# 14.0 Energy Generation and Storage

The Air Force has a continuing need for more efficient and system-compatible energy generation and storage devices. By far the most important energy generation devices used on aircraft are auxiliary power units (APUs), which are characterized by reasonable power densities (greater than 100 kW/kg) and moderate energy densities that are determined by the amount of fuel on board (typically greater than 70kW·hr/kg for a three-hour flight). Although batteries with better performance characteristics are available (Table 14.1), we do not see any other technology replacing the APU or engine-driven electric generators for aircraft power, even in the "more-electric aircraft" (MEA) or the "all-electric aircraft" (AEA). The reason is simply that potentially competing technologies (e.g., batteries and supercapacitors) are so inferior in low-temperature start-up characteristics that we cannot envision technological advances over the next few decades that would change this conclusion. Instead, it appears that the rational approach to enhancing reliability for MEA or AEA is to employ redundant APUs.

*Table 14.1 Specific Energy, Specific Power, and Cycling Characteristics of Potential Aircraft Power Systems[*]*

| | **Specific Energy (W· hr/kg)** | **Specific Power (W/kg)[!]** | **Cycle Life[**]** |
|---|---|---|---|
| **Supercapacitor** | **<10** | **<600** | **--** |
| **Li/Solid Polymer Electrolyte** | **250** | **100-400** | **<150** |
| **Ni/Hydrogen** | **65-80** | **600-900** | **30,000+** |
| **Ni/Metal Hydride** | **175** | **200-400** | **1000+** |
| **Ni/Cadmium** | **80-100** | **600-900** | **10,000+** |
| **Lead/Acid** | **30-50** | **600-900** | **30,000+** |
| **Flywheel** | **20[@]** | **Very High[#]** | **•** |
| **APU** | **70[$]** | **>100** | **Very Large** |

**(*) Typical values. (**) Cycle life decreases with increasing depth of discharge. (!) Highly dependent on design and on method of determination (pulse vs. steady-state). (@) Scales with**

There are opportunities for impressive advances in airborne power generation for MEA/AEA applications that depend on advances in magnetic materials. These include development of superior soft magnetic materials possessing simultaneously high strength, high critical temperature and high magnetic strength, and low electrical loss for advanced motor and generators directly integrated with small and large turbine engines for airborne power and self-starting aircraft, and advanced hard magnetic materials for bearing applications on these same systems.

Impressive improvements seem possible. Examples are twice the mechanical strength, and an order of magnitude lower electrical loss for soft magnetic materials for 550°C operating temperatures and an increase in operating temperature for hard magnetic materials from 300°C to 450°C, with extended life at these temperatures and a factor of two increase in energy product. In the long term, there are real possibilities for nano-structure or mesostructure technologies to provide superior advanced magnetic materials. Laminated solids would replace the present physical stack of laminations separated by a thin insulator in core materials for generators and motors. Near-term, diffusion bonding techniques for metal-to-metal and ceramic-to-ceramic interfaces would improve the stiffness and strength of core materials. We should note, however, that our conclusion with regard to the future of batteries in MEA and AEA applies strictly to the primary power source, and not to internal engine and APU start functions, or to power conditioning. Advanced batteries and supercapacitors will almost certainly be employed for these secondary functions, particularly as efforts are made to reduce the reliance of aircraft on ground support equipment. The state of development of advanced batteries and supercapacitors, and the likely courses of development of these technologies in the future, are reviewed later in this section.

Perhaps the greatest need in the Air Force for advanced energy storage is for spacecraft. Energy generation and storage is required for a wide variety of missions, ranging from low earth orbit (LEO), surveillance (optical, IR, and radar), information processing, asset mapping, directed energy weapon systems, geosynchronous communications and GPS. The power requirements range from a few kilowatts for passive systems to greater than 10 MW for directed energy systems, and include both continuous power and pulsed power. A number of energy generation and storage technologies are possible, including:

- Photovoltaics
- Thermionics
- Nuclear thermoelectrics
- Flywheels
- Tethers (a long wire cutting the Earth's magnetic field—used on the Navy's Transit satellite 20 years ago)
- Secondary batteries
- Supercapacitors
- Superconducting rings

Each of these technologies offers advantages and disadvantages which render them more or less appealing for specific applications. Several are summarized below.

The most commonly used technology is photovoltaic electricity generation with secondary battery storage. Photovoltaic conversion has been in use for more than 30 years and is likely to be the mainstay power source for the great majority of space systems for the next 50 years.

The current technology is based on silicon p-n junctions, in which primarily single-crystal materials are used. Because of electron-hole recombination, which is promoted by defects (grain boundaries, dislocations, impurities), the quantum efficiency is low (less than 15 percent in the laboratory, less than 10 percent in the field for polycrystalline materials), and slightly higher for single-crystal materials, which requires the use of excessively large solar arrays. Also, the cost of producing photovoltaic materials of optimum properties is very high, so that the cost per kilowatt of produced power is also high.

While photovoltaics will remain the mainstay of power generation in space systems over the next five decades, as noted above, we expect that significant advances might be made in photovoltaic materials that will result in higher conversion and lower fabrication cost, which will translate into higher energy densities and lower specific power cost. These anticipated developments include more extensive use of compound semiconductors with high conversion efficiencies. One way to enhance the performance of solar cells is by tuning the semiconductor band gap to match the solar spectrum. This increases the portion of the sun's energy that can be converted to electricity. There are many new single layer and multilayer compounds that have yet to be explored for designing new high efficiency solar cells.

As an example of the payoff in this area, multi-junction solar cells composed of GaInP/GaAs/Ge have demonstrated a record breaking conversion efficiency of 27 percent. The photoabsorption in the solar cell can also be enhanced by using textured surfaces and anti-reflection coatings. The textured surfaces are designed to increase the optical path length through thin semiconductor layers increasing the probability that all the incident photons will be absorbed. Silicon solar cells with these surface treatments have recently demonstrated conversion efficiencies of 24 percent.

Another means for higher efficiency is to discover semiconductor materials which generate more than one electron per photon, through hot electron or Auger generation processes. These types of materials are predicted to have conversion efficiencies approaching 50 percent.

In addition to conversion efficiency, an important property for solar cells in space applications is radiation resistance. In space, solar cells often experience high radiation environments, especially during solar flares. To provide longer lifetimes for spacecraft, materials must be selected which are less susceptible to damage by radiation, which degrades the power performance of the solar cell. The disadvantage of high-efficiency semiconductor solar cells is the cost per cell. However, this increased cost can be offset by the reduced launch costs associated with lighter weight arrays that require less stowage volume.

Synthesis of photo-stable, low cost, organic p-n junctions offers high payoff. Many conjugated organic systems (polyacetylene, polythiophene, polyaniline, and polyphenylene, to name a few) are already doped to produce p-type or n-type materials. Because these materials may be readily processed as thin films using inexpensive processing technologies, it is possible to envisage low-cost p-n junctions in the form of large-area thin films being fabricated. The major problems are that many of these polymers have poor photostabilities and exhibit low conversion efficiencies; however, it is fair to note that the efficiencies are no lower than they were for silicon-based materials at a comparable stage of development. The photostability problem may be difficult to solve, because the degradant is the hot hole, which is an entity formed within the p-n junction on photoabsorption. For space applications, these materials need to be radiation resistant and thermally stable as well as photo-stable. It is clear that new materials, possibly doped conjugated inorganic systems, for example, $-(SN)_x-$, $-(SiN)_x-$, $-(PN)_x-$ , should be explored, because the potential payoff is very high.

Synthesis of composite photovoltaic materials, in which an inorganic semiconductor is contained within a functional matrix also offers potentially high payoff. The matrix may be developed to enhance the conversion efficiency by converting the energy of hot electrons and holes that escape from the particle surfaces into thermal energy or it could be devised to screen the semiconductor from the more energetic photons in the spectrum.

In all of these technologies it is evident that computationally designed materials will play increasingly important roles. Thus we are now on the verge of being able to tailor the electronic properties of compound semiconductors by first-principle calculation (i.e., solving Schroedinger's equation). This capability will allow us to specify systems and compositions that more exactly meet our needs than is possible with current systems.

For LEO craft, the battery cycles between charge and discharge every 90 minutes, and must do so for at least 30,000 cycles corresponding to a life of five years. Currently, the only batteries that are capable of delivering this cycle life are nickel-hydrogen and advanced nickel-cadmium for small systems requiring less than 1.5 kW. In both cases, the cycle life is a function of temperature and of the depth of discharge, with cycle life decreasing as more energy is extracted from the battery per cycle. The degradation in cycle life results from restructuring of the nickel positive electrode, and it is irreversible. In order to achieve the desired cycle life, the depth of discharge must be limited to about 40 percent of the theoretical value. This means that a significant amount of inaccessible active mass must be carried into space. Given that the energy densities of these battery systems are already low (65 - 80 W·hr/kg), the inaccessible active mass (60 percent) further reduces the effective energy density (to 26 -32 W·hr/kg) and hence reduces the balance of payload for the mission. To put the problem into perspective, consider a satellite that has a lower power storage requirement of 30 kW·hr. Because of the need for long cycle life, the effective capacity of the nickel-hydrogen battery is of the order of 28 W·hr/kg.

Battery and supercapacitor technology is rapidly evolving (Figure 14.1), with the developments being driven by the need for zero-emission automobiles. In the U.S., this effort is being supported by the U.S. Advanced Battery Consortium (ABC), a partnership between the DOE and the "Big Three" automobile manufacturers (GM, Ford, and Chrysler). The ABC has identified advanced lead-acid and nickel-cadmium as the near-term batteries, but both have energy densities impractically low (less than 100 W·hr/kg) for the MEA. The middle-term technology has been identified as nickel-metal hydride, which has demonstrated an energy density of about 175 W·hr/kg. This battery shows good cycling characteristics, but the potential for developing the energy density to 500 W·hr/kg seems small to nonexistent. The ABC has identified lithium/solid polymer electrolyte/intercalation cathode (Li/SPE/IC) batteries as the most promising long-term technology, and already batteries of this type have attained energy densities in excess of 250 W·hr/kg, with claims of energy densities as high as 400 W·hr/kg being made on occasion. However, these latter claims are almost certainly based on the masses of the active material alone and do not take into account packaging. In any event, on the basis of specific energy the

Li/SPE/IC systems appear to be promising long-term candidates for back-up power sources for the MEA.

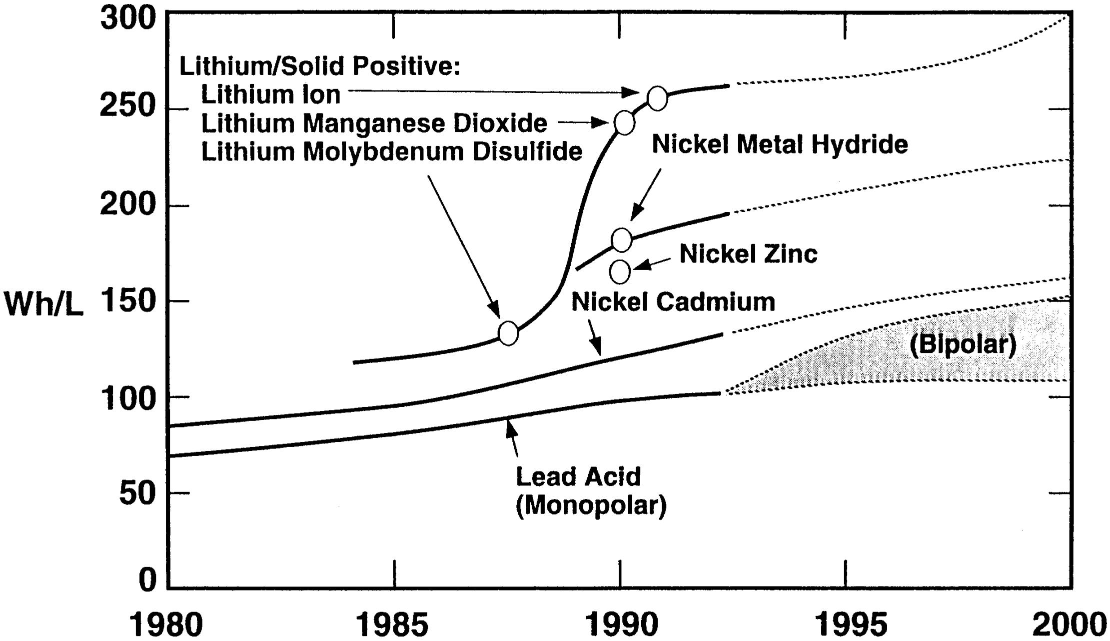


*Figure 14.1 Battery and Supercapacitor Technology Trends: 1980-2000*

While the energy densities of the Li/SPE/IC systems appear attractive, they generally have low power densities and poor cycling characteristics. The latter problem arises from the fact that the lithium metal anode does not cycle well, and test cells have managed to achieve cycle lives of only about 100 cycles before failure. However, it is fair to note that cycle life as a characteristic is generally developed late in the overall development of a battery, so that we might reasonably look towards a life in excess of 1000 cycles within the next few decades. One approach to enhancing the cycle life has been to use a Li-C intercalation anode. Because the maximum loading of the carbon corresponds to $LiC_6$ (i.e. 3 gm of lithium to 72 gm of carbon), this approach significantly degrades the energy density of the battery. So far, a Li/SPE/IC battery having high energy density, high power density, and a long cycle life, the combination of requirements for the BUPS for a MEA, has not been developed. Furthermore, the prospects that such a battery will be developed within the next two decades are small. This option must be viewed only as long-term for an MEA main power source battery.

With regards to supercapacitors, the ABC middle-term goals for specific power and specific energy are greater than 500 W/kg and greater than 5 W·hr/kg respectively. The ABC long-term goals—greater than 20 years—for these parameters are greater than 1600 W/kg and greater than 15 W·hr/kg. The prospects for achieving these latter goals in the near term are good, and at least one laboratory claims to have exceeded these performance characteristics. A specific power of 1600 W/kg implies a capacitor bank of a little over 300 kg to meet the power requirement of 500 kW, so that the weight of the battery is 1070 kg (236 pounds). If, on the other hand, the nickel-hydrogen battery could be discharged to 100 percent of theoretical capacity and still retain the cycle life, the weight of the battery becomes 430 kg (940 pounds). Assuming a launch cost of $10,000 per pound, the additional inactive battery weight costs $14M. Thus, a huge penalty is paid per launch to ensure adequate cycle life.

The cycle life is the Achilles' heel of many secondary battery systems, and the cycle life requirement of 30,000 cycles for a LEO satellite can be met only by nickel-hydrogen, advanced nickel-cadmium, and possibly lead-acid. Before progressing with this discussion it is worth examining why electrode degradation occurs.

Charge storage in secondary batteries occurs via reversible charge transfer reactions that result in the formation and annihilation of chemical species. Some of these reactions are dissolution processes (e.g., on discharge of a cadmium electrode in a nickel-cadmium battery) in which case restructuring of the active mass occurs on recharge deposition and subsequent cycling. Other species are solids, $Ni(OH)_2$ and NiOOH as in alkaline nickel electrodes, and each of the solids has a different molar volume. Charge cycling generates cyclic stresses, which gradually fracture the active mass and hence disrupt the transfer of electrons and ions through the electrode structure. Unfortunately, this process is irreversible so that when the capacity is reduced below a tolerable level, the battery must be discarded. Electrode degradation is the principal problem facing developers of advanced Li/SPE/IC batteries.

## Superconducting Rings

Superconducting rings provide an intriguing concept for energy storage, and this technology is now being commercialized for use as a standby power source. Both conventional (niobium-based) and high-temperature (oxide-based) superconductors have been used or proposed. However, the energy density is low and it appears that this technology is not suitable for flight operations unless other parts of the system are also operated at cryogenic temperatures.

## Flywheels

Flywheels are an attractive mechanical energy storage technology actively being developed for zero-emission automobiles. Flywheel systems are now being considered for space systems. Although the energy density is low for rotating disks in the 200 pound class (approximately 20 W·hr/kg), when compared with batteries (Table 14.1), the energy density squares with the mass so that a ten-fold increase in the mass of a disk rotating at the same angular velocity would result in a one hundred-fold increase in the energy density. Thus, large flywheels become very attractive as high energy density power sources, because energy densities in excess of 1 kW·hr/kg can be envisioned. Other advantages of flywheels include:

- An effectively infinite life
- Low losses with ultralow-friction (magnetic) bearings
- Very high specific power that is determined only by the ability of the generator to extract energy from the system.

However, flywheels generate considerable gyroscopic forces that need to be recognized when designing the flight system. Another problem is that flywheels still have too great a "self-discharge" rate. The important materials issue is to devise materials that have high densities and are able to withstand very high centrifugal stresses. Composite materials are promising in this regard.

## Nuclear Systems

Nuclear thermoelectric and thermionic power sources have been employed on spacecraft, although the reluctance on the part of designers and the public to accept nuclear power, even in the form of isotope heating, has severely limited these systems. While the conversion efficiencies are low (approximately 6 percent for thermoelectrics and approximately 20 percent for advanced thermionics), the energy and power densities of the sources can be very high, and hence they are attractive on purely technical grounds. The materials issue with these systems is enhancement of the conversion efficiency. The general opinion is that both the thermoelectric conversion efficiency and the thermionic conversion efficiency will continue to improve, but that no spectacular improvements are on the horizon.

## Tethers

A tether is a long wire, attached to a satellite, that produces power by induction from the earth's magnetic field. This system is flight proven (on the Navy's Transit satellite), and it works well. However, its low energy density and low power density are not suitable for most space power applications. One interesting problem is that as energy is extracted from the earth's magnetic field, the satellite slows down. To compensate, it is necessary to provide periodic boosts using conventional rockets. Accordingly, the weight of the rocket must be included in any energy density or power density calculations.

## Fuel Cells

Fuel cells are electrochemical devices that continuously convert chemical energy directly into electrical energy, so that in many respects they share features with batteries. However, unlike secondary batteries, fuel cells are not electrically recharged and hence they do not cycle in the conventional sense. Because they are continuous energy converters, the effective energy density is determined by the relative masses of the converter (the cell) and the fuel and oxidant. As the relative mass of the latter increases, the energy density of the system becomes increasingly determined by the energy density of the fuel and oxidant, multiplied by the conversion efficiency.

A most attractive feature of a fuel cell is that the efficiency is not determined by Carnot's theorem, which applies to heat engines. In the case of fuel cells, the efficiency, e, is given by:

$$\varepsilon = \Delta G/\Delta H = 1 - T(\Delta S/\Delta H)$$

where $\Delta G$, $\Delta H$, $\Delta S$ and T are the changes in Gibbs energy, enthalpy, and entropy of the cell reaction, and the Kelvin temperature, respectively. Typically, for a $H_2/O_2$ fuel cell, the efficiency is approximately 0.65 compared with about 0.3 for an internal combustion engine. Practical efficiencies of 0.5 have been achieved in phosphoric acid cells and in polymer exchange membrane cells of the type used in the Gemini and Apollo programs. Note that if S/H is negative, the efficiency can exceed unity. In this case, heat is transferred into the cell from the surroundings in response to the positive change in entropy of the reaction. We know of no practical cell where this is observed.

Fuel cells are used extensively on manned spacecraft, and have been the primary power source for all spacecraft since Gemini. These cells are of the proton exchange membrane type and employ hydrogen as the fuel and pure oxygen as the oxidant. This is a well-established technology, and it works well in spacecraft because of the low sensitivity to cost compared with other applications, such as automobiles. Even so, the cost is high—greater than $50,000/kW—which can be traced to the need to use noble metal catalysts at high loadings, the high cost of the membrane, and the low volume of production. However, there are other potential applications of interest to the AF. These include standby power, power for supporting ground-based facilities such as radars, and as ground power for servicing aircraft. The advantages of ambient temperature fuel-cells for these applications is that they are silent and have very low IR signatures. However, they become even more attractive if they can employ a liquid fuel, rather than gaseous hydrogen, and air as the oxidant. Again, this technology is highly developed in that systems are available commercially that produce hydrogen fuel for the cell by reforming hydrocarbons or partially oxygenated fuels, such as methanol. However, the reformer is a high temperature system that emits IR radiation as well as CO, $CO_2$, and low levels of $NO_x$. What is needed is an ambient temperature fuel cell that employs a liquid fuel directly without the need to reform.

Direct oxidation of methanol in fuel cells is being actively explored by DOE and by various companies, mostly with DOE funding. To date, these efforts have met with only very limited success, with the principal impediment being the lack of a good electrocatalyst for the anode (fuel electrode). The conventional noble-metal catalysts cannot support high enough current densities at sufficiently low overpotentials to yield useful powers.

One approach is to increase the temperature, but this can be done only at the loss of LO. In the case of PEM cells, electrolyte dehydration limits the cell temperature to 80 - 100°C, which is too low to yield useful power using currently available electrocatalysts. What is needed is a revolution in electrocatalysis to produce materials upon which the oxidation of methanol or liquid hydrocarbons is fast. Various materials, such as tungsten bronzes, and activated carbons, are being explored, but to date little success has been achieved. While the Air Force may choose not to directly invest in this effort, it should keep abreast of developments because of the potentially high payoff.

One solution to this problem might be to use a highly soluble, easily oxidized organic fuel, such as sugar, in conjunction with a suitable enzyme (adenosine tri-phosphate) as the catalyst. This cell would emulate, in a simple way, the utilization of sugars by higher organisms and hence represents a biologically inspired system.