

## ASPEC—SOLAR POWER SATELLITE

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## INTRODUCTION

The solar power satellite (SPS) will provide a clean, reliable source of energy for large-scale consumption. The system will use satellites in geostationary orbits around the Earth to capture the Sun's energy. The intercepted sunlight will be converted to laser beam energy that can be transmitted to the Earth's surface. Ground systems on the Earth will convert the transmissions from space into electric power. Figure 1 shows the overall system concept.

The preliminary design for the SPS consists of one satellite in orbit around the Earth transmitting energy to a single ground station. The SPS design uses multilayer solar cell technology arranged on a 20 km<sup>2</sup> planar array to intercept sunlight and convert it to an electric voltage. Power conditioning devices then send the electricity to a laser, which transmits the power to the surface of the Earth. A ground station will convert the beam into electricity. Typically, a single SPS will supply 5 GW of power to the ground station. Due to the large mass of the SPS, about 41 million kg, construction in space is needed in order to keep the structural mass low. The orbit configuration for this design is to operate a single satellite in geosynchronous orbit (GEO). The GEO allows the system to be positioned above a single receiving station and remain in sunlight 99% of the time.

Construction will take place in low Earth orbit (LEO); array sections, 20 in total, will be sailed on solar wind out to the GEO location in 150 days. These individual transportation sections are referred to as solar sailing array panels (SSAPs). The primary truss elements used to support the array are composed of composite tubular members in a pentahedral arrangement. Smart segments consisting of passive and active damping devices will increase the control of dynamic SPS modes.

## PROJECT BACKGROUND

Modern society is based on technology that depends primarily upon burning fossil fuels as an energy source. Unfortunately, dependence on this form of energy has many associated problems. Regional, political, and religious conflicts can disrupt worldwide distribution of fossil fuels, which can threaten world stability and peace. The search for alternative sources of energy has led to the development of solar power. Compared to fossil fuels, the Sun promises to be an infinite source of energy. Technology has already created the means to harness the power of the Sun cheaply and efficiently without the drawbacks of fossil fuels. This study builds upon a concept formulated in 1968 by Peter Glaser and on research conducted in the late 1970s on Satellite Power Systems. ASPEC's objectives are to make an integrated satellite design and to update previous findings with the application of modern technologies.

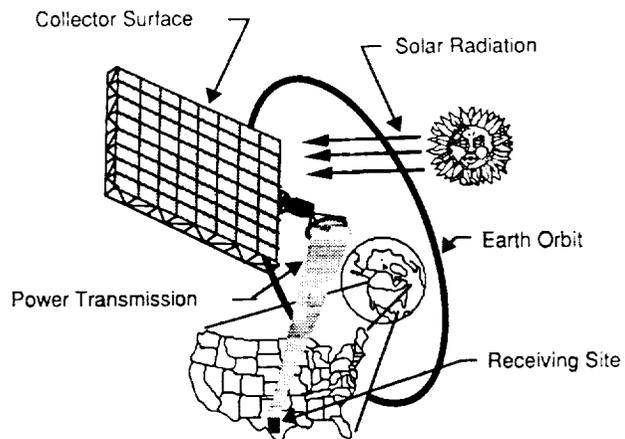


Fig. 1. Overall system concept.

## SYSTEM GUIDELINES

Guidelines for the Satellite Power System design have been established by the Request for Proposal in the form of assumptions and requirements. The following are selected assumptions used to guide system development: (1) technology available by the year 2000; (2) cost is not a design parameter; (3) launch failure rate is 1%; and (4) weight growth factor of 15% should be reflected in final mass estimates. The following are the basic system requirements: (1) the SPS will supply 5 GW to a ground site; (2) damage to Earth and space environment is minimal; (3) space debris from construction/operation is minimal; and (4) system life is 30 years.

## SOLAR TECHNOLOGY

The selection of a solar to electrical energy conversion method is a primary consideration in realizing the SPS concept. This study researched the two methods of energy conversion considered to be feasible for use by the year 2000, solar dynamic systems and solar photovoltaic cells. After completing research on these two types of energy conversion methods, solar photovoltaic cells were selected for use on the SPS. This selection was based upon a comparison of the relative advantages and disadvantages of the two conversion methods.

ASPEC proposes to reduce the costs of the solar array by using plastic lenses to concentrate sunlight onto small-area single crystals. The concentrator lens/solar cell approach has additional advantages over single crystal units. Since the cells are small and located behind lightweight optics, they are shielded for improved radiation resistance leading to higher end-of-mission performance. Also, the use of smaller size solar cells leads to

higher manufacturing yields. As Fig. 2 shows, assuming one defect per wafer, the material utilization is 90% in the small concentrator cell approach, as opposed to 64% for large flat plate solar cells. Lightweight, plastic Fresnel lenses have been chosen for the SPS design. In addition to their low weight, the lenses can be manufactured easily and inexpensively in mass quantities<sup>(1)</sup>.

In the last decade, solar cells have consisted of a single layer of material converting a specific range of the solar spectrum to electricity. Efficiencies as high as 24% in the space environment have been recorded using this approach. Recent breakthroughs in solar technology have led to the development of double- and triple-layer cells. Current work with two-layer tandem cells has produced cells achieving efficiencies as high as 31%<sup>(2)</sup>. Predictions have been made for three-layer tandem cells with conversion efficiencies of 48.6%. Such highly efficient cells are ideally suited for the SPS, resulting in a reduction of the number of cells and the size of array panels needed to produce 5 GW.

The Solar Technology subgroup conducted research to select the appropriate materials for each layer of the stacked cell. Current research indicated GaAs and AlGaAs as prime candidates for the top layer. Silicon, GaSb, or InP are possibilities for the second layer. The most work remains to be completed in the manufacturing of the third layer. By the year 2000, based upon trends in solar technology, the major candidate for the bottom layer is InGaAsP<sup>(3)</sup>. In developing efficient multilayer solar cells, each layer must be made transparent to certain frequencies of light used in the lower cells. To accomplish this, the solid metal backing normally used to collect and conduct the current on conventional cells is eliminated. In its place is a grid of fine metal lines on the top of the cell that perform the same function<sup>(2)</sup>.

The concept of a multiple stack concentrator cell is demonstrated in Fig. 3. The concentrating lens is fixed above the stack (typically at a height of 1"). Light passes through the lens and is focused onto the smaller cell assembly where it first strikes a prismatic Entech cover. This cover bends the light around the metal gridlines on the surface of the solar cell.

**ORBITS AND CONTROLS**

Control of the SPS is accomplished by integrating the components used on SSAPs into a complete system once at the GEO station. The SSAPs will be assembled at a space factory in LEO.

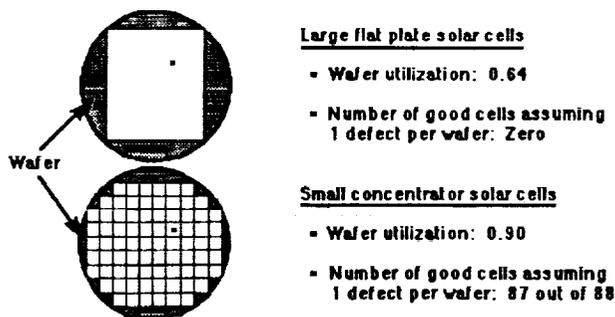


Fig. 2. Small concentrator cells lead to higher manufacturing yields.

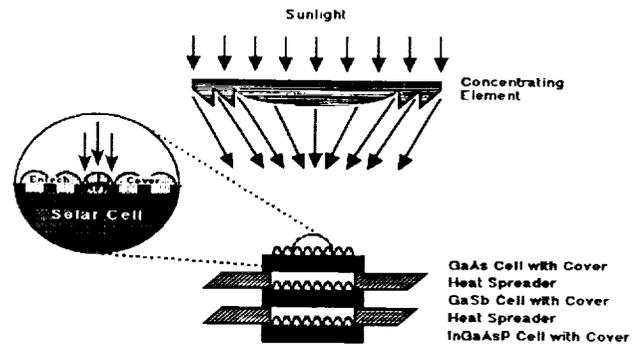


Fig. 3. Multistack solar cell.

All the materials required for this will be sent up to LEO with a heavy lift launch vehicle (HLLV). This could be accomplished with a smaller vehicle, but even with an HLLV that can carry  $2.5 \times 10^5$  kg to LEO, it will take at least 165 launches.

Each SSAP will consist of a 1-sq-km section of the solar array, four gimballed ion thrusters, two cylindrical pressure vessels that each contain 77,200 kg of argon, and an attitude reference determination system (ARDS). The ARDS consists of a charged coupled device (CCD), Sun sensor, two CCD star sensors, a set of three rate gyros, and a processor that will interpret the sensor readings and control the thrusters. The total mass of each SSAP is  $2.055 \times 10^6$  kg. Figure 4 shows an SSAP.

After the SSAP is assembled, it will spiral out with a constant tangential, low thrust to GEO where the fully assembled SPS will be. The SSAP will power itself with its solar array that will remain perpendicular to the Sun's rays. The SSAP will also have batteries for power during shadow. The transfer will be powered by four ion engines; preliminary calculations show that the resulting thrust should be tangential to the transfer path. The total time of this transfer is approximately 150 days.

Once the SSAPs arrive at GEO, they will be integrated into the SPS. This will be done by telerobotics. The thrusters and ARDS will be removed from each of the SSAPs and the SSAPs will be joined together to form the SPS. The thrusters will be attached to the corners of the SPS (20 at each corner), one pair of ARDSs will be located at each corner of the SPS, one pair will be located at the center of mass of the SPS, and one pair will be located on each side of the transmission dish. The processors will be removed from the remaining six ARDSs and evenly spaced along the SPS array and converted to monitor damage. The leftover sensor and gyros will be stored with the robots in case they are needed later as replacement parts. The thruster system features an argon ion bombardment thruster reaction control system operating an average of 36 thrusters at a time. Each thruster is an argon ion bombardment thruster with a specific impulse of 13,000 sec and a thrust of 23 N. They require 1275 kW of power, and a 1-m aperture. The thruster system will be controlled by the attitude control computer. The attitude control computer will receive its information for the processors from each of the ARDSs.

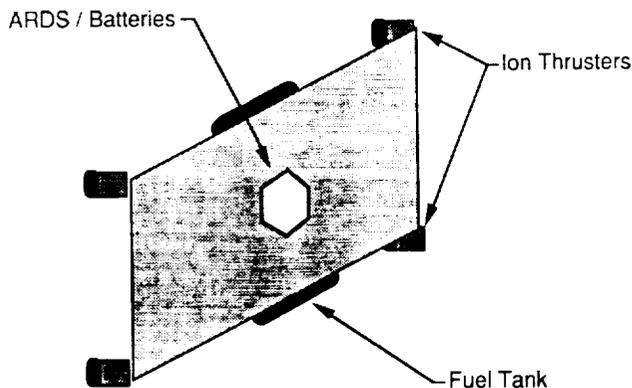


Fig. 4. Configuration of an SSAP

### POWER TRANSMISSION

The Power Transmission subsystem studies selected a CO<sub>2</sub> laser-based subsystem. Laser and microwave were compared based on five criteria: size of transmission optics, efficiency, flexibility of system, development of technology, and area of ground station required.

Size of transmission optics was considered the most important criterion. Depending on the type of laser chosen, the transmitting antenna will be 10 m to 60 m in diameter and weigh from 10,000 to 100,000 kg<sup>(4)</sup>. The next criterion is electric-to-beam conversion efficiency. Laser conversion is estimated to have significantly lower efficiency (30%-80%, depending on the type of laser) than microwave conversion (80%-90%)<sup>(4)</sup>. This is the only area where the laser concept falls below that of the microwave. Flexibility of the system is incorporated into future possible operating scenarios. Since the laser beam is small, it could be employed for aircraft propulsion or to provide power for spacecraft or space stations. The development of laser technology is behind that of microwave, but research is continuing to advance laser capabilities, especially in SDIO studies. Finally, the area of the ground station is a relatively minor criteria, because the cost of purchasing real estate may be considered negligible when compared to the other costs of this project. The amount of area required for a ground station to receive a laser beam (about 200 acres) is much smaller than the area required to receive a microwave beam (about 80,000 acres)<sup>(4)</sup>. After considering and weighing the previously described criteria, ASPEC chose laser as the best mode of power transmission for the SPS.

The Laser Power Transmission Subsystem (LPTS) will consist of four major elements: electrical power supply, the closed cycle laser, heat removal, and optics. These elements are detailed in the following section. A side view of the LPTS is shown in Fig. 5.

The LPTS will require some power conditioning of electricity that is produced by the solar arrays. This power conditioning is needed to convert lower-voltage solar cell power into high-voltage power for laser pumping. This can be done at an efficiency of 95% or higher<sup>(5)</sup>.

Four types of laser considered were the carbon dioxide laser, carbon monoxide laser, iodine solar pumped laser, and semi-

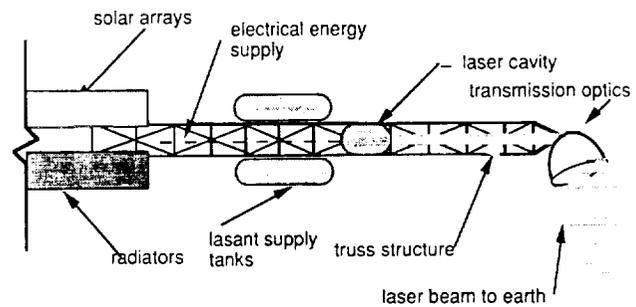


Fig. 5. Laser subsystem—side view (not to scale).

conductor diode lasers. The first electrically driven laser developed was the carbon dioxide (CO<sub>2</sub>) laser. It has a wavelength of 10.6  $\mu\text{m}$ . A geosynchronous satellite will require a 60-m-diameter aperture to beam a 10-m-diameter spot on the ground. As of 1989, the CO<sub>2</sub> laser is the most developed high-powered gas laser and promises an open cycle efficiency of greater than 60% operating at 409 K<sup>(5)</sup>.

The heat removal element of the LPTS consists primarily of radiators. If it is assumed that the selected CO<sub>2</sub> laser can operate at 80% efficiency, then 1.316 GW will be absorbed by the lasant and must be removed continuously to maintain the lasant at operating temperature. This task will be performed by radiators nearly 1.22 sq km in area. The radiators will be located near the transmission end of the SPS, underneath the solar arrays, in order to protect the radiators from heating and solar degradation<sup>(6)</sup>.

An adaptive optical system employing active controls to remove beam aberration aims and focuses the laser radiation. The transmitting aperture expands the narrow beam from the laser device and corrects for any beam distortion. A Cassegrain aperture configuration using a large concave primary mirror and a small convex secondary mirror is employed. The primary mirror surface is composed of small mirrors supported by 5 actuators on a truss structure. The combination of these actuators and mirror segments conforms the primary mirror to the desired shape<sup>(7)</sup>.

### SAFETY

There are many safety concerns associated with beaming lasers to Earth. The primary concern is the effect laser beams might have on humans in the vicinity of the reception site. This problem is avoided by locating the receiving site in an area of sparse population and building a fenced buffer zone around the target area. Another safety concern is whether airplanes will be able to fly through this beam. A radiation level as high as 1.5 W/cm<sup>2</sup> is permitted for aircraft, but the system will beam as much as 10 W/cm<sup>2</sup> to the ground. Thus, airplane flights will have to be restricted away from the vicinity of the beam<sup>(4)</sup>.

## STRUCTURES

With a required solar array area on the order of 20 sq km (about 7 sq m), the SPS will be by far the largest man-made structure ever placed in orbit. The supporting truss structure is required to support the cell arrays, support the subsystems, and give accuracy to the pointing of the arrays. Three types of trusses were considered: tetrahedral, A-frame, and pentahedral. The pentahedral truss combines ease of serviceability and load handling efficiency. This design contains no tension members while allowing access to the square sub-arrays, which easily lend themselves to modular design. As a result of these advantages, the pentahedral truss was chosen to be the primary supporting structure for the SPS.

## MATERIALS

The choice of materials is another important consideration in the design of the SPS structure. Availability, low manufacturing costs, and a large amount of existing performance data make conventional alloys primary candidates for use as materials for structural members. Aluminium alloys feature a high stiffness-to-density ratio and excellent workability and a low level of magnetism. Unfortunately, aluminum's low yield strength may be prohibitive<sup>(6)</sup>. Composites combine high strength, extremely light weight, low thermal conductivity, and tailorable elastic properties making them another worthy candidate for use as structural member materials. Effective oxidation coatings are essential, however, because even slight damage to the surface (which may be ignored with conventional alloys) can destroy the integrity of the composite fibers, resulting in a catastrophic failure. In addition to the special coating, electrical grounding must be achieved by using conductive strips located throughout the structure. As a result of these drawbacks, composites have been previously relegated to roles as secondary structures<sup>(6)</sup>. New developments in the field, however, are occurring at a rapid pace, and it is thus not unreasonable to expect that solutions to such problems may be found in the very near future<sup>(8)</sup>.

As a result of these projected developments, composites have been chosen as the primary material for the SPS truss structure. Specifically the material data for DuPont Kevlar 49 was used in all structural calculations.

## SMART STRUCTURES

The large, flexible supporting structure required by the SPS will require an advanced structural control system. Active structural elements that will be able to independently vary their damping coefficients will be dispersed throughout the structure where they will automatically respond to minimize any damaging effects. Active members using electrorheological (ER) fluids as a stiffening mechanism show particular promise<sup>(9)</sup>. Electrorheological fluids possess the unique property of a viscosity that varies with an applied electric field. As a result, a nearly immediate increase in damping in response to structural vibrations

is possible. Besides controlling the damping electronically, a structural increase in damping can be accomplished by using an elastomer between layers in the composite tubes. The inner and outer tubes can then shear independently and excess energy is absorbed in the elastic layer.

## MODULAR CONSTRUCTION

Due to the sheer size of the SPS, it is not feasible to attempt to assemble the entire satellite in LEO and then transport it to GEO. Thus, the structure must be designed with some degree of modularity. The SPS will be constructed from a number of individual SSAPs. The SSAPs are in turn composed of smaller individual solar panels. These panels will also be incorporated into individual modules containing their own lenses, solar cells, and rigid backing structures. Thus, the solar panels are designed to be easily removed and replaced. Construction of the SPS will take too long and be far too dangerous to make human assembly feasible. Thus, most of the assembly tasks will be performed robotically.

Launches from Earth will primarily carry preprocessed materials into LEO where an orbiting "space factory" will extrude the tubular members and assemble the truss structures. This eliminates the need for a collapsible structure designed to fit inside the payload bay of a launch vehicle. Prototype remote facilities for manufacturing structural members and constructing truss structures like the Grumman beam builder have already been built and tested.

The primary steps in assembly of the SPS are: (1) Establish a "space factory" in LEO with facilities to manufacture the structural elements and assemble the SSAPs; (2) Launch the pre-processed structural materials for manufacture of structural elements. The solar panels will be manufactured on Earth and launched for assembly in LEO; (3) Assemble the truss structure from its individual elements and mount the solar panels until an entire SSAP is produced; (4) Transport the SSAP to GEO using ion thrusters powered by electricity generated by the SSAP itself; and (5) Rejoin final assembly in GEO as robots assemble the arriving SSAPs to form the operational SPS.

## ROBOTIC MAINTENANCE

Robots will be used extensively to perform both routine maintenance and unscheduled repairs of the SPS. The robotic maintenance system will be primarily composed of two robots mounted on a railing fixed to the SPS. As shown in Fig. 6, the mounting rail will move the robots over the length of the SPS, while the robots themselves will move transversely along the rail. This system, which operates much like an ordinary computer plotter, allows any point on the SPS to be easily reached. These rail-mounted robots will be primarily used to perform routine repairs, especially replacement of damaged solar cells. The mounting rails will extend around the edge of the SPS to allow the robots to service the rear of the structure. Direct human involvement will only be required if a problem arises that is too complex to be handled entirely by the robots.

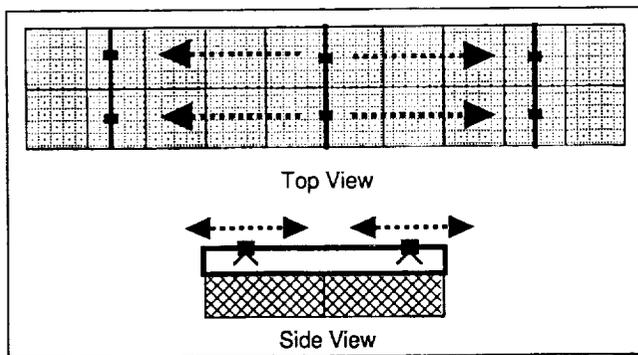


Fig. 6. Rail mounted robot concept.

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