# An Overview of Electric Power: A Key Technology for Electric Propulsion

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## Abstract

There is a natural synergism between electric power and electric propulsion for spacecraft in which each technology can work together for the overall enhancement of the performance of the spacecraft. This paper provides a summary of currently available or soon-to-be available electric power technologies of use to electric propulsion missions. New, low-mass solar arrays, improved nuclear power sources, high-energy-density batteries and smaller power management and distribution (PMAD) subsystems will be discussed. Reductions in electric power system mass on the order of 50% can be realized which means reducing the overall mass of the spacecraft or doubling the power production with the same mass envelope -- a possibility of distinct interest to designers of electric propulsion systems.

## Introduction

Electric power and electric propulsion are two technologies which, when combined, can provide a natural synergism that greatly improves the performance of spacecraft. For example, the use of advanced electric power system technologies can reduce the overall mass of the spacecraft, hence reducing the specific mass (kg/kWe) that is such an important parameter in performance calculations of electric propulsion system benefits. Conversely, the reduction in mass can be applied to a larger power generation, meaning more power is available for electric thrusters. One specific advantage with the newer solar array technologies is that the array size can be reduced which in turn reduces the drag area and moments of inertia meaning less propellant is required for drag makeup and/or attitude control.[1]

The objective of this paper is to present an overview of recent developments in the technologies of spacecraft electric power systems so that spacecraft and mission designers and, in particular, the electric propulsion community will have a good, general knowledge with which to make informed decisions about using improved electric power systems. In particular, the paper will show that it is possible with today's existing technology to reduce the mass of state-of-practice electric power systems in half or more.

The organization of the paper will follow the classic three major elements of spacecraft electric power systems: (1) power source (either solar or nuclear); (2) energy storage (either chemical or mechanical); and power management and distribution (PMAD), sometimes referred to as power conditioning and control subsystem (PCCS).

## Power Source Development and Technology

Two solar power sources (photovoltaic and dynamic) and nuclear power sources will be covered in the following subsections.

### Photovoltaic Power Sources

The classic photovoltaic power source consists of the solar cells mounted on some kind of mechanical array structure. Advances have been made in both technologies. The principal requirements on solar arrays are mass, area, reliability/lifetime, radiation tolerance, availability, and cost.[2] Two figures of merit are often used: specific power (We/kg) and areal power density (We/m$^2$). For reference purposes, state-of-practice solar arrays typically have had specific powers in the range of 10 We/kg to 25 We/kg.[3] The overall specific power of an advanced photovoltaic/battery power system is roughly 10 We/kg[4] and the end-to-end efficiency for large photovoltaic/battery systems (e.g., International Space Station) is estimated to be about 4%.[5] However, in comparing the attributes of different solar arrays one must carefully consider the particular application. For example, some arrays achieve their highest specific powers at high powers while others may perform better in hostile (e.g., high-radiation) environments.

Solar Cells

Solar cells are the principal contributors to the mass of a solar array so naturally much U.S. work on decreasing the mass of solar arrays has gone into decreasing the mass of the cells. Improving the efficiency reduces the number and size of the cells and, in turn, reduces the size and mass of the structure and deployment system.[2]

Silicon (Si) solar cells, which have been the most used, have an efficiency on the order of 14% at air-mass zero (AM0) (although a laboratory model has achieved an efficiency approaching 21%) while the newer, commercially available gallium arsenide (GaAs) cells have efficiencies on the order of 18.5% at AM0.[6] Just from the gain in efficiency a GaAs array can be over 30% smaller in area than a silicon-cell array.

Most work in the U.S. on improved solar cells concerns either multiple-band-gap solar cells or radiation-tolerant solar cells. The former can be either several cells stacked on top of each other or the upper cell can be grown on top of the lower cell material (cascade cell).[2] Some examples from the focus of current U.S. research include [2,6,7]

• Dual-junction gallium indium diphosphide on gallium arsenide ($GaInP_2$/GaAs) cell with efficiencies in the range of 21.5% under AM0. With a concentrator lens arrangement this cell reaches an efficiency of about 24% at 7.5 Suns.

• Triple-junction of the above cell on germanium with an efficiency goal of 24%.

Work on radiation-tolerant solar cells is driven primarily by concerns about operating in the Van Allen radiation belts. Two basic cell types are being studied for improved performance in a radiation environment:[2,6]

• Indium phosphide (InP) cells which have efficiencies close to those of GaAs cells with much improved radiation resistance.

• Thin-film cells made from thin (1 - 5 μm) semiconductor layers deposited on an inert substrate or superstrate material. These include copper indium diselenide ($CuInSe_2$, sometimes abbreviated "CIS") and cadmium telluride (CdTe). Efficiencies are typically in the range of 7% to 10% but the very thinness of the cells compared to crystalline cells promises specific powers in the range of kilowatts per kilogram with high radiation resistance. Multiple-band-gap thin-film cells could achieve efficiencies on the order of 15% to 20%. Spacecraft experience remains to be developed.

Other cells (e.g., InP/InGaAs, AlGaAs/Si, GaAs/InGaAs, AlGaAs/GaAsInP/InGaAs, and ZnO/CdS/InP)[2] have been studied. A cascaded or tandem solar cell involving gallium arsenide on gallium antimonide (GaAs/GaSb) has exhibited an efficiency of 25.5% at one Sun and 29.5% at 40 Suns.[8]

Clearly from cell technology alone the potential exists to reduce the mass and area of photovoltaic power sources by at least 50%.

Solar Arrays

To reduce the mass and cost of solar arrays, research is under way in three major categories of array designs: improved rigid arrays, flexible blanket arrays, and concentrator arrays.[2]

Rigid Solar Arrays

Rigid arrays can be pushed to about 93 We/kg for a 200-We-class solar array wing by using an inflatable torus concept developed by L'Garde, Inc.[9] This is about four times better than state-of-practice arrays.

Flexible Blanket Solar Arrays

Flexible blanket arrays, which replace the rigid array with thin blankets kept in tension with guide wires, have been pushed by TRW to 130 We/kg in a geosynchronous Earth orbit (GEO) design for a 12-kWe design at beginning of life (BOL).[3] A variation of this design will be used on the Earth Observing System (EOS) AM-1 spacecraft.[10] Earlier flexible arrays have been flown on Milstar, Hubble Space Telescope, Olympus-1, and two European Remote Sensing satellites (ERS-1 and ERS-2).[2] AEC-Able Engineering Co., Inc. has developed the UltraFlex solar array which offers specific powers >100 We/kg (Si cells) and >180 We/kg (multi-junction cells).[11]

Concentrator Solar Arrays

Concentrator arrays achieve mass, area, and cost reductions by using optical systems which are less expensive than the cells to concentrate the solar power onto a reduced cell area. Concentrator arrays also provide improved radiation tolerance because they use smaller cells which are easier to protect. The solar concentrator array with refractive linear element technology (SCARLET™) being developed by

AEC-Able Engineering Co., Inc. under DoD sponsorship offers the potential of having arrays with specific powers of 100 We/kg.[2,12,13] To power the ion thruster and other equipment on NASA's New Millennium Deep Space 1 spacecraft a near-term cell technology ($GaInP_2$/GaAs/Ge cells) will provide ≥50 We/kg in a 2.6-kWe array for a concentration ratio of 15:1 at AM0 and one astronomical unit (AU) from the Sun.[2,14]

Astro Aerospace has developed the Astro-Edge array which uses a channel-like design on a rigid planar array to concentrate the sunlight. A similar concept under development by the Naval Research Laboratory is aimed at providing about 100 We/kg with a concentration ratio of 2.5:1.[2]

Overall, it can be stated with confidence that the technology exists to achieve a two- to five-fold increase in the specific power (or equivalent reduction in the specific mass) of photovoltaic power sources. With advanced technologies such as thin-film arrays the eventual improvement could be on the order of ten-fold yielding arrays with ≥1000 We/kg.

## Solar Dynamic Power

An alternative form of solar power is to use the Sun's solar energy flux to heat a working fluid that in turn powers a turbine-alternator or linear alternator to convert the heat into usable electrical power. In principle, such dynamic conversion systems can achieve efficiencies on the order of 30% without suffering radiation damage and without needing electrochemical energy storage. NASA's Lewis Research Center has conducted the world's first full-scale demonstration of a complete space-configured 2-kWe solar dynamic power system based on the closed Brayton (gas) cycle in a relevant space environment. For high-power missions this technology can be very competitive with photovoltaic-battery systems.[5]

## Nuclear Power

Nuclear power provides another alternative for missions which must operate in places of limited sunlight or in hostile environments. Two types of nuclear power sources have been used: radioisotope and reactor. The most recent application is the Cassini spacecraft which carries three radioisotope thermoelectric generators (RTGs) to power the spacecraft into the cold, dark, radiation-rich environment of Saturn. All told, the U.S. has a demonstrated track record with 44 RTGs and one reactor having been successfully used to power 26 different space systems.[15]

The advantages of nuclear power include self-sufficiency (no dependence on the Sun), high tolerance to radiation, long lifetimes, and high reliability.[15]

### Radioisotope Power Sources

The RTGs on Galileo, Ulysses, and Cassini represent the current state-of-practice in radioisotope power sources. These power sources, known as the general-purpose heat source RTG (GPHS-RTG), can provide over 300 We at a specific power of over 5.3 We/kg at BOL and a system-level thermal-to-electric conversion efficiency of about 6.8%.[16]

A range of conversion system options exist that can possibly double or triple this conversion efficiency. These include dynamic conversion systems such as the previously mentioned turbine-alternator systems (Brayton and Rankine) and the linear-alternator system (Stirling). There are also two static conversion systems, one based on solar-cell technology (thermophotovoltaics or TPV) and the other based on a thermally regenerated sodium concentration cell (alkali metal thermal-to-electric conversion or AMTEC). Currently, AMTEC is being studied for the proposed Pluto Express mission.[17]

Two recent studies have shown that radioisotope power sources can provide a viable near-term nuclear powered electric propulsion system for a number of challenging and scientifically rewarding science missions.[18,19]

### Reactor Power Sources

For higher powers (≥10 kWe) and/or for special applications space nuclear reactors are the preferred nuclear power source. Over the years a number of technologies have been examined; however, in the interests of technical focus the following paragraphs will discuss the most mature U.S. space nuclear reactor technology: SP-100 space nuclear reactor power system.

It should be noted that the U.S. flew the first space nuclear reactor, the Systems for Nuclear Auxiliary Power 10A (SNAP-10A) reactor, launched on 3 April 1965. In its early, unoptimized form, SNAP-10A had a specific power in the range of 1.1 We/kg to over 1.4 We/kg and could produce over 500 We from its thermoelectric conversion system. Nevertheless, SNAP-10A demonstrated the feasibility of operating a liquid-metal-cooled reactor in the zero-g, vacuum environment of space.[20] Higher performing concepts based on the SNAP-10A reactor technology were proposed and some were tested.

Over the years a number of studies have been conducted on the benefits of using nuclear reactors to power electric propulsion systems for space exploration.[21] Clearly there is a synergism between nuclear reactors and electric propulsion.

In the U.S., the SP-100 space nuclear reactor power system represents the state-of-the-art in terms of proven technology (although no system was built). The technology development program for SP-100 was conducted from 1983 to 1994 with a goal to develop a space nuclear reactor technology that could support a range of projected future missions including planetary surface operations and nuclear electric propulsion for science missions. A generic flight system (GFS) configuration was established to support operational missions requiring relatively high power (100-kWe class) for 10-year mission durations, but scalable from about 10 kWe to 1000 kWe and with high specific power. One of the most attractive features of the SP-100 design approach is that it decouples the reactor from the conversion system so the conversion system is not exposed to the hostile environments of heat, radiation, and corrosive fluids. For low powers (≤100 kWe), the GFS employed thermoelectric conversion.[22,23]

With a restart of the SP-100 program, first-generation technology is available to support near-term science missions requiring powers in the range of 20 kWe to 40 kWe. Depending upon the technology and power level, the SP-100 design has projected specific powers ranging from 8 We/kg (current technology at 20 kWe) to 26 We/kg (mature thermoelectric technology at 100 kWe).[22,23] The SP-100 reactor could also be coupled to higher efficiency conversion systems such as Brayton, Rankine, Stirling, TPV, AMTEC or out-of-core thermionics for further improvements.

Coupling a 40-kWe version of SP-100 with ion thrusters allows near-term payloads of over 2000 kg to be used in a Mars orbiter with Phobos and Deimos rendezvous, multiple main belt asteroid exploration, and asteroid sample returns. Using more mature technology with powers up to 100 kWe, missions such as the Jupiter mini-grand tour, Saturn ring rendezvous, Uranus orbiter/probe, Neptune orbiter/probe, and Pluto orbiter/probe can be accomplished with payloads up to 2000 kg.[23]

The benefits of nuclear electric propulsion are also present at higher powers. For example, studies have shown that scaling up the SP-100 2.4-MWt reactor to 24 MWt and using a potassium-Rankine turbine-alternator conversion system (turbine inlet temperature of 1300 K) and megawatt-class ion thrusters would enable NEP cargo missions (4 MWe with one reactor) and piloted missions (8 MWe with two reactors) having transit times comparable to nuclear thermal propulsion (NTP) missions.[24]

In summary, nuclear power can enhance and/or enable outer planetary and extra-solar-system electric propulsion missions at powers ranging from hundreds of watts to megawatts.

## Energy Storage Development and Technology

At the present time all operational satellites in Earth orbit use nickel-based battery systems such as nickel-cadmium (NiCd) batteries or nickel-hydrogen ($NiH_2$) batteries for energy storage.[25] For energy storage, two parameters are of particular interest: specific energy (watt-hours/kilogram) and energy density (watt-hours/liter). Obviously it is desirable to maximize both parameters. Typical state-of-the-art cell specific energies for NiCd are on the order of 39 watt-hours per kilogram (We-h/kg) and for $NiH_2$ they are on the order of 50 We-h/kg.[26] As in any technology, actual values are dependent upon the specific application including cycle life and depths of discharge.

Alternative energy storage technologies include lithium-based batteries, sodium-sulfur (NaS) batteries, mechanical (i.e., flywheel) energy storage, and capacitors. (Fuel cells are candidate energy storage systems for high-power space missions and they may enable achieving 500 We-h/kg to 1000 We-h/kg.[27])

The following sections provide a brief overview of the principal energy storage technologies: Nickel-based batteries; Lithium-based batteries; Flywheel systems; and Capacitors.

### Nickel-Based Batteries

The focus of this section will be on $NiH_2$ batteries because of their expanded use and potential; however, in fairness, it should be noted that while $NiH_2$ batteries are becoming the choice for most new space missions, improved NiCd designs are showing that for cell sizes under 32 ampere-hour (A-h) NiCd batteries should have useful lifetimes equal to that of $NiH_2$ at a lower unit cost and equivalent specific energy.[25,28]

A number of approaches are being pursued to raise the specific energy of $NiH_2$ batteries which have a theoretical limit of >400 We-h/kg. For example, combining two or more cells within a single vessel to create a common pressure vessel (CPV battery) has led to reductions of 50% in mounting footprint, 30% in cell volume, and 10% in mass.[25] The first planetary launch of a two-cell CPV battery was accomplished in 1996 with the Mars Global Surveyor spacecraft. This design has now been selected for the New Millennium Deep Space 1, Mars '98, and Discovery Stardust missions.[14]

The next step is to combine all the cells within a single unit to create a single pressure vessel (SPV) battery such as was successfully used on the Clementine mission. In a 15 A-h battery, the mass was reduced by 25%, the volume by 80%, and specific energy was more than 70% greater than for an 11-by-2 cell CPV battery of the same capacity.[25]

Combining cells such that each supports the next in a dependent pressure vessel (DPV) battery leads to a calculated specific energy of 76 We-h/kg. Stacking electrodes back to back within a single pressure vessel to create a bipolar stack should also provide significant savings in mass and volume.[25]

### Lithium-Based Batteries

With $NiH_2$ technology now accepted for deep-space missions, rechargeable lithium cell technology, with its promise of even higher specific energies and energy densities, is the focus of development as the next rechargeable battery system. Cycle life demonstrations for small cells (~1 A-h) have now exceeded 5000 cycles. Lithium-ion cells have now been scaled up to 20 A-h in a joint NASA/JPL/USAF program. Cell level specific energies of more than 100 We-h/kg have been achieved. Lithium-ion-polymer systems are also in development with the potential for specific energies of more than 150 We-h/kg. These cells are planned for use on planetary landers and probes, and for orbiters as duty cycles appropriate to low-Earth orbit (LEO) (~30,000 cycles for a five-year design life) are demonstrated.[14]

From the foregoing discussion it is clear that the technology exists to reduce state-of-practice battery mass by at least 50%.

### Flywheel Systems

As a result of recent advances in the development of high-power (tens of kilowatts) flywheels for terrestrial applications there has been a renewed interest in the use of flywheels on spacecraft. The terrestrial flywheel systems have achieved wheel speeds greater than 60,000 revolutions per minute (rpm) by using composite rotors and magnetic bearings. The usable specific energies are greater than 66 We-h/kg at 75% depth of discharge. Combining flywheels with attitude control may offer even greater benefits. NASA is preparing a plan to develop flywheel technology for aerospace applications.[29]

### Capacitors

Recent work on a chemical double layer capacitor has shown that it is possible to improve the charge storing capability of capacitors such that they have both higher specific power and higher specific energy. While the specific energy is less than most battery technologies, the specific power is factors of 10 to 50 times greater than that of most batteries such that for certain high-specific-energy and high-specific-power applications a combination of batteries and capacitors offers the ideal solution.[30]

Recently the Russian thruster with anode layer (TAL) electric propulsion system was successfully powered by a chemical double layer (CDL) capacitor bank having a capacitance of 3.5 F at a charge voltage of 400 V and powers ranging from 450 We to 1750 We.[31]

## Power Management and Distribution Development and Technology

Historically on planetary spacecraft the mass fraction for the power management and distribution (PMAD) subsystem, using conventional packaging and older power system topologies, has increased toward 10% as the dry mass of the spacecraft approached 200 kg. However, the next generation of planetary spacecraft are forcing a switch to higher density packaging and higher efficiency power conversion for low-load powers such that the PMAD mass fraction is reduced to about 2% to 4% of the total dry mass of the spacecraft. To meet this goal will drive electronic designs and technologies to mass and volume reductions of 65% and 80% respectively.[32]

By building upon the breakthroughs that have occurred in terrestrial chip technologies it is possible to achieve reductions in mass and volume of the PMAD subsystem. Instead of the current state-of-practice of using discrete electronic parts mounted on planar printed circuit boards, extensive use of hybridization technology is planned. For example, a power hybrid has been implemented on the Cassini spacecraft with the development of a solid-state power switch.[32]

Current plans call for flying advanced power electronic technologies on board the New Millennium Deep Space 1 mission. The goal under the New Millennium program is to go from Cassini-class power electronics with specific powers in the range of 16 We/kg and power densities less than 0.015 We/cm$^3$ to power micro-electronics with specific powers of 250 to 1100 We/kg and power densities of 6 to 30 We/cm$^3$.[14] As we have seen with power sources and energy storage, mass reductions of at least 50% are achievable with the PMAD subsystem.

## Concluding Remarks

The technology exists today to reduce the mass of state-of-practice spacecraft electric power systems by at least 50%. These improvements mean that designers of missions employing electric propulsion can take advantage of a 50% reduction in the specific mass (kg/kWe) of the electric power system. Alternatively, for the same mass fraction, the power production can be doubled making the addition of electric propulsion even more attractive. Truly, electric power technology provides an enhancing synergism with electric propulsion technology.

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NOTE: In addition to the references cited in this paper, the interested reader is also referred to Refs. 33 and 34 and the September-October 1996 issue (Vol. 12, No. 5) of the *Journal of Propulsion and Power* for more information on advanced space power systems.


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