ENERGY STORAGE OPTIONS FOR LOW-COST SPACECRAFT APPLICATIONS

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Abstract

Several energy storage options currently exist for small satellite power systems. These include nickel-hydrogen, nickel-cadmium and nickel-metal hydride batteries. Nickel-hydrogen is available only as a space-flight qualified system and is therefore relatively high in cost. Nickel-metal hydride batteries are available only in a small capacity, commercial cylindrical version which limits usefulness in aerospace applications. Both aerospace and commercial nickel-cadmium batteries are available, providing another degree of freedom in matching battery selection to the specific cost and power requirements of the spacecraft. Other near-term options which may become available include aerospace grade nickel-metal hydride, silver-metal hydride and lithium-ion batteries. Other options for specialized applications include lead-acid batteries and silver-zinc and a variety of primary systems such as lithium-carbon monofluoride, lithium-thionyl chloride or thermal batteries.

Introduction

Nickel-hydrogen (NiH₂) batteries are the system of choice for low-earth-orbit (LEO) and geostationary-earth-orbit (GEO) spacecraft. NiH₂ batteries are currently flying aboard several small satellites including TUBSAT B, APEX and MSTI 2. The current trend towards “smaller, cheaper and faster” has created a non-traditional spacecraft market oriented towards low-cost programs and utilization of commercial off-the-shelf (COTS) components and technology. Additional energy storage options exist for small satellites which do not have the spacecraft volume or budget to utilize flight-qualified NiH₂ batteries or aerospace nickel-cadmium (NiCd) batteries. Commercial NiCd, nickel-metal hydride (NiMH) or lithium-ion (Li-Ion) cells can be tested, screened and matched into a suitable aerospace battery package for many low-cost space applications. This can be particularly effective using premium-grade commercial cells.

The use of commercial-grade cells in space applications provides many benefits including lower cost and improved delivery. Disadvantages include lower inherent reliability and lack of flight heritage and database. Detailed analyses and trade-off studies need to be performed at the specific program level to determine if commercial-grade cells will satisfy mission requirements. Commercial cell factors must be considered such as initial cell cost, attrition of cells during screening and selection, the cost of cell screening and matching, the possible requirement of flying redundant cell strings in the spacecraft to achieve necessary reliability levels, possible cell venting in space endangering other equipment, mechanical, electrical and thermal cell and battery design, launch vibration resistance, mission radiation environment, cell divergence during operation, potential premature cell failure on orbit and other potential performance and reliability issues. The lack of heritage and database is a significant problem for the future use of commercial cells in space applications. Lack of design configuration control and other manufacturing/quality control issues defeats the possibility of developing a user database to support future space missions. Commercial cell materials, process or design changes may be implemented by the manufacturer at will, which negate any previous quality or reliability testing/verification which has been done.

Other power system design options include using primary, non-rechargeable cells such as lithium-carbon monofluoride (Li-CFX), depending on the total power requirements for the mission. In the case of primary batteries, the savings in weight at the spacecraft level would be significant by eliminating the solar arrays, battery charge control and power conditioning electronics. This would allow additional batteries to be carried aboard the spacecraft.
Nickel-Hydrogen Spacecraft Batteries

Eagle-Picher NiH₂ batteries are currently flying aboard more than 75 operational satellites and have accumulated more than 140,000,000 cell-hours in orbital spacecraft operation. Ground-based testing has demonstrated more than 108,000 accelerated LEO charge/discharge cycles; 59,000 real-time LEO cycles and more than 30 real-time GEO eclipse seasons at 75% DOD maximum. Figure 1 indicates typical life test data for a 30% DOD life test which has completed more than 12 years of continuous real-time testing. Batteries are currently being manufactured for more than 25 spaceflight programs including the International Space Station Alpha, the Global Positioning System (GPS) Block II R, the Mars Global Surveyor and the Iridium® satellite constellation program. The NiH₂ battery system has an extensive flight history database. There is also an extensive ground testing database. A full summary of NiH₂ testing at Eagle-Picher has been previously published (1). There are currently more than 150 flight-type NiH₂ cells on life test under several different cycle regimes and depths-of-discharge (DOD).

Smallsat Nickel-Hydrogen Batteries

There is currently a trend in the industry to develop smaller, lower mass LEO satellites to replace many of the functions of the larger, more expensive GEO spacecraft. The applications range from communications systems to military and scientific spacecraft. These “smallsats” require less power and are designed for a shorter operational life expectancy. A large GEO satellite may be required to deliver 15 years of orbital operation, where “smallsats” may be designed for only a 2 or 3 year mission duration. Reduced power and useful life requirements have opened up many new possibilities for spaceflight qualified cell and battery designs. These designs have been developed to meet the cost structure of the smallsat program. A new, smaller 2.5 inch (64 millimeter) diameter cell design has been developed for the emerging small satellite market.

Flight qualified common pressure vessel (CPV) nickel-hydrogen (NiH₂) cell and battery designs are being developed for these small satellite applications. NiH₂ batteries provide a number of unique advantages for the developing small satellite industry. NiH₂ batteries provide high energy density, long cycle life and the highest levels of reliability in the industry. Flight qualification of the small diameter CPV technology has included thermal vacuum testing, mechanical vibration testing, fracture mechanics analysis, cell and battery thermal analysis and performance cycle life testing. Smallsat battery designs use the same basic electrochemical technology as standard flight cell designs. More than three hundred 2.5 inch (64 millimeter) diameter CPV NiH₂ cells have been delivered by Eagle-Picher for a number of small satellite programs. The TUBSAT B spacecraft, launched in June 1994 aboard a Russian Cyclone rocket, was the first satellite to carry CPV NiH₂ technology into space. TUBSAT B was built by the Technical University of Berlin. TUBSAT C is currently under construction and is slated to also use NiH₂ batteries. Recent launches include two Orbcomm spacecraft and a Microlab spacecraft built by Orbital Sciences Corporation. Small diameter CPV cells are also flying on the MSTI 2 spacecraft and have been manufactured for other programs such as “Apex” and “Seastar”.

Small Diameter CPV Cell Design

An initial description of the basic 2.5 inch diameter NiH₂ cell design was published in 1992 (2). Two basic small diameter NiH₂ cell designs are currently in production. Both cell designs have dual electrode stacks internally and have a cell output voltage of 2.5 volts. Cell electrical capacity is determined by the number of
larger diameter cell designs. These cell designs allow additional flexibility in the overall spacecraft power system design. The CPV design is more suitable to the high voltage, low capacity range of battery design. Small diameter cells can also be built in an IPV configuration. The IPV design would be more efficient in the higher capacity, lower voltage range.

Performance and Testing

Figure 6 shows typical charge voltage performance for the RNHC-10-1 cell. The cell is charged at a C/10 rate (1.0 Amperes) at three different temperatures, -5°C, 10°C and 20°C. The cell end-of-charge voltage (EOCV) ranges from about 2.96 VDC to 3.16 VDC over the indicated temperature range. The higher voltage occurs at the colder temperatures, as is typical for alkaline rechargeable batteries. The initial portion of the charge curve shows a relatively flat voltage response as the cell is charged. Near the end of the charge the voltage increases slightly, indicating cell overcharge, and then levels off again. This temporary, rapid increase in the rate of change of voltage with respect to time provides a good indication that the cell is completely charged. The increased cell voltage is due to oxygen evolution at the nickel electrode, as the nickel active material is completely charged. Oxygen recombines at the catalytic electrode to form water, with the large excess of hydrogen present in the cell. This unique chemistry provides the extensive overcharge capability of the NiH₂ battery. The cell EOCV increases significantly at the colder temperatures. This is partially due to the increased impedance of the alkaline electrolyte at the colder temperature.

Figure 7 shows discharge performance data for the same cell at the same temperatures as above. All three discharges were performed at the C/2 (5.0 Amperes) rate. The cell delivers more capacity, though at a slightly lower voltage, at the colder temperature. Again, this is typical performance for an alkaline system. The difference in the mid-point discharge voltage (MPDV) over the indicated temperature range amounts to about 120 millivolts at this discharge rate. The cell discharges at a MPDV of 2.52 VDC at 20°C and 2.40 VDC at -5°C. The cell delivers 10.0 Ah at -5°C and 9.0 Ah at 20°C. There is very little change in the cell capacity delivered between -5°C up to 10°C. Cell capacity begins to decrease only at temperatures above 20°C.

Current results from ongoing cycle life testing is indicated in Figure 8. The cells have currently completed more than 12,000 LEO cycles. The test is operating under a ninety minute regime with a 55 minute charge and a 35 minute discharge. The test is maintained at 10°C. The data in Figure 8 is for an RNHC-10-1 CPV, 2.5 inch diameter cell. The cell is operating at 40% DOD. The chart shows the EOCV and the end-of-discharge voltage (EODV) for the cell as a function of cycling. The EOCV is the highest voltage attained by the cell at the end of the 55 minute charge and the EODV is the minimum discharge voltage at the end of the 35 minute discharge. These two values are excel-
lent indicators of the state of health of the cell. As is
shown in the graph, the EOCV and EODV are flat and
stable, indicating excellent cell performance and the
absence of any performance degradation. Another
important figure-of-merit in monitoring cell performance
is the standard discharge capacity. This measurement
is also taken at intervals to determine if any performance
degradation has occurred. No decrease in cell capacity
has been observed to date, indicating that the cell has
not degraded from its initial condition.

Nickel-hydrogen batteries provide a viable option
for the small satellite program. NiH₂ batteries provide
increased specific energy, higher reliability levels and
much longer cycle life than other aerospace battery sys-
tems. The batteries can be routinely operated at a higher
DOD than NiCd batteries, resulting in a net increase in
the specific energy delivered at the power system level.
This corresponds to a net decrease in battery weight for
equivalent power levels. Nickel-hydrogen batteries of-
fer many other unique advantages, including reliable
state-of-charge measurement through the spacecraft
telemetering system. The NiH₂ system is the most fault-
tolerant battery design option for the spacecraft power
system designer. The overcharge and overdischarge
capabilities of the NiH₂ system greatly reduce the bat-
tery controller and charging system complexity. The
possibility of battery performance degradation, dam-
age or premature failure due to accidental mismanage-
ment of the battery is also reduced. Small diameter, low
capacity NiH₂ cell and battery designs offer the small
satellite user the same technology heritage and data-
base as that currently flying in large GEO spacecraft.

Nickel-Cadmium Spacecraft Batteries

Eagle-Picher has been manufacturing aerospace
grade nickel-cadmium (NiCd) batteries for more than
forty years. Cells and batteries of many different de-
signs have been produced for a wide variety of aero-
space, military and spacecraft applications. Both vented
and sealed batteries are manufactured. Spacecraft bat-
teries are typically sealed, electrolyte starved designs
and are maintenance-free. Cycle life and performance
is very good, although somewhat less than NiH₂. Sealed
NiCd batteries were extensively developed throughout
the 1960's and 1970's and this provided the background
for the development of the NiH₂ system. Extensive test-
ing and qualification has been performed on the NiCd
system, including a long-term cycle life test which com-
pleted more than 65,000 charge/discharge cycles under
a LEO test regime. NiCd cells and batteries are also
produced for aviation use. The primary application is
for aircraft engine starting. This application requires an
extremely durable, rugged battery design capable of
extremely high rate pulse loads. For some applications,
the batteries must be capable of delivering in excess of
2000 amperes for short periods of time. The environ-
mental requirements are also severe, ranging from the
desert in summer to arctic conditions in the winter.
Aviation NiCd batteries have been manufactured for a
variety of applications including the B-1 and B-2 bom-
ers, the AC-130 gunship and the B-52 bomber.

NiCd batteries provide very good performance and
cycle life, particularly if the batteries are operated prop-
erly. A number of options exist with the NiCd system
including sealed aerospace cells, "super" NiCd cells and
a variety of commercial grade cells. Aerospace grade
NiCd cells have been in use for many years and are
manufactured primarily to NASA standards in terms of
sizes, capacity ratings and cell designs available. Ex-
tensive literature is available concerning aerospace
NiCd's. The "super" NiCd battery has been in produc-
tion at Eagle-Picher for several years and is used pri-
arily on communications satellites. The major differ-
ces in the "super" NiCd is the method by which the
electrodes are manufactured and the separator material
used. An electrochemical deposition method is used in
electrode manufacturing, similar to that used in the space
qualified NiH₂ battery. This provides higher cell spe-
cific energy and increases the depth-of-discharge ca-
pability and cycle life of the battery. The “super” NiCd also uses an inorganic separator material, similar to that used in the NiH₂ battery, which is more stable in the alkaline cell environment than standard nylon separator. Organic polymer separator materials tend to hydrolyze and degrade in the aqueous potassium hydroxide electrolyte, limiting cell performance and life. The “super” NiCd cell provides increased performance compared to standard aerospace NiCd’s. The disadvantage is that the “super” NiCd is relatively high in cost compared to commercial NiCd batteries.

Eagle-Picher has been involved in the smallsat industry for several years. Sealed, aerospace nickel-cadmium batteries were being manufactured for smallsats as the more advanced NiH₂ technology was being developed. An example of an early smallsat program was the SCD-1 small satellite, developed by the Instituto de Pesquisas Espaciais (INPE) in Brazil (3). The spacecraft is a 115 kg, spin stabilized design. The satellite was launched aboard the Pegasus vehicle in February 1993. The Pegasus was deployed by a B-52 carrier aircraft at an altitude of 42,000 feet and delivered the satellite to an altitude of 392 nautical miles. The Pegasus spun up the spacecraft to 120 rpm prior to payload separation. The satellite is currently flying in a circular orbit inclined at 25 degrees with respect to the equatorial plane at an altitude of 750 km. The satellite collects environmental data from remote ground transmitters and relays the information to the Brazilian Cuiaba tracking station.

Nickel-Metal Hydride Spacecraft Batteries

Nickel-metal hydride batteries have the potential of increased energy density and lower cost than NiH₂ and improved specific energy compared to NiCd. Nickel-metal hydride (NiMH) batteries have about 30% higher gravimetric specific energy than aerospace nickel-cadmium and about twice the volumetric energy density of nickel-hydrogen. Nickel-metal hydride batteries are currently available only in small capacity cylindrical cells, similar to commercial NiCd cells. As yet, larger capacity cells and prismatic cell designs are not commercially available. Some of the development work underway with prismatic NiMH electric vehicle batteries may eventually be adapted to the aerospace market. Electric vehicle batteries are typically larger sizes, around 100 Ah, so these designs would have to be scaled down for small spacecraft. Eagle-Picher has done a considerable amount of research and development oriented towards small capacity, sealed aerospace quality cells (4,5). Cells have been manufactured, tested and delivered to various organizations for further testing and evaluation. NASA Lewis Research Center did extensive testing on Eagle-Picher aerospace grade nickel-metal hydride cells and reported in excess of 8000 LEO cycles at 40% DOD (6).

The nickel electrode used in NiMH cells is similar technology to those used in NiCd, NiFe, NiH₂, and NiZn batteries. The hydride electrode can be either of two alloy systems classified as AB₂ or AB₅. The AB₂ alloy contains primarily iron-titanium or nickel-titanium with other metals added to improve performance. Most battery manufacturers use AB₂ type alloys, because of the increased performance and cycle life available with this system. The AB₅ alloy is primarily lanthanum-nickel with other elements added to improve the performance. AB₂ type mischmetal-nickel alloy is also considered as useful battery electrode material and provides excellent battery performance. Mischmetal based alloys are frequently used in commercial grade battery electrodes because of lower basic material cost. Most of the work done at Eagle-Picher has been focused on custom formulated rare-earth based alloys in order to provide improved performance, reliability and reproducibility. Mischmetal composition varies considerably depending on the vendor source of the material, where it is mined and other factors. Manufacturing the alloy directly from the base elements insures that each lot of hydride electrode material will be of correct composition and of reproducible quality. This is absolutely necessary to insure aerospace grade performance and reliability.

Nickel-Metal Hydride Aerospace Cell Design

The low pressure operation of the metal hydride system allows cells to be constructed using a prismatic geometry similar to NiCd. The prismatic metal hydride cell contains only electrodes, separation, electrolyte, tabs and terminals. This simplicity of design and lack of complex internal components makes the cell cost effective to produce and more reliable in operation. In addition, the cells are hermetically sealed and mainte-
nance free. The electrode stack is contained within the cell case and consists of a multiplicity of nickel electrodes and hydride electrodes interspersed with a suitable separation. Several commercial separators are compatible with the NiMH system and aerospace nickel-cadmium or nickel-hydrogen separators can be used in premium applications. The cell is activated with aerospace grade aqueous potassium hydroxide electrolyte. The concentration of the electrolyte generally ranges from 26% to 35% depending on the application. The same construction methods and materials can be used to build cells over a wide range of electrical capacity. This design versatility is one of the major advantages of this type of construction.

Nickel-Metal Hydride Aerospace Battery Design

A nickel-metal hydride cell develops about 1.25 volts at the midpoint of discharge, which is the same as nickel-cadmium or nickel-hydrogen. Most applications require higher voltages which necessitates connecting multiple cells electrically in series. A prototype aerospace NiMH battery is shown in Figure 9. This battery has been built and tested at Eagle-Picher. The battery contains ten cells for a nominal output of 10 Ah at 12.0 VDC. Battery construction is straightforward and simple. The two endplates are machined from aluminum with numerous cut-outs to reduce weight. The connecting rods joining the two endplates are stainless steel rods threaded on both ends. Connectors, wiring, instrumentation and on-board electronics are usually dictated by the application and can be integrated into the design as required. Another possible battery design includes cylindrical “C” size NiMH cells packaged into a flight configuration aerospace battery. This type of battery has utility in the small satellite industry where the cost and/or life expectancy of the spacecraft does not warrant the construction of full-fledged aerospace batteries. This type of packaging could be used with virtually any size of commercial cell.

Silver-Metal Hydride Spacecraft Batteries

Silver-metal hydride (AgMH) is a new battery system under development for aerospace and possible commercial applications. The chemistry is based on extensive experience with the silver-zinc, nickel-hydrogen and nickel-metal hydride battery systems. Silver-metal hydride combines the high energy density of the silver electrode (compared to the nickel electrode) with the longer cycle life of the hydride electrode (compared to the zinc electrode). Silver-metal hydride batteries offer hermetically sealed, maintenance-free operation with improved cycle life over the silver-zinc system. Development work is being done at the materials, electrode and full cell levels. Prototype silver-metal hydride cells have been constructed and are being characterized by electrical testing, cycle life testing and by electrochemical impedance spectroscopy analysis (7,8). Improved separator systems are being developed in order to mitigate silver migration and improve performance and cycle life.

Currently, the nickel-metal hydride (NiMH) battery system is in commercial production. Significant advances over the past few years in reversible hydrogen absorbing electrode materials have made hydride-based batteries practical. The major specific energy limitation of the NiMH battery is the nickel electrode, which results in the system offering only incremental improvement over the nickel-cadmium (NiCd) battery system. One possible solution to significantly increase the energy density of the hydride-based battery is to replace the nickel electrode with a higher energy density electrode such as silver. The silver electrode has several advantages over other electrodes including the superior conductivity of the silver material. As the silver electrode is discharging, silver-oxide is being reduced to silver metal, which decreases the impedance of the
electrode. This continuous decrease of electrode impedance during discharge counteracts polarization effects, resulting in a flat, uniform discharge voltage profile. This effect gives the electrode excellent discharge rate capability as well. AgMH provides an intermediate hybrid system between NiMH and AgZn. The disadvantages of the AgZn system include limited cycle life, limited wet life and an ill-defined end-of-life failure. These limitations are primarily due to zinc migration or "shape change" that occurs in the zinc electrode. Replacing the zinc electrode with the more stable hydride electrode significantly increases battery cycle life, wet life and overall performance.

The silver electrode undergoes two distinct oxidation/reduction reactions during charging and discharging of the battery. These reactions can be combined into an overall reaction for the silver electrode:

$$\text{AgO} + \text{H}_2\text{O} + 2\text{e}^- = \text{Ag} + 2\text{OH}^-$$

The chemistry of the hydride electrode has been previously discussed (9) and can be represented by:

$$\text{MH}(x-1) + \text{H}_2\text{O} + \text{e}^- = \text{MH}_x + \text{OH}^-$$

where M represents a material capable of reversibly forming a metallic hydride and the lower case letter "x" is an integer (x = 1, 2, 3...) and represents some hydride state of the metal. Combining the two reactions yields the overall silver-metal hydride cell reaction that results from combining the silver and hydride electrodes into a secondary alkaline battery. This is represented by:

$$\text{AgO} + 2\text{MH}_x = \text{Ag} + 2\text{MH}_{(x-1)} + \text{H}_2\text{O}$$

This reaction represents the overall cell discharge reaction as written. The charge reaction is the reverse.

Testing and characterization of AgMH cells (including sealed aerospace designs) has been underway for some time (10). Preliminary results indicate that a considerable increase in energy density is possible over the corresponding nickel cell. Figure 10 shows a direct comparison of the nickel and silver-hydride systems on a milliamper-hour per gram basis (mAh/g). The chart shows the full cell potential of both a NiMH and a AgMH cell. Both cells were discharged at the C/4 rate at room temperature. This data reflects the inherent higher energy density of the silver electrode over the nickel electrode. The silver cell yields about three times the electrical capacity of the NiMH cell. The plateau voltage is slightly lower than the nickel cell with the silver-hydride mid-point discharge voltage occurring at about 1.0 volt. The increase in capacity more than makes up for this decreased voltage on a watt-hour per kilogram (Wh/kg) specific energy basis.

Testing of prismatic aerospace silver-metal hydride cells is still underway. Electrochemical impedance spectroscopy provides a useful analytical tool for system evaluation. The results to date are very promising. It is anticipated that the silver-metal hydride chemistry will function well in aerospace applications. The system is ideal for the new generation of small satellites being developed for communications, surveillance and tactical satellite programs. Potential military applications include tactical electric vehicles, swimmer delivery vehicles, underwater power systems, C4I, communications equipment, GPS receivers, the SOLDIER combat system, battlefield computers and any man-portable battery operated equipment. The system may also be useful in premium commercial applications such as cellular telephones, laptop computers and palmtop computers, where the increased energy density, and correspondingly longer run time, offsets the higher initial cost and relatively shorter cycle life of silver-based batteries. The silver-metal hydride battery system promises excellent performance and cycle life at a reasonable cost, as compared to other aerospace battery systems.
Lithium-Ion Batteries for Aerospace Applications

Lithium-ion batteries have become commercially available recently, such as those available from Sony. These are small, cylindrical cells delivering about 3.6 VDC each. Sizes currently available range up to only a few Ampere-hours. Larger cells and prismatic designs are not yet available. The advantages of the rechargeable lithium intercalation battery include a high operating voltage (compared to 1.2 VDC for an alkaline rechargeable) and very high energy density. Lithium is a very lightweight and extremely energetic material. This is advantageous for specific energy calculations but can also be a problem from a safety aspect. Lithium-ion batteries are inherently safer than lithium metal anode battery systems. Lithium-ion cells deliver about 80-100 Wh/kg compared to 40 Wh/kg for NiCd and 50-60 Wh/kg for NiMH. Packaging varies depending on the application but 65-70 Wh/kg is obtainable at the finished lithium-ion battery level. One disadvantage at the system level is the sensitivity of the lithium-ion system towards overcharge and overdischarge. Cells have to be controlled and bypassed individually to avoid safety problems. This increases the complexity of the power system and charge control and decreases overall system reliability. Also, cold temperature performance is relatively low and may pose a problem in a small spacecraft where thermal control may not be adequate to maintain battery temperature within a narrow range.

The lithium-ion battery system is based on “rocking chair” technology where lithium ions are shuttled between the cathode and anode during charge and discharge. The cathode or “positive electrode” consists of a lithiated transition metal oxide such as lithium cobalt-oxide, lithium nickel-oxide or lithium manganese-oxide. These materials are typically a spinel structure (Fd3m) in which the transition metal occupies the octahedral sites (16d) and the lithium ion is intercalated into the tetrahedral sites (8a). Less than one lithium ion can be accommodated per transition metal atom which provides a theoretical energy density limitation for these materials. Cathodes range from about 170 mAh/g up to about 300 mAh/g depending on the material and various other factors.

The discharge anode or “negative electrode” is made of carbon, usually with the graphite structure. The lithiated anode has the formula Li_xC_{6} where 0<x<1. This poses a theoretical specific energy limitation for carbon-based materials of about 370 mAh/g. The carbon structure used is one of the most critical factors in determining electrode performance and cycle life. Changes that occur in the carbon structure during cycling can lead to rapid degradation of cell performance. Corrosion, surface passivation and many other problems are inherent to this material, which provides some unique materials research opportunities. There is a variety of carbon-based anode technology available and this is one of the more active research areas in this technology.

The electrolyte is typically an organic solvent or mixture of organic solvents such as ethylene carbonate (EC), propylene carbonate (PC), dimethyl carbonate (DMC) or diethyl carbonate (DEC). A lithiated inorganic salt is typically added to the electrolyte solvent in order to increase conductivity (much like adding potassium hydroxide to water for alkaline battery electrolyte). Lithium hexafluoro-arsenate (LiAsF_{6}), lithium perchlorate (LiClO_{4}), lithium tetrafluoro-borate (LiBF_{4}) and lithium hexafluoro-phosphate (LiPF_{6}) are used as electrolyte additives. Even so, the electrolyte conductivity is typically much less than that of aqueous systems and is one of the limiting factors in battery performance.

Materials level problems in the lithium-ion system include co-intercalation of solvent molecules into the cathode, electrochemical reduction of solvated species, precipitation of insoluble reduction products, surface passivation of the cathode and anode, reduction induced polymerization of the solvent, dissolution of solvated electrons into the organic electrolyte, electrochemical breakdown of the organic electrolyte and irreversible capacity loss. Some of the disadvantages at the cell level include the high reactivity of lithium, contamination sensitivity during manufacture, sensitivity to the electrode and electrolyte materials used, manufacturability, materials handling, potential toxicity and corrosivity of materials, the use of organic solvents and general safety concerns. Cost is one area of concern for most potential users. Proponents of the lithium-ion battery system talk about how cheaply the cells can be manufactured, but the price tag is still inordinately high compared to alkaline batteries. Safety and reliability are also viable
concerns. The database is not yet sufficient to accurately estimate the level of concern posed by these issues.

Some recent work has been done to evaluate the application of current lithium-ion cell technology to space applications. NASA Jet Propulsion Laboratory (JPL) recently published a summary of aerospace testing performed on commercial cylindrical Sony cells (11). Two types of cells were tested, one delivered 70.0 Wh/kg and the other more advanced design delivered 80.5 Wh/kg. Both were based on the LiCoO₂ cathode technology and both delivered a rated open-circuit voltage of 3.8 VDC. This testing showed one potential problem with lithium-ion which is the sloping discharge curve as capacity is removed from the cell. The cell starts at 4.1 VDC initially and drops steadily to the cutoff voltage of 2.9 VDC. At the power system level, this means that the bus voltage will drop 1.2 VDC per cell over the course of the discharge, equivalent to nearly a 5.0 VDC voltage drop for a 12 VDC battery. The second generation advanced cell design has completed 2500 cycles at 40% DOD under an accelerated LEO regime at JPL. No prediction is made on the ultimate life expectancy and the data presented shows only a slight degradation in end-of-discharge voltage over the 2500 cycles completed. A second paper from JPL (12) describes a lithium-ion battery flight experiment to be flown on a space shuttle Hitchhiker canister system. This is considerably different than using lithium-ion as the primary power system on a spacecraft but should provide some good data on the potential of the system for space applications. No launch date for the flight experiment is given. Lithium-ion batteries will probably not be flown in a spacecraft power system before 1998 and will not be generally available for aerospace applications until after 2000.

Conclusions

Commercial nickel-cadmium batteries provide a viable option for low cost, short duration spacecraft missions. The decreased performance and reliability of this option must be considered at the system level. Redundant cell strings may be required, decreasing system specific energy. Both commercial and aerospace grade nickel-cadmium cells are available, offering design flexibility and trade-off of cost and reliability issues. The primary advantage offered by aerospace grade nickel-cadmium cells is increased volumetric energy density, compared to nickel-hydrogen. For spacecraft with increased power requirements, high reliability levels and long cycle life requirements, nickel-hydrogen provides the best solution. Nickel-metal hydride batteries are available only in small capacity, commercial cylindrical designs, which limits their usefulness for space applications. Reliability and cycle life are major issues with the nickel-metal hydride system. Silver-metal hydride batteries offer an interesting alternative to nickel-cadmium and nickel-metal hydride because of the significantly higher specific energy available. However, silver-metal hydride is available only on a custom manufactured basis and has not yet been flight qualified. Lithium-ion batteries are in the initial stage of commercial development and are not yet being produced in sizes large enough for spacecraft power systems. Also, lithium-ion has not been well characterized enough to adequately evaluate the potential risks associated with this system.

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