solar orbit and took moon photos. Mariner 2, containing one battery of 18, 40 Ah, Ag-Zn cells, was launched August 27, 1962, and was the first successful interplanetary mission to Venus.

Nickel-Cadmium Batteries—The first use of Ni-Cd batteries for primary power was on Explorer 6, which survived for only three months. In April 1960, NASA launched the first successful long-term low earth orbit (LEO) weather satellite, TIROS I. Eight TIROS spacecraft were subsequently launched. The TIROS system contained three strings of 21 Ni-Cd cylindrical F-5 cells containing glass-metal seals to insulate the positive terminal from the metal case. Capacity was selected so that depth of discharge (DOD) was very low, only 3%, so as to extend battery life.

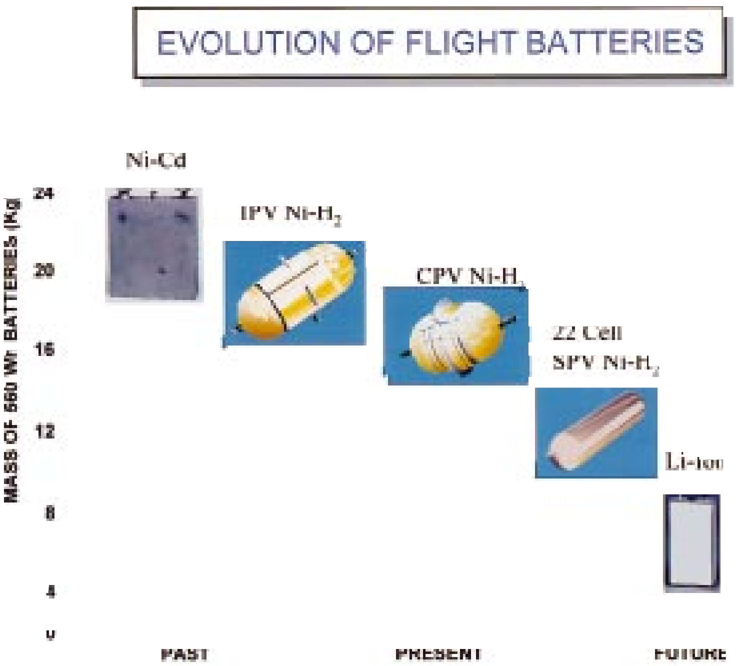


Fig. 1. The evolution of flight batteries. (Photo courtesy of Jet Propulsion Lab.)

The long life capability was achieved at the expense of increased battery size and cost.

In November 1964, the first prismatic Ni-Cd cells, produced by Gulton Industries, were flown on Explorer 23. These were configured in a close knit battery pack held together with end plates and metallic rods. As such, they provided a more efficient battery design than cylindrical cells. General Electric of Gainesville, Florida, and Eagle-Picher Company of Joplin, Missouri, developed prismatic batteries that operated successfully in space for many years.

In 1966, the Orbiting Astronomical Observatory (OAO) series of spacecraft developed by the prime contractor, Grumman Aerospace, utilized three batteries of 20 Ah prismatic Gulton cells uniquely assembled into two battery frames. Pairs of cells were interspersed within the two assemblies to minimize temperature variation. Until this time there was little application of charge control and charge was carried out in the sun at the 10-20 hour rate.

The OAO power system utilized a temperature-compensated voltage (V_T) charge control system that applied a constant voltage to batteries during charge. This method resulted in application of a high current from the solar arrays until the battery reached a preset limit. At the preset voltage, the charge current tapered until the end of the sunlight period, thus reducing the overcharge and reducing the I^2R heat that is a cause of cell degradation. The selected voltage limit was based on a parallel set of temperature compensated voltage curves (V_T curves). The V_T curve selection used to limit the charge voltage provided flexibility to account for unexpected high depths of discharge and/or imbalance between cells and/or batteries.

In the mid-70s, NASA undertook a program to develop "standard" flight hardware. To this end, Goddard Space Flight Center was responsible for developing the "standard" Ni-Cd cell and battery. The cells, manufactured by General Electric and later the Gates Co., were assembled into a standard battery and installed with the remainder of power electronics into the modular power subsystem by McDonnell-Douglas. The first lot of standard 20 Ah cells in standard 20 Ah batteries were flown successfully on the Solar Max mission for more than eight years. When the mission was terminated, the battery capacity was found to be an amazing 16 Ah. Subsequently, the technology was extended to 50Ah cells, which were used on several NASA spacecraft, such as Landsat, TOPEX, UARS, and GRO.

The "super" Ni-Cd cells, developed by Eagle-Picher, were the next step to enhance the Ni-Cd energy density and life. These cells utilized electrochemically deposited plates of the technology developed for Ni-H_2 cells. The non-woven nylon separator was replaced with an inorganic PbO-impregnated "Zircar" to minimize separator degradation. NASA utilized these in the late 80s on small satellites, such as the small Explorer series.

TABLE I. Chronological List of First Use of Batteries in Space

Launch Date	Spacecraft	Life in Space	Battery/Fuel Cell Type	
12/6/56	Vanguard	Failed	Zn/HgO	First U.S. Launch
2/1/58	Explorer 1	3.8 Months	Zn/HgO	Van Allen Radiation Belt
8/6/59	Explorer 6	2 Years	Cylindrical Ni/Cd	First Earth Photos
3/13/61	IMP 1	3.5 Years	Ag/Cd	Non-Magnetic
1/26/62	Ranger 3	Solar Orbit	Ag/Zn	Moon Photos
4/26/62	Ariel I	14 Years	Prismatic Ni/Cd	1st in LEO
8/21/62	Gemini	7 Days	PEM Fuel Cell	PEM Fuel Cell
8/27/62	Mariner 2	Venus	Ag/Zn	1st Planetary
6/23/63	Syncom-2	N/A	Cylindrical Ni/Cd	1st in GEO
5/20/65	Apollo Command Module.	Short Life	Ag/Zn	Limited Cycle Life
6/23/66	NTS-2	5 Years	Ni/H_2	12 Hour Polar
9/23/66	USAF	Classified	Ni/H_2	LEO
9/7/67	Biosatellite 2	3 Months	PEM Fuel Cell	1st Use of Nafion
10/11/68	Apollo 7	11 Days	Alkaline Fuel Cell	1st Manned Apollo
2/14/80	Solar Max	8 Years	Ni/Cd	"Standard Battery"
4/12/81	Shuttle (STS-1)	2 Days	Alkaline Fuel Cell	1st Shuttle
5/19/83	Intelsat V	14 Years	Ni/H_2	GEO
4/4/83	STS-3	Days	Li-BCX	Astronaut Use
4/6/84	LDEF	6 Years	Li Cells	Exposure to Space
10/18/89	Galileo	Hours	Li-SO_2	Jupiter Probe
4/25/90	Hubble Space Telescope	In Orbit	Ni/H_2	NASA LEO
6/10/90	Leasat	Orbiting	"Super" Ni/Cd	GEO
1/25/94	Clementine	5 Months	SPV Ni/H_2	Lunar Mapping
1/25/94	Tubsat-B	4 Years	2 Cell CPV	Store Messages
5/1995	Centaur	1st Mission	Li-$SOCl_2$	28v, 250 Ah Battery
5/5/96	Iridium-1	Commercial	50 Ah SPV	88 S/C to Date-LEO
11/19/97	Flight Experiment	USAF Experiment	Na/S	7 Day Experiment

Nickel-Hydrogen Batteries—The nickel-hydrogen (Ni-H_2) battery was developed in the 60s. It made use of the NiOOH electrode from the Ni-Cd cell and the H_2 electrode from a fuel cell. These cells employed an individual pressure vessel to contain hydrogen at a pressure of 400-600 psi. The replacement of the cadmium electrode with a hydrogen electrode reduced weight and increased energy, thus almost doubling the specific energy over the Ni-Cd cell. However, because of the cylindrical configuration of the pressure vessel and the wider spacing of the cells on the baseplate, the specific energy of the battery was similar to that of the Ni-Cd battery on a gravimetric basis. On a volumetric basis, the energy was significantly less than that of the Ni-Cd battery. However, this system offered the capability of extended cycle life at higher DOD and calendar life than the Ni-Cd battery. The first launch of Ni-H_2 battery was in the Navy's NTS-2 spacecraft where it was used as a back up to the main Ni-Cd battery. Comsat was the first to develop this battery and use it in the Intelsat V spacecraft in a geostationary (GEO) mission. The Ni-H_2 battery was first flown on Intelsat V, a GEO spacecraft in 1983. Almost all GEO spacecraft now use Ni-H_2 batteries. Hughes Aircraft Corp. also played a major role in the development of Ni-H_2 cells and batteries for space. The first NASA LEO spacecraft to use Ni-H_2 batteries was the Hubble Space Telescope launched in 1990. The International Space Station is also planning to use Ni-H_2 batteries.

In 1983, Eagle-Picher was successful in housing two Ni-H_2 cells in the same cylinder, and this design has been designated as the common pressure vessel (CPV) configuration. The first significant NASA application of a CPV battery, was in the Jet Propulsion Laboratory (JPL) Mars Global Surveyor mission in 1994. This battery contained 3 1/2″ diameter cells and was rated at 20 Ah. A smaller (16 Ah) battery containing 2 1/2″ diameter CPV cells was also used in the Mars 98 and Stardust spacecraft. These spacecraft were designed and assembled by Lockheed-Martin Aerospace Corp. In parallel with these developments, Johnson Controls developed a single pressure vessel Ni-H_2 battery in which 22 cells were mounted in the same structure. This assembly was used for the first time in 1994 in Clementine, a Navy satellite. Currently, these are being manufactured by Eagle-Picher and are used in the commercial iridium satellites developed by Motorola. More than 60 iridium spacecraft have been launched.

Lithium Primary Batteries—Primary lithium batteries, including Li-SO_2, Li-$SOCl_2$, LI-BCX, Li-$(CF)_x$, and Li-MnO_2 systems, have been used for a number of applications in astronaut equipment, planetary probes, and rovers. Li-$(CF)_x$ batteries were used as the emergency destruct battery in launch vehicles. Li-SO_2 batteries were used in the Long Duration Exposure Facility and in the Galileo, Cassini, and Stardust Probes. Li-BCX cells, a spin-off from biomedical applications, and manufactured by Wilson Greatbatch, have been in use since 1983 aboard the shuttles in astronaut equipment. Li-$SOCl_2$ batteries were used in the Sojourner Rover and in the DS-2 Mars Penetrator.

Lithium-ion Rechargeable Batteries—Li-ion rechargeable batteries are compact, lightweight, and have already appeared in many consumer products. These are indeed attractive but have not yet been used in space. For this reason, NASA and the USAF have established a joint interagency program to develop these for aerospace and aircraft applications. NASA is planning to use these batteries for a number of future space missions such as Mars 2001 Lander, Mars 2003 Rover, Europa, New Millennium ST4, and Solar Probe. Plans are also being made to replace the existing hydraulic auxiliary propulsion unit of the shuttle with an electrically controlled system using 100-150 kWh Li-ion batteries. The USAF is considering these cells for use in aircraft, unmanned aircraft vehicles, and GEO and LEO spacecraft.

Fuel Cells—The first use of a fuel cell system in space was in the Gemini program on August 21, 1962. At that time, the first of seven Gemini earth-oriented, manned spacecraft was launched with a proton exchange membrane (PEM) electrolyte fuel cell, known at that time as the solid polymer electrolyte ion exchange membrane fuel cell. Six more Gemini spacecraft were successfully flown with this fuel cell through 1966. The Biosatellite 2, launched September 7, 1967, utilized a PEM fuel cell system with an important change involving the use of an improved membrane material known as Nafion (perfluoroalkanesulfonic acid polymer), a registered trademark of the DuPont Company. Since then, Nafion has been the membrane of choice for all PEM fuel cells including JPL's newly discovered direct methanol fuel cell. While the PEM fuel cell served well in this initial application, it did not have the power density capabilities of the alkaline type of fuel cell that was concurrently under development. Subsequent Apollo manned flights (1968-72) utilized the alkaline electrolyte fuel cell containing potassium hydroxide electrolyte held in an asbestos type separator. The shuttle orbiter fuel cell power plant, developed by United Technologies Corp. and produced today by International Fuel Cells, contains three H_2/O_2 alkaline fuel cell power plants supplying 12 kW at peak and 6 W average power in performance. The operating temperature is 83-105°C. The current density is 66-450 mA/cm^2. The system is capable of 2,000 hours of operation. The shuttle orbiter fuel cell power plant is 23 kg lighter and delivered eight times the power of the Apollo fuel cell system. PEM fuel cells based on Nafion are presently being considered for the shuttle orbiter.

Space Applications

The following sections describe the requirements of batteries and fuel cells for various space applications. The major government agencies involved in the development of batteries and fuel cells for space include: NASA Centers (Goddard Space Flight Center, Glenn-Lewis Research Center, Johnson Space Center, Marshall Space Flight Center, and Jet Propulsion Laboratory); the USAF (Wright Laboratory, Phillips Laboratory, and Aerospace Corp.); and the U.S. Navy (Naval Research Laboratory and Naval Surface Warfare Center/Crane). Much of the U.S. Department of Defense (DoD) information on DoD applications is not readily available, therefore the information below is primarily that of NASA.

Rockets and Launch Vehicles—In rockets and launch vehicles, batteries are primarily used for ignition of the solid rocket motors, and powering the pyro systems, guidance and control electronics, and communication systems. Batteries required for these applications must possess high specific energy and specific power. In addition, they must have long storage life. Cycle life requirements of these missions are minimal. Both primary and rechargeable Ag-Zn batteries have been used in sounding rockets and launch vehicles.

Reserve Ag-Zn and thermal batteries are the choice for use in missiles. Ag-Zn batteries have been developed and produced by Yardney, Eagle-Picher and BST. Li-$SOCl_2$ (7 kWh, 250 Ah, 28V) batteries were developed by Yardney and SAFT for Centaur launch vehicles to replace the Ag-Zn batteries, in order to extend operating time in placing payloads in orbit.

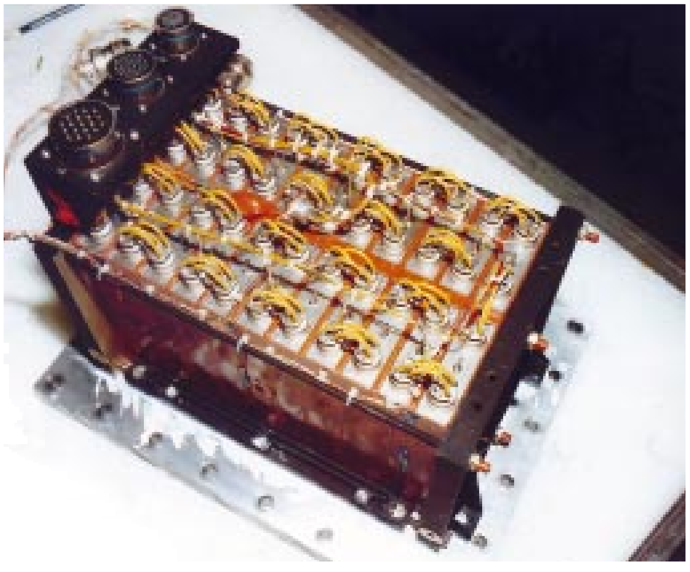
LEO and GEO Spacecraft—Circling the earth every 100 minutes, the LEO spacecraft, located approximately 100 miles above the earth, is in the sun approximately 65 minutes and eclipsed for 35 minutes. During the sun exposure, solar arrays convert the sun's energy to electrical power, which operates the spacecraft and charges the battery. Thus, because of the continuous 100-minute sun/eclipse periods, LEO spacecraft require batteries that experience 5,000 charge/discharge cycles per year. Generally, LEO spacecraft require batteries capable of operating for a period of five years and delivering more than 30,0000 cycles. Ni-Cd and Ni-H_2 batteries have this required cycle life capability and are presently being used in several LEO spacecraft (see Figs. 2 and 3). Lighter weight Li-ion batteries are available but these require improved cycle life capabilities before they can be considered for LEO applications.

GEO spacecraft are located approximately 22,000 miles above the earth in a fixed location relative to the earth. The GEO spacecraft are in full sun for 135 earth days followed by an eclipse season of 46 earth days. This process occurs twice each year and is repeated continuously for the life of the spacecraft in GEO orbit. During the 135 days of full sun, power for the spacecraft loads and battery charging is supplied by the solar arrays. The full sun period is followed by an eclipse season characterized as follows: 23 earth days of increasing daily eclipse periods from 1 up to 70 minutes (remainder of each day in full sun), followed by 23 days of decreasing daily eclipse periods from 70 minutes down to 1 minute (remainder of each day in full sun). During the varying eclipse periods, power for the spacecraft loads is supplied by the batteries. During the remainder of each earth day, when the spacecraft is in full sun, e.g., from a max of 23:59 minutes to a min of 22:10, the solar arrays provide power for battery charging and spacecraft power. The maximum discharge period occurs only twice a year at the 23^{rd} day midpoint of each eclipse season. At the midpoint day, the batteries are subjected to the greatest depth of discharge, which can range from 40 to 70% DOD. Thus the 23^{rd} day serves as the design point for the GEO battery in that it must provide this maximum power for tens of years. As in the LEO spacecraft, it is during the eclipse period when the spacecraft requires stored energy from the battery to provide power for the instrument loads as well as spacecraft communications, attitude control, and power conditioning.

Ni-Cd batteries were originally used for GEO spacecraft applications. Presently Ni-H_2 batteries are being used in most of the GEO spacecraft due to their long calendar life and availability in large sizes. Eagle-Picher and SAFT are the primary source of Ni-Cd and Ni-H_2 cells. Li-ion batteries are presently being developed for these applications.

Space Shuttle—The space shuttle requires a power source that can provide 6-12 kW for 2,000 hours. Batteries cannot satisfy this application, as the required battery weight would be prohibitive. The application can and has, however, been met with an alkaline fuel cell operating on hydrogen and oxygen stored separately in cryogenic tanks. International Fuel Cells is providing alkaline fuel cells for the shuttle orbiter applications. This system has been in use for the past 18 years. Plans are underway to replace the alkaline fuel cell system with an advanced PEM-based system. The replacement of the hydrazine-powered auxiliary power unit (APU) with an electric APU powered by 100-150 kWh Li-ion batteries is also underway.

Astronaut Equipment—Astronauts have a number of applications needing batteries to power portable equipment such as cameras, tools, laptop computers, and lights. Key requirements of these batteries are that they be safe as well as compact and lightweight so that they do not adversely impact astronaut mobility. Silver-zinc batteries met these requirements in the early stages of the manned flight program. Primary lithium batteries can reduce size and weight to an even greater extent than Ag-Zn batteries, but could not be used until their safety had been demonstrated. With the application of adequate safeguards, and after extensive testing, NASA/Johnson Space Center (NASA/JSC) approved the use of



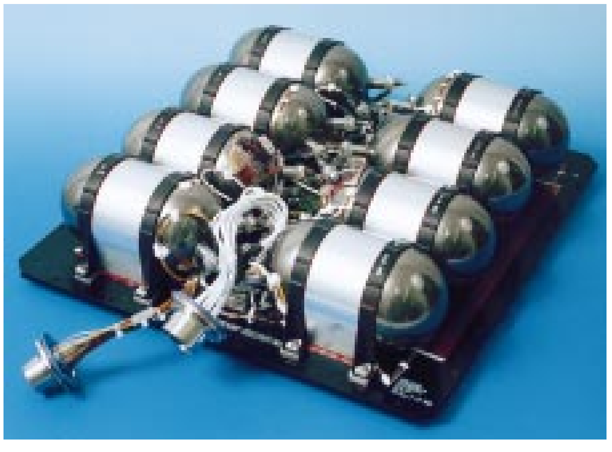


FIG. 2. (left) Ni-Cd Battery. (Photo courtesy of Jet Propulsion Lab.)

FIG. 3. (above) Mars Global Surveyor. 2 cell CPV Ni-H_2 Battery. (Photo courtesy of Jet Propulsion Lab.)

selected primary lithium batteries for specified astronaut equipment. NASA/JSC has subsequently developed safety requirements for all batteries considered for use in astronaut equipment. Several specific cells of the following types have been approved for use in astronaut equipment: alkaline, Ag-Zn, Ni-Cd, Ni-MH, and Li-BCX (Li-$SOCl_2$ cells with bromine chloride). The Li-BCX system is specifically being used in the helmet lights and TV cameras. Plans are being developed to replace the limited cycle life of the Ag/Zn battery in the manned maneuvering unit with a Li-ion battery.

Planetary Landers, Rovers, and Probes—Planetary landers require rechargeable batteries that can provide high specific energy (> 100 Wh/kg) and long active shelf life (> 10 months). In addition, these batteries must be capable of operating at temperatures as low as -40°C. Cycle life requirements of these missions are modest, less than 300 cycles, at moderate depth of discharges. Ag-Zn batteries manufactured by BST were used in the Mars Pathfinder mission (see Fig. 4). Li-ion batteries are being considered for future Mars Landers.

Battery requirements for planetary rovers are similar to those of the landers. Silver-zinc batteries were used on the Moon Rover vehicle. The Sojourner (Mars Rover launched along with the Mars Pathfinder) employed primary Li-$SOCl_2$ batteries manufactured by SAFT (see Fig. 5). Low temperature rechargeable Li-ion batteries are being developed for future Mars Rovers.

Planetary probes require primary batteries that can provide high specific energy and energy density and possess long active shelf life (six to eight years). In addition, some of the missions require batteries to operate at temperatures as low as -80°C and withstand 80,000 G shock/acceleration. Li-SO_2 batteries were used for the probe on the Galileo mission to Jupiter. The probe of the Stardust mission has also employed Li-SO_2 batteries. Li-$SOCl_2$ batteries, capable of operating at -80°C, were used on the two penetrators that were launched along with Mars 98 spacecraft.

The Future of Batteries and Fuel Cells in Space

In the next millennium, NASA is planning a number of exciting and challenging space programs and missions to explore our universe. The major goals of the NASA space program are: (1) to obtain an improved understanding of the evolution and formation of universe, galaxies, stars, and planets; (2) to determine the existence of life, in any form, that may exist elsewhere than on planet Earth; (3) to identify the existence of Earth-like planets beyond our solar system; (4) to utilize the knowledge of the Sun, Earth, and other planetary bodies to develop predictive environmental, climate, natural disaster, and natural resource models, to help ensure sustainable development and improve the quality of life on Earth; and (5) to determine the feasibility of establishing a permanent human presence in space. These programs and missions require revolutionary technology advances in several areas including new power sources and energy storage devices. Existing batteries (Ni-Cd, Ni-H_2 and Ag-Zn) may satisfy a limited number but cannot be expected to satisfy all of these new and challenging mission requirements.

Some of the planetary exploration missions require batteries that can operate at ultra low temperatures in the range of -20 to -100°C (probes, landers, rovers, and penetrators); withstand ultra high G forces to 80,000 G (penetrators); and provide exceptionally long cycle life capability (orbiters). In addition, the requirements demand that these batteries be very lightweight and compact. The majority of the far term solar system exploratory missions are projected to use very small spacecraft of the "shoe box size." Also being considered are robotic devices like

FIG. 4. (above) Mars Pathfinder. Silver-Zinc Battery. (Photo courtesy of Jet Propulsion Lab.)

FIG. 5. (right) Sojourner Rover. Li-$SOCl_2$ Batteries. (Photo courtesy of Jet Propulsion Lab.)

micro- and nano-rovers. These microspacecraft will, in turn, require microbatteries, batteries on a chip, micro-capacitors, and mW fuel cells.

Future earth-orbiting missions require large size batteries with long-cycle, and calendar-life capabilities. Future LEO missions will require batteries that can provide a cycle life in excess of 50,000 cycles at 50% or greater DOD. Future GEO missions will require large size batteries capable of operating over 15-20 years.

NASA also plans to develop revolutionary new advanced transportation systems that can accommodate humans during travel to distant destinations. Among these are crewed missions to explore planetary and other bodies in the solar system. NASA will fully integrate and utilize the International Space Station, the space shuttle, and other international contributions to achieve these goals. These missions require power sources that can operate by utilization of local resources. Advanced fuel cells are presently being considered for surface power generation. High specific energy batteries, capable of operating at low temperature, may also be required for manned rover applications. ■

Acknowledgments

The work described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

About the Authors

Gerald Halpert, *past Chairman of the Battery Division, has more than 40 years experience in batteries and fuel cells for Aerospace and Defense applications. He recently retired as Program Manager from the Jet Propulsion Laboratory.*

Harvey Frank *has more than 40 years experience in fuel cell and battery development and recently retired as Senior Member of the Technical Staff from Jet Propulsion Laboratory.*

Subbarao Surampudi*, Chairman of the Battery Division, has 25 years of experience in electrochemical technologies. He is currently Supervisor of the Electrochemical Technologies Group at the Jet Propulsion Laboratory.*