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# Technologies for Spacecraft Electric Power Systems

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**There is a growing push within the federal government and many private sector space organizations to build and launch spacecraft that are smaller, that can be built and deployed quicker, and that cost less. Even in the classic large communications satellites there is a push to reduce the utility mass so that more transponders can be added or the launch mass reduced, or some combination of both. Furthermore, there is pressure to spin off technologies into the commercial sector as well as to spin in technologies to the space program. The classic electrical power system consists of the power source, energy storage, and power management and distribution (PMAD). This article addresses these electrical power technologies, including high-performance photovoltaic devices, solar dynamic systems, batteries, and PMAD architectures, showing that in each case new technologies are available that can reduce the overall mass of the electrical power system by at least 50%.**

## Introduction

REQUIREMENTS for space power systems have changed dramatically in the last few years. More effort is being directed toward small, low-mass spacecraft where the future demand is expected to grow dramatically because of funding limitations in the space program. With reduced size, mass, and cost, it should be possible to launch more spacecraft such as some of the planned communications satellites (satcoms) and proposed scientific spacecraft, because the launch costs will be reduced and, in many cases, several spacecraft can be launched on the same vehicle. Moreover, for planetary missions, reduced mass can produce indirect cost savings through shorter transit times and mission duration.[1]

A review of the typical Earth orbiting satellite or planetary spacecraft shows that electrical power and onboard propulsion can consume one-half to three-fourths of the mass of the spacecraft.[2,3] Clearly, improvements in power and propulsion could greatly reduce the mass of the spacecraft or allow more of the spacecraft's mass fraction to be devoted to payload. In fact, power and propulsion technologies can be worked synergistically to the overall benefit of the spacecraft design; for example, by using lower mass power system components more power can be provided for the same overall power system mass and this extra power can be used on more efficient electric thrusters to extend the mission and/or to reduce the mass of the propulsion system.[4]

To meet the challenging goals set for the next generation of spacecraft, new electrical power technologies have to be brought to use immediately. This article provides an overview of some of the major new technologies for power sources (energy conversion), energy storage, and power management and distribution (PMAD). Some of these technologies have already been qualified on the ground.

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## Generic Electric Power System

The basic configuration of the electric power system (EPS) of a spacecraft is shown in Fig. 1. The EPS consists of three principal elements: 1) power source; 2) energy storage; and 3) the PMAD system that conditions, controls, and transfers power from the power source directly and/or through the energy storage to the different loads (e.g., sensors, transponders, etc.) on the spacecraft. For most spacecraft, the power source is a solar array using solar cells mounted on the spacecraft (body-mounted) or on a separate wing (or wings). Other options include nuclear power sources that are discussed in Ref. 5 and solar dynamic power.[6] This article focuses mostly on solar cell arrays as power sources. Energy storage is usually accomplished through the use of rechargeable or secondary batteries; although fuel cells have been used, particularly on human missions.[7] PMAD, sometimes referred to as power conditioning and control, consists of regulators, converters, control circuits, etc., necessary to condition and transfer the power. In the following sections we will visit each of these three elements of the overall EPS by describing some of the new technologies available to improve EPS performance.

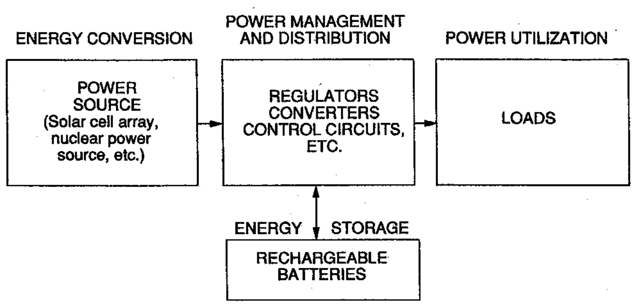


**Fig. 1 Basic configuration of a spacecraft electrical power system.**

## Solar Power Sources

Two principal types of solar power sources will be considered: 1) photovoltaic arrays and 2) solar dynamic power sources. With respect to the former, both solar cell technology and solar array technology will be discussed.

### Solar Cells

The silicon (Si) solar cell was developed first at the Bell Laboratories in 1953. Since then many developments have taken place in solar cells. Table 1 lists some of the promising solar cells whose technology is in such a state of maturity where they can be tried for practical applications. In the last few years a major revolution has occurred in photovoltaic power sources. The ubiquitous Si solar cell is being replaced by the more expensive gallium arsenide (GaAs) solar cell. The natural question to ask is how this can be since the GaAs cell on a germanium (Ge) substrate can be up to five times more expensive than the Si cell? The first explanation of this revolution was given by Datum and Billets.[8] The GaAs cell has an efficiency of about 18% compared to Si at 14%, it is more radiation tolerant, and it shows lower loss of power with temperature. (Note: in fairness, it must be mentioned that thin Si cells with efficiencies above 14% are now becoming available from foreign suppliers.) These characteristics lead to an array with smaller area per unit power. Thus, when the costs are considered at a panel level rather than at a cell or component level, the GaAs array can be within 15% of the cost of a comparable Si array, despite even up to a fivefold cost disadvantage at the cell level. Figure 2 shows this impact. Because of this efficiency advantage, existing satellites can deliver increased power without changing array design with potentially profound effects on mission costs.

**Table 1 Solar power, new technologies**

| |
|---|
| Solar cells |
| Thin GaAs/Ge solar cells |
| InP solar cells |
| $GaInP_2$ solar cells |
| GaAs/GaSb solar cells |
| Minidome Fresnel refractive type |
| Concentrator GaAs/Ge solar cells |
| Cassegrainian reflective type |
| Cascade solar cells, GaAs/GaSb |
| Cascade solar cells, GaAs + $CuInSe_2$ |
| Cascade solar cells, $GaInP_2$/GaAs |
| ALACIC |
| Cover glasses |
| BRR reflective solar cell cover glasses |
| Solar arrays |
| APSA |
| Inflatable torus solar array |
| UltraFlex fan solar array |
| SCARLET |
| Enhanced power generation by |
| Optical solar reflectors |
| SLATS |
| Solar dynamic |
| Solar-heated closed Brayton cycle |

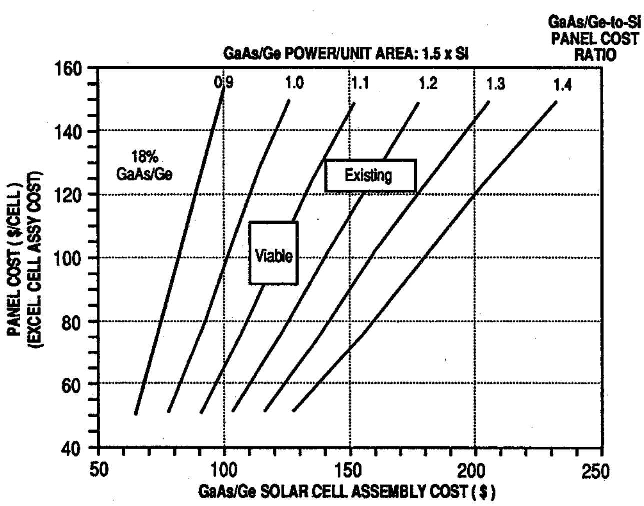


**Fig. 2 Solar panel cost comparison of GaAs/Ge cells vs Si solar cells, assuming that GaAs/Ge cells can be up to five times as expensive as Si cells. Recent experience indicates that the cost of GaAs/Ge cells is much closer to Si cells, making GaAs/Ge arrays even more viable.**

Conventional wisdom in the past was that multijunction cells were much too expensive to be considered for use. It is likely that bijunction cell efficiencies can reach 23% in production and have yields similar to the GaAs cell of today. Thus, today's conventional wisdom using an analysis based on Datum and Billets's approach,[8] suggests that bijunction cell arrays will cost approximately the same as today's Si. The next step to trijunction cells can be expected to lead to further cost and mass reductions. The efficiency goal for this cell is 30% with a cost only slightly above the bijunction cell. Additionally, production yields must equal those of GaAs/Ge. Such an achievement will lead to a major reduction of spacecraft mass and cost.

A brief description of the principal cell technologies is given in the following subsections. Additional information on advanced cells may be found in Refs. 9 and 10.

#### *Thin GaAs/Ge Solar Cells*

Thick (8-mm) GaAs/Ge solar cells have been flown in space and, more recently, thin (0.14-mm) GaAs/Ge solar cells have been flown on the Clementine spacecraft.[11] In the case of the Clementine array, thin GaAs/Ge solar cells were mounted on a low-mass graphite–epoxy/aluminum honeycomb core substrate to yield an array specific power of 53 W/kg.[11] Thin (0.14-mm) GaAs/Ge solar cells on a flexible blanket array are planned to be used on the Earth observing system (EOS) AM-1 spacecraft that is scheduled to be launched in 1998. The flexible blanket array configuration is based on the advanced photovoltaic solar array (APSA) flat-pack foldout concept.[12]

Use of thin (2- to 3.5-mm) cells offers high specific power with an efficiency of >19.1%. A coupon was part of the photovoltaic array space power plus diagnostics (PASP Plus) flight experiment.[13] This technology is ready for space application and it is very useful for the spacecraft that experiences higher radiation. The use of thin GaAs solar cells reduces the solar array size by >36% compared to Si cells.

In addition, GaAs cells anneal at about 200°C, which was verified in laboratory experiments. An annealing experiment of the GaAs cells was conducted onboard the Combined Release and Radiation Effects Satellite (CRRES) spacecraft.[14] Table 2 presents the annealing methods, operating temperatures, and the improvements achieved. Annealing by forward biasing has produced maximum improvement.

#### *Indium Phosphide Solar Cells*

Indium phosphide (InP) cells anneal at about 100°C, which was verified in laboratory experiments, and hence, the degradation caused by radiation is very minimal, as confirmed by the PASP Plus flight experiment.[13] These cells exhibit an ef-

**Table 2 Annealing of GaAs/Ge**

| String number | Annealing method | Operating temperature | EOL and BOL maximum |
|---|---|---|---|
| 2 | Constant heating | 170°C | 0.77 |
| 4 | Pulsed heating | 250°C | 0.79 |
| 6 | Forward bias pulse heating | 190°C | 0.82 |
| 8 | No heating | Reference (~80°C) | 0.75 |

ficiency of >19.1%. Use of InP cells reduces the solar array size by about 50% compared to Si cells. InP cells are usually grown on an InP substrate, which leads to an increase in mass compared to Si cells; however, the much greater resistance of InP to radiation and the greater efficiency of InP compared to Si cells can outweigh this mass difference for high-radiation applications using Datum and Billets's approach.[8] Use of other types of substrates to lower the density of these cells is expected. Recently, results were reported on InP cells that were made on lightweight Si wafers that have half the density of GaAs, Ge, or InP. In effect, by trading beginning-of-life (BOL) efficiency the end-of-life (EOL) power density can be increased by over 50%. Calculations have shown that in very high radiation environments (e.g., Van Allen proton belts), these InP/Si cells can provide over twice as much EOL power density as GaAs/Ge or Si cells.[15]

*Gallium Indium Phosphide Solar Cells*

Gallium indium phosphide ($GaInP_2$) cells offer very high radiation resistance because they will anneal in orbit. These cells exhibit an efficiency >19%. Radiation performance and efficiencies of these cells are usually presented for $GaInP_2$ grown on a GaAs bottom layer ($GaInP_2$/GaAs).[10] The use of $GaInP_2$ cells will reduce the solar array size by about 50% compared to Si cells.

*Concentrator Gallium Arsenide-on-Gallium Antimonide Solar Cells—Mini-Dome Fresnel Refractive Concentrator*

The gallium arsenide on gallium antimonide (GaAs/GaSb) concentrator cell using a minidome Fresnel lens represents state of the art in photovoltaic refractive concentration technology. Use of a concentrator cell inherently provides additional shielding against radiation; in fact, the GaAs/GaSb minidome concentrator module on PASP Plus has shown the least amount of degradation of any of the PASP Plus experiments.[13] As the actual cell size decreases with increasing concentration of sunlight, shielding can easily be increased without adding much mass to the overall array. A significant advantage resulting from concentrated sunlight (50× to 100×) is the reduced photovoltaic area required for power production. The GaAs/GaSb Fresnel concentrator technology is now part of the solar concentrator array with refractive linear element technology (SCARLET) program,[16,17] which is planning to provide the solar array to be used on the first New Millennium spacecraft (although, because of schedule, the SCARLET array on the first New Millenium spacecraft will use $GaInP_2$/GaAs cells on a Ge inactive substrate).[18] The SCARLET array offers concentration levels of about 15× and array specific powers up to 100 W/kg compared to currently used rigid planar arrays at about 25 W/kg.[16]

*Concentrator GaAs/Ge Solar Cells—Cassegrainian Reflective Concentrator*

The GaAs/Ge mini-Cassegrainian concentrator represents state of the art in photovoltaic reflective technology and has many of the same concentrator advantages listed earlier.

*Cascade Solar Cells*

In recent years researchers have developed cascade solar cells having efficiencies in a space solar or air mass zero (AM0) environment as high as 25%.[19] The GaAs/GaSb tandem solar cell described earlier exhibited an efficiency of 25.5% at one sun and 29.5% at 40 suns.[20]

The GaAs plus copper indium diselenide cell ($CuInSe_2$, often abbreviated CIS) represents a high-efficiency approach using multibandgap photovoltaics, mechanically stacking cells in a series/parallel arrangement. Such a cell stack offers high efficiency (>22%) and excellent radiation resistance. A coupon of these cells is part of the PASP Plus experiment.[13] This technology is very useful for spacecraft that experience higher atmospheric drag.

The damage coefficients of a $GaInP_2$ single-junction cell deduced from experimental testing[21] have been used to predict the performance of the $GaInP_2$/GaAs tandem cell. Such a tandem cell is capable of producing a minimum average cell efficiency over 25% (at AM0 at 28°C) at BOL, with more than 82% of the power remaining after exposure to an electron irradiation of the cell of $10^{15}$ electrons/cm$^2$ (1-MeV equivalent). For comparison, present state-of-the-art GaAs/Ge solar cells[20] provide BOL efficiencies of 18%, with only 75% of the power remaining after exposure of the cell to $10^{15}$ electrons/cm$^2$ (1-MeV equivalent). The overall advantage in using cascade cells comes from the reduction of the solar array size by about 50% compared to single-junction silicon cells.

*Advanced Large Area Cover-Interconnect-Cell*

The advanced large area cover-interconnect-cell (ALACIC) design combines a conventional cover-interconnect-cell (CIC) assembly with a large area cover to produce a circuit subassembly.[22] The resulting ALACIC provides a large area (30 × 30 cm$^2$) standardized building block circuit suitable for use on various advanced solar array structural designs. This results in less handling at the panel lay-down stage, and cost reductions beyond that achieved by large area cells. This design is compatible with Si, GaAs, and cascade cell technology; it allows manufacturing mechanization at the circuit level; and it eliminates individual cover overhang and cleanup concerns as well as reducing adverse plasma interactions in low Earth orbit.

**Solar Cell Cover Glasses**

The efficiency of the solar cells decreases as a function of time in space as a result of the susceptibility of the cell to the space nuclear particle radiation. The use of cover glasses will minimize the damaging effects of this radiation. One technology advancement of special note in this area is described next.

*Blue/Red Reflective Solar Cell Cover Glasses*

Solar cells with conventional cover glasses absorb infrared (IR) energy from sunlight but do not convert that solar power into electrical power. In fact, this IR energy is converted into heat and this results in a higher operating temperature for the solar array. To put this in quantitative context the unconvertible solar energy content (outside the response regions of the solar cells) in the ultraviolet (uv) and IR is about 41% for the GaAs cells and 31% for the Si cells. Cover glasses with blue/red reflector (BRR) coatings reflect the unusable energy back into space.[23] With this reflection the solar array will operate at a lower temperature and produce more power. It is estimated that a solar array using GaAs cells with BRR cover glasses will operate about 15°C cooler than with conventional cover glasses. This reduction in temperature results in an increase (gain) of about 3% in the power output of the solar array.

**Solar Arrays**

A solar array is normally composed of suitable series–parallel combinations of solar cells to produce the required power and the desired voltages and currents. Solar arrays are usually fabricated by mounting the cells on honeycomb or fiberglass substrates. One consideration in selecting a substrate is the ability to withstand the initial launch vibration and acceleration stresses as well as the operational thermal stresses. The following subsections describe some of the advancements in solar panels/arrays.

*Advanced Photovoltaic Solar Array*

The advanced photovoltaic solar array (APSA), which is shown in Fig. 3, has been developed and tested, showing that it is possible to obtain 130 W/kg in geosynchronous Earth orbit (GEO) 12-kW applications at BOL using currently available technology and components, compared to the 10–25 W/kg with state-of-practice arrays.[24] As noted earlier, this technology, which places the solar cells (e.g., thin Si cells or GaAs

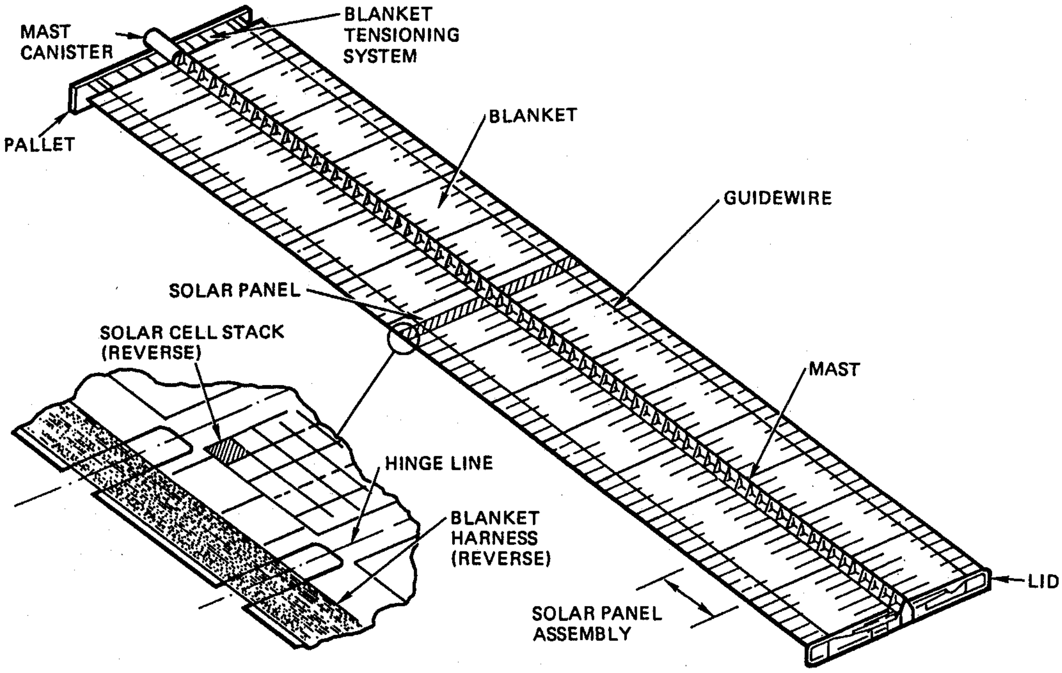


**Fig. 3 Generic wing structure for the APSA. For a 5.8-kW GEO deployed wing the length would be 15.25 m for a 40-cell-covered panel blanket, plus two leader panels, and the blanket width would be 2.85 m.**

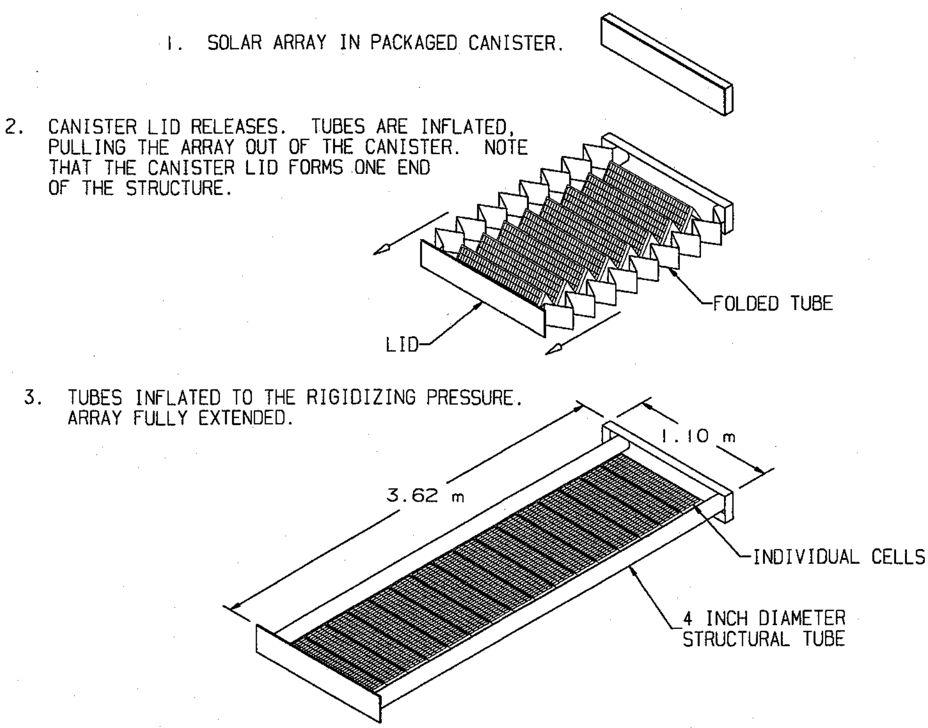


**Fig. 4 Diagram of the inflatable torus solar array showing the method of operation.**

cells) on flexible Kapton substrates, has been accepted for use on the EOS, which is to operate in low-Earth orbit (LEO). Clearly, the APSA technology by itself, allows at least a fivefold reduction in solar array mass or a fivefold increase in power for the same mass. (In the modifications made specifically for EOS, including the use of thicker GaAs cells than planned for APSA, the APSA technology will deliver about 39 W/kg at BOL, but this is still better than state-of-practice arrays.)

*Inflatable Torus Solar Array with High Specific Power*

A variation on the APSA approach is the recently constructed inflatable solar array designed for the 200- to 1000-W range with specific powers as high as 93 W/kg for a 200-W-class wing, including structure and deployment mechanism. A test article has already been built showing 59 W/kg without using the improved components.[25] Instead of a mast or a set of rigid panels, two inflatable cylindrical tubes constructed of a polyimide–aluminum film laminate are attached to a thin polyimide-substrate solar cell blanket. The tubes are sized for the array's mass properties and the expected loads in the deployed state. The array system is deployed by controlled tube inflation as shown in Fig. 4. The tubes are then rigidized mechanically by controllably introducing a slight overpressure.[25] For large systems (>1000 W), chemical rigidization, e.g., through uv action, can possibly be utilized instead. Because of

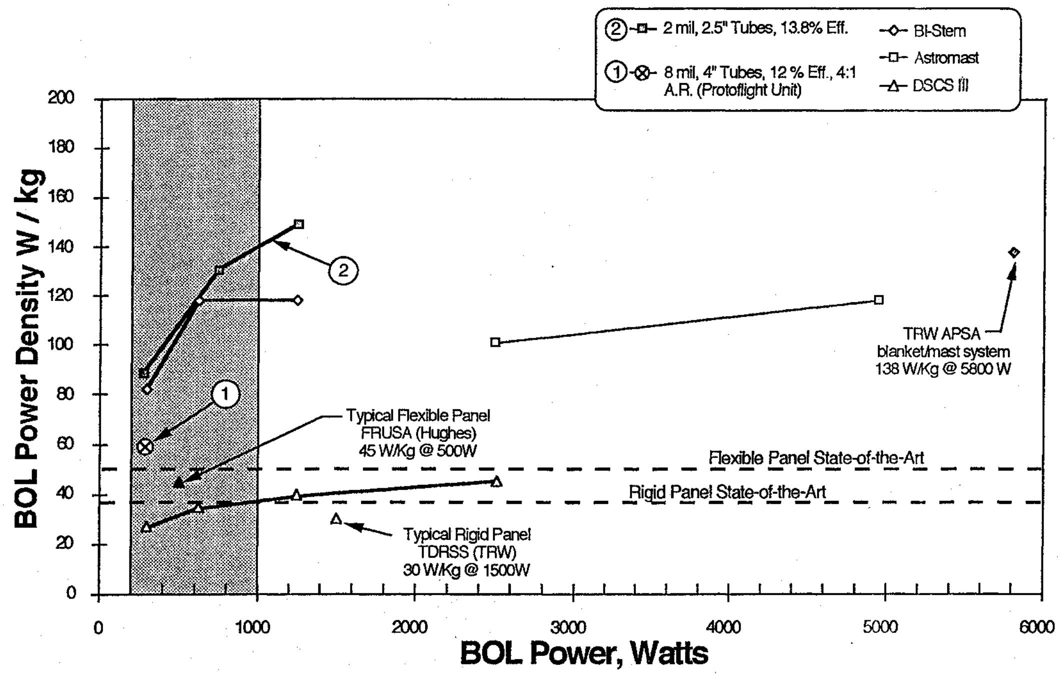


**Fig. 5 BOL specific power (watts/kilogram) as a function of BOL power (watts) for the inflatable torus solar array.**

the low-mass deployment/structural system, such inflatably deployed solar arrays offer the promise of lower stowed volume, cost and mass, especially for low-power spacecraft. For large arrays (>1000 W), as illustrated in Fig. 5, specific powers larger than 140 W/kg can be expected.[25]

*UltraFlex Fan Solar Array with Very High Specific Power*

The UltraFlex solar array[26] incorporates the use of a blanket substrate, which is thermally compatible with silicon and other materials typical of advanced multijunction cells. The blanket materials 1) are intrinsically insensitive to atomic oxygen degradation, 2) are space rated, and 3) are compatible with standard cell bonding processes. The deployment mechanism is simple and reliable and the structure is inherently stiff (high natural frequency). Mechanical vibration modes are also readily damped. The specific power performance data for several rigid and flexible solar arrays including UltraFlex have been compiled to compare with UltraFlex. Such an array offers specific powers >100 W/kg with a high stowed-volume efficiency. For small solar arrays the specific power may drop somewhat. An engineering model has been built and tested.

*SCARLET*

Conventional wisdom suggests that only planar arrays will be used in space. However, with the emphasis on cost reduction, the old concentrator array has seen a rebirth. With 50-fold concentration, the cell area becomes an insignificant part of the array. As stated in Ref. 17,

> . . . concentrator technology allows arrays to have much lower cell area for a given power level. For instance, a concentrator array with a 15:1 geometric concentration ratio requires about 7% the active solar cell area of a traditional planar array. This equates to a direct 93% reduction in solar cell material costs which are a large component of total array costs.

The optics are refractive Fresnel lenses that are inexpensive to produce. It is anticipated that concentrator array costs with GaAs cells will be approximately 50% that of a comparable planar array. Figure 6 shows the latest embodiment of the optical light-ray trace for SCARLET. The linear Fresnel lens provides great off-pointing tolerance in one direction. With channels orthogonally positioned, this array should have great tolerance to many off-pointing conditions. Figure 7 indicates that even with a 40-deg off alignment, this concentrator array will still produce about one-half its maximum power with single-axis tracking. SCARLET should provide EOL specific powers in the range of 70–100 W/kg.[17]

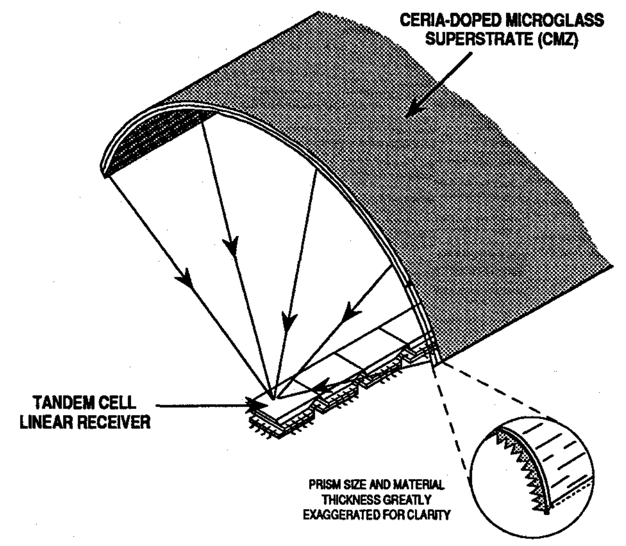


**Fig. 6 Partial optical ray tracing of an element of a linear Fresnel lens concentrator element with a line-focus tandem cell receiver.**

*Enhanced Power Generation by Use of Optical Solar Reflectors*

A novel arrangement has been proposed to enhance the power generating capabilities of a spin-stabilized geostationary satellite (spinner). In this arrangement, the unilluminated solar array area of the usual spinner (as sunlight illuminates only one side) would be illuminated by employing despun optical solar reflectors. This arrangement can increase the power generation by about 2.7 times that which an ordinary spinner can generate. The mass per unit power and cost per unit power will decrease, respectively, to 0.5 and 0.4 times that of an ordinary spinner.[27]

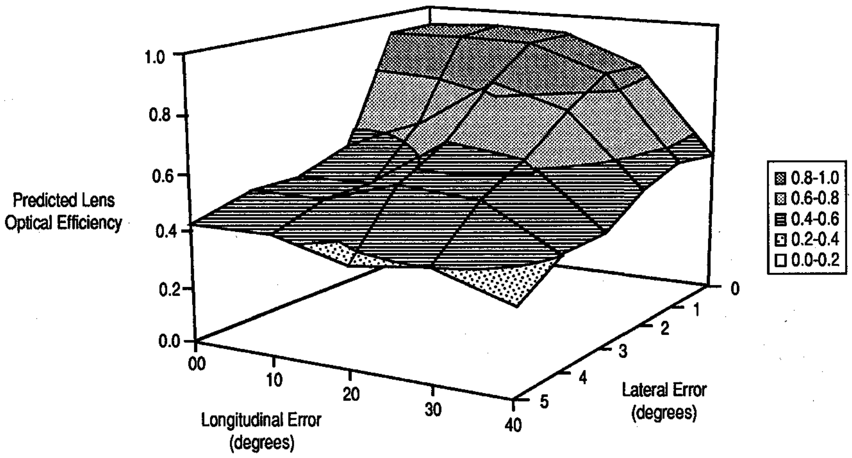


**Fig. 7 Predicted optical lens efficiency as a function of off-pointing for a linear refractive concentrator of the single-axis tracking design (without an optical secondary).**

*Modular Concentrator with High Efficiency Photovoltaics*

A conceptual design has been developed for a modular parabolic trough photovoltaic solar concentrator that could provide power for an evolutionary space station with reduced mass and area compared to current baseline technology. The design, which has been termed SLATS (solar low aperture troughs), features a cylindrical parabolic mirror that focuses sunlight onto the back of an adjacent mirror upon which a solar cell assembly is placed. SLATS improves the specific mass and area through the inherent heat sinking and shielding provided by the mirror, which also reduces the solar cell size required per watt by virtue of concentrating the sunlight. Solar energy incident on the mirror is reflected onto the solar cell at a geometrical concentration ratio of 20:1. Optimization studies show an ability to exceed 50 W/kg and 200 W/m$^2$ using demonstrated 30%-efficient solar cells (e.g., GaAs/GaSb cells) at the EOL for a 10-year panel life. This technology would be very useful for spacecraft that experience higher radiation.[28]

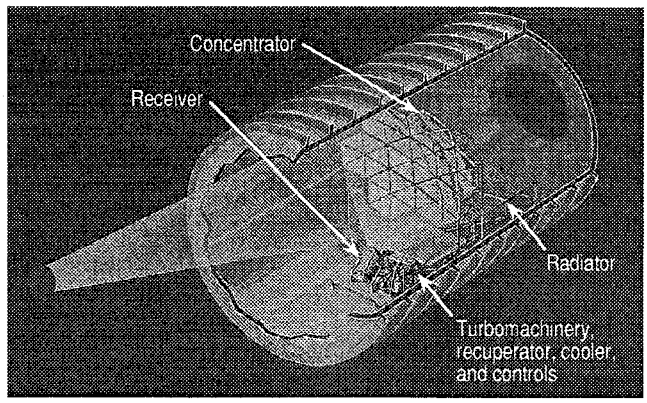


**Fig. 8 Artist's concept of the 2-kW solar dynamic ground test demonstrator unit in Tank 6 at NASA Lewis Research Center.**

**Solar Dynamic Systems**

In contrast to photovoltaic systems, solar dynamic power systems utilize the sun's solar energy flux to heat a working fluid to drive a turbine–alternator power conversion system. Such dynamic conversion systems can, in principle, achieve conversion efficiencies of 30% or more and, through the use of thermal energy storage materials for eclipse periods, they can eliminate the need for electrochemical (battery or fuel cell) energy storage systems. In the 1960s and 1970s, interest in solar dynamic power systems was high. Space station studies in the 1980s showed that solar dynamic systems had tremendous life-cycle cost benefits compared to silicon-cell solar arrays. This led ultimately to the ongoing 2-kW solar dynamic ground test demonstration project, which is providing the first system-level demonstration of this technology for space use.[6] Success in this test, which is shown diagrammatically in Fig. 8, will pave the way for the utilization of solar dynamic power on many missions. To date, the ground testing has shown end-to-end system efficiencies ranging from 13.8 to 16.1%, which compare very well with the end-to-end efficiencies of about 4% for large photovoltaic/battery systems.[6]

## Energy Storage: Batteries

Energy storage is the second major element of electrical power systems and, since it can consume up to 10% of the mass of a spacecraft, improvements are clearly needed.[29] Through energy storage a spacecraft can continue to be powered when the power source is not providing power (such as during the eclipse phase of an orbit), or the power provided by the power source can be augmented for short periods as required. Energy storage is usually provided by electrochemical batteries; although fuel cells have been used on missions such as Apollo and the Space Shuttle.[7] Electromechanical systems such as flywheels can also be used to store energy. Batteries generally come in two types: 1) primary (used once) and 2) secondary (rechargeable). Primary batteries are used on launch vehicles[30] and certain specialized missions such as the Galileo Probe. Secondary batteries are generally used on spacecraft that must operate for a long time in cyclical shadowing applications, and so they will be the focus of this section, which is divided into nickel-based batteries and other technologies. Table 3 lists some of the promising secondary batteries that will be discussed.

**Nickel-Based Batteries**

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.[29] Typical state-of-the-art cell specific energies for NiCd are on the order of 39 watt-hours per kilogram (W-h/kg) and for $NiH_2$ are on the order of 50 W-h/kg.[31] Because of its longer life and greater depth of discharge (DOD), $NiH_2$ batteries are replacing NiCd batteries, especially in GEO and in satellites operating at more than 1 kW.[29] Recently, however, $NiH_2$ batteries have been replacing NiCd batteries for LEO missions. The breakthrough that made this revolution in LEO was the use of 26% potassium hydroxide (KOH) as the electrolyte instead of 31% KOH and the use of catalytic wall wicks.[32,33] In turn, these breakthroughs in LEO designs could be used to improve the performance of GEO satellites. Certainly, lifetimes of 40,000 cycles at 60–80% DODs for LEO cycles may open the door to new uses of $NiH_2$ batteries in GEO.[32,33]

**Table 3 Chemical energy storage, new technologies**

| |
|---|
| Nickel-based batteries |
| NiCd batteries (improved) |
| $NiH_2$ batteries |
| Individual pressure vessel |
| Common pressure vessel |
| Single pressure vessel |
| Dependent pressure vessel |
| Bipolar |
| Nickel–metal hydride cells |
| Additional battery technologies |
| NaS batteries |
| Lithium ion |
| $Li-TiS_2$ |
| Lithium polymer |

*NiCd Batteries*

NiCd batteries were the early choice for satellites and, for a long time, they were considered a mature, cost-effective technology that also had a strong technical base through use in terrestrial systems. Unfortunately, a series of problems such as degradation of the electrodes and hydrolysis of the separator limited the lifetime and performance of NiCd batteries.[29] Also, cadmium is a material that must be controlled for environmental reasons. However, NiCd batteries have been improved recently, and may, for cell sizes under 32 ampere-hours (A-h), have useful lifetimes and specific energies comparable to state-of-the-art $NiH_2$ batteries.[29]

*$NiH_2$ Batteries*

$NiH_2$ batteries can be built in several designs: individual pressure vessel (IPV), which is the system currently in use; common pressure vessel (CPV); single pressure vessel (SPV); dependent pressure vessel (DPV); and bipolar.[29,34] Programs are under way to improve the specific energy of $NiH_2$ batteries beyond the state of the art of 50 W-h/kg. (The theoretical specific energy is >400 W-h/kg.[29]) With the positive electrode and the pressure vessel accounting for >70% of the mass of a cell, these have been natural foci for mass reduction efforts.[29]

The CPV approach achieves mass reductions on the order of 10% by combining two or more cells within a SPV.[29] The SPV design extends the CPV approach by having all of the cells within a single unit such that only the full battery connections are external. For the Clementine mission, the SPV approach in a 15-A-h battery capacity reduced the mass by 25%; the volume was reduced by 80% such that the specific energy was more than 70% greater than for an $11 \times 2$ cell CPV battery of the same capacity.[29]

The DPV design improves upon the $NiH_2$ battery by having each cell support the next much like a stack of pie plates.[29,34] The calculated specific energy for this DPV design is 76 W-h/kg.[29] The bipolar design achieves its improvements by fabricating thick electrodes back-to-back, positive-to-negative, and then stacking them within an SPV to provide significant savings in mass and volume.[29]

*Nickel–Metal Hydride Cells*

There is a growing market for smaller, lower-cost satellites that require higher specific energy batteries than NiCd batteries, but at a lower cost than $NiH_2$ batteries. Small satellites typically do not have the spacecraft volume or the budget required for $NiH_2$ batteries. Metal–hydride batteries provide the ideal solution for these applications.[35] Hydrides are a large class of chemical compounds (including both metallic and nonmetallic) known to reversibly store relatively large quantities of hydrogen under a variety of conditions. By storing the hydrogen as a solid hydride instead of a free gas, the volume of the battery can be reduced. The metal–hydride system contains no toxic materials such as lead, cadmium, or mercury. This provides enormous environmental benefits over other battery systems in terms of manufacture, disposal, and recycling of spent batteries. These cells, packaged similarly to NiCd cells, offer specific energies similar to $NiH_2$ batteries, but with a >25% reduction in volume and a 50% reduction in mass over the $NiH_2$ IPV battery design.[35]

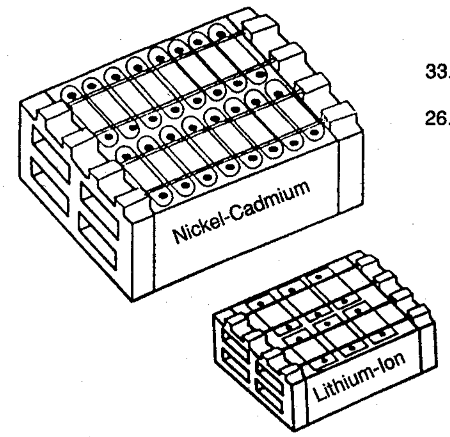


**Fig. 9 Comparison of 42-A-h battery technologies showing the reductions in mass and volume that can be achieved with the higher specific energy technology of lithium ion batteries.**

**Additional Battery Technologies**

With nickel-based batteries currently at specific energies on the order of 50 W-h/kg (although with improvements projected to take $NiH_2$ batteries to $\geq 100$ W-h/kg), there is clearly room for improvement.[29] Two technologies that are currently being pursued for future spacecraft are sodium–sulfur (NaS) and rechargeable lithium (Li) systems.[29] NaS batteries promise 100 W-h/kg and Li systems can achieve up to 150 W-h/kg.[29,31]

*NaS Batteries*

NaS batteries offer the possibility of very high-specific energies (~100 W-h/kg) compared to the nickel-based systems. The NaS system offers a single-cell, open-circuit potential of 2.07 V (working voltage of 1.8–1.9 V), which means fewer cells are required per battery. The operational temperature of 350°C (vs 20°C for NiCd and $NiH_2$) requires the use of multilayer insulation and thermal standoffs and the possible use of external batteries to bring the NaS battery up to operating temperature.[31,36]

*Lithium Battery Systems*

Three types of lithium battery concepts have been considered recently: 1) lithium–ion (~95 W-h/kg), 2) lithium titanium disulfide ($Li-TiS_2$) (~135 W-h/kg), and 3) lithium polymer (~150 W-h/kg).[29,31,37] Small, 1-A-h lithium–ion cells have demonstrated several thousand cycles, and cells of up to 5-A-h capacity have demonstrated 300 cycles at 50% DOD. This technology will provide stored energy of about 100 W-h/kg for small spacecraft requiring several thousand cycles. This technology is envisioned to be an important technology for future planetary science missions. As an example of the benefits of lithium–ion batteries, Fig. 9 compares the mass and volume of the NiCd battery used on Mars Observer with an equivalent 42-A-h lithium–ion battery.[31] $Li-TiS_2$ technology offers the potential of even higher stored specific energies and over 1000 cycles have been demonstrated at 50% DOD. However, further work is required to ensure safe operation of this cell that utilizes a metallic–lithium anode. Small capacity lithium polymer cells have been fabricated and tested to >100 cycles at 100% DOD.[37]

## Power Management and Distribution

The third leg of the EPS triad is PMAD or, as it is sometimes termed, the power conditioning and control system (PCCS). In any type of power system, the outputs of the solar cell array and the energy storage battery are to be conditioned so as to match the requirements of the various subsystems (e.g., matching voltage and current requirements for sensors or transponders). The battery has to be charged from the solar cell array during the orbital day and discharged to provide power during the orbital night, or when the load demand exceeds the solar cell array capability. All of these functions are carried out by the PMAD system.

Historically, the mass of the PMAD system has been increasing toward 10% of the dry mass of the spacecraft. Current packaging technology, which is based on discrete electronic parts, leads to a power density of 0.02 W/cm$^3$ and a specific power of 0.05 W/g. To meet the requirements for future smallsats, the goal is to reduce the mass to 2–4% of the total spacecraft dry mass, which means that the electronics designs and technologies will have to lead to mass and volume reductions of 65 and 80%, respectively. Already some of these goals are being achieved through hybrid electronics packaging and high-efficiency switching and conversion components.[37] An advanced solid-state switching module and a high-efficiency dc–dc converter are planned to be used on the first New Millennium spacecraft. The use of intercalated graphite composites can reduce the mass of electronic boxes while providing excellent shielding against electromagnetic interference (EMI). It has been estimated that this change can lead to savings of about 17% in power conditioning system mass, with no other advances in power system technology.[38] The following sections elaborate on a few of the exciting new ideas in PMAD technology.

### Solar Array Positive Grounding

All space systems in LEO interact with the ionospheric plasma, producing surface and system potentials required for net zero current. With conventional satellite power distribution systems moving toward higher voltages to reduce ohmic power losses, the results of flight tests are critical to determining the performance of power systems in LEO. In the case of the space station with its high-voltage, negatively grounded power system, it has been found that these interactions would produce unacceptably large system floating potentials; with consequent arcing, sputtering, and related destruction to thermal control surfaces.

In the early 1980s a flight test to determine the voltage operating limit of solar arrays was proposed, yet never flew. Recently, the solar array module plasma interactions experiment (SAMPIE),[39] an experiment to determine the plasma interactions of the space station and other solar cell modules, flew successfully. The test results conclusively demonstrated that the negative grounding scheme did require a plasma contactor to prevent arcing, and that present theories predicted the effects and the magnitude of collected currents with good fidelity.[40,41] Thus, 120-V dc systems with negative grounding and flying in LEO must take special care. Other strategies for potential control include positive grounding of arrays to the structure, design of the arrays to minimize or eliminate the electron collection, selection of conductive surface coatings to maximize ion collection, control of system and power system voltages and operating modes, or some combination of these.

### Miniaturized Microprocessor-Controlled Peak-Power Tracker

To meet the demanding requirements of spacecraft, it is necessary that new and improved methods of electrical power conditioning and control be developed. In recent years, the use of microprocessors for power processing have been successfully implemented, resulting in improved performance.[42–44] For example, a miniaturized microprocessor-controlled peak-power, tracker-type power system has been developed. In particular a 100-W peak-power tracker has been built and qualified. In these systems the battery is connected at the output of the peak power tracker and load and, thus, it offers low impedance to the loads.

Use of a peak-power tracker can reduce the solar array size by 1) >15% for nontracking arrays [e.g., the Thermosphere–Ionosphere–Mesosphere Energetics and Dynamics (TIMED) spacecraft that have to fly edge-on]; and 2) >10% for tracking arrays in LEO (depending upon the type of solar array).

### Advanced Photovoltaic Array Regulator Module

As part of the trend toward smaller, more reliable, and less expensive spacecraft, a modular PMAD system has been designed based on an innovative dc voltage boost converter called the series connected boost unit (SCBU).[45,46] By using an isolating dc–dc converter and adding a unique series connection, the SCBU offers higher efficiency (94–98%), specific powers above 1000 W/kg, inherent fault tolerance, and lower parts count than conventional series and shunt regulators.[46] This SCBU architecture is capable of performing solar array peak power tracking and regulated payload bus operation. A photovoltaic regulator kit experiment, based on the SCBU concept, has been designed and fabricated using commercial off-the-shelf power converter electronics and support circuitry. This experiment will be tested as part of the small spacecraft technology initiative (SSTI) program.[47]

## Conclusions

It is clear that a major revolution in thinking has taken place in the design of spacecraft. The desire to reduce costs and maintain performance has led to the consideration of new (and some not-so-new) technologies. As we have shown, ultra-high-efficiency solar cells, low-mass solar arrays, improved battery technology, and innovative power management technologies have made and can make substantial impacts on spacecraft. In summary, the technology exists today to reduce the overall mass of the electric power system to at least 50% of state-of-practice. This means a typical spacecraft can free up on the order of 12% or more of the total mass for payload, or the spacecraft can have double the power output for the same mass. The increased power can be used for electric propulsion, which allows even more improvements in performance.[4]

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