Solar Power Satellites

An AIAA Position Paper

Prepared by the AIAA Technical Committee on Aerospace Power Systems and the AIAA Technical Committee on Space Systems

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INTRODUCTION
The search for "inexhaustible" energy resources to satisfy long-term needs is a high priority undertaking which has been recognized by the government and the public alike. Potential resources of this type include nuclear fission breeder reactors, nuclear fusion reactors, deep dry-rock geothermal wells, and various forms of solar-derived energy, including wind, hydroelectric, biomass, and ocean thermal. Most terrestrial solar resources require considerable energy storage capability to meet the demand for baseload electric power, which compromises their utilization for that purpose.

The solar power satellite (SPS) concept proposed by P.E. Glaser in 1968 is one of the few solar options which offers baseload capability. Although it appears to be technically feasible, a considerable effort will be needed to determine its economic, environmental, societal, and political viability.

The AIAA has studied the SPS concept and its implications in considerable detail, and offers in this paper the Institute’s collective professional position on the subject, including specific recommendations for pertinent research and technology efforts.

SUMMARY OF THE AIAA POSITION

- The SPS is one of several potentially competitive options for providing a nondepletable source of baseload electric power in the future.
- The SPS appears to be technologically feasible. Its economic viability, environmental impact, safety, societal desirability, and international acceptability (including the consequences of aggressive action) are yet to be demonstrated in relation to alternative energy-supply options.
- The range of possible SPS concepts is wide, and the optimum one has almost certainly not yet been formulated. Continued concept innovation should therefore be encouraged and supported.
- Much technology needs to be explored and evaluated before a rational basis will exist upon which to make the many choices needed to select any one concept for development. The selection of a baseline concept in the absence of such technology background data is therefore premature. The formulation of one or more "paper-design" reference systems may, however, be appropriate to help define the details of required technology efforts.

- It is desirable to determine whether or not the SPS concept is a sufficiently attractive long-term energy supply option to warrant development. That decision, as with any other energy supply option, should be made as soon as it is possible to do so rationally, so that energy policy and planning for the various competitive options can be formulated based on reasonably confident knowledge of their key characteristics. An aggressive concept innovation and technology verification program should therefore be initiated and conducted in parallel with programs which support the other energy-supply alternatives to that the necessary rational comparisons with alternative sources can be made more or less simultaneously. The AIAA has estimated that the initial ground-based portion of this program could take about five years, including current Department of Energy (DOE) environmental studies.
- A low-risk phased program plan should be formulated, with the above mentioned ground-based technology verification constituting the first phase. Subsequent technology experiments could be conducted in space using the shuttle. Scheduled milestone accomplishments should be identified as the basis for program review decisions prior to making commitments to successive steps. Synergistic utilization of technology efforts applicable to other space activities (e.g., advanced communications systems) should be maximized.

SOLAR POWER SATELLITE FEATURES

Overview. A solar power satellite system collects solar energy in space, converts it to electricity by one of several possible options, transmits it to Earth, and converts it into a form suitable for delivery to the existing electric power distribution system. Concepts which simply reflect sunlight to the ground or which relay power from one point on Earth to another were not assessed in this study.

The principal advantage of the space location is its independence of weather and the day-night cycle. A satellite in geosynchronous orbit, for example, receives about ten times as much incident solar energy as a ground-based location in the southern latitudes of the United States, and the almost continuous supply of energy obviates the need for major energy storage capability. A second advantage is the absence of such deleterious Earth-surface conditions as rain, hail, snow, atmospheric contamination and corrosion, wind, storms, and earthquakes, although the presence of ionizing radiation in space requires consideration. A third advantage is the ability to dissipate waste heat, a necessary consequence of the second law of thermodynamics, in space instead of in the Earth’s biosphere.

The principal disadvantage of using the space location is the cost and, to a lesser extent, the potential environmental impact associated with placing the necessary hardware in space. A second disadvantage is the need to transmit the collected power through the Earth’s atmosphere, which raises further questions of cost and possible environmental impact. Other concerns include international, military, and societal considerations, including possible competition with satellite communication systems for geostationary orbit locations and transmission bands.

Configuration. SPS concepts can be categorized in many ways. The major classifications involve how much gross power should be generated by each satellite, how the energy is collected and converted, how it is brought together aboard the satellite, and how it is transmitted to the Earth. Minor classifications involve spacecraft design, structural materials, construction, stabilization, and deployment.

By far the widest range of possibilities appears in the energy conversion scheme. It can be photovoltaic, solar thermal, or thermionic. If photovoltaic, it can use planar arrays or concentrating collectors. The cells can be made of silicon, gallium arsenide, or one of several new materials under development, and can vary in size, thickness (and hence mass), construction, and performance. In solar thermal concepts the power conversion system can utilize Brayton, Rankine, or combined cycles, including thermionic topping. Photovoetaic planar array conversion currently seems to be the leading SPS candidate.

Fewer options have been identified for channeling the power from the solar panels to a central collecting point. The principal alternatives to conventional hardware transmission lines are wave-guides and radio-frequency intrasatellite links. The larger the spacecraft, the more seriously these alternatives will be considered.

The choices for the transmission link to Earth are limited to either microwaves or lasers, with the 2.45 GHz industrial microwave band the most thoroughly studied candidate. The major questions regarding these transmission schemes center on their environmental impact. Much more needs to be known about the interaction of such beams with the ionosphere, and there is considerable divergence of opinion about safe intensity levels for birds, other wildlife, vegetation, or humans living in the area surrounding a receiving antenna.

Once the above major (and interrelated) choices have been made, attention can be given to the other aspects of system definition. The size and shape of the individual solar panels in the satellite will be determined as much from electrical considerations as from structural ones. The choice of structural material will be based on cost, mass, fatigue life, thermal coefficient, the electrical, thermal, out-gassing, and plasma interaction characteristics, and manufacturing and assembly requirements. Spacecraft construction concepts will depend in turn on the selected design and materials as well as on techniques to be developed during the next decade. For example, the geosynchronous equatorial orbit (GEO) appears to be the preferred location for an SPS because it places the satellite overhead and therefore able to transmit power continuously to the ground receiving antenna. There are, however, a number of possible options for building and assembling the system and transporting it to that location. Assembly may take place at GEO, in low Earth orbit (LEO), or employ construction bases at both locations. These deployment options may eventually involve the development of a heavy lift launch vehicle for transporting the required millions of tons of materials from Earth to LEO. Orbit transfer vehicles or other transportation techniques may also need to be developed to move equipment and personnel from LEO to GEO. Should these developments prove necessary, the cost, risk, and environmental impact of transportation system development, production, and operation must be considered as part of the total SPS program, although such transportation capabilities would, of course, have payoffs to other large space system deployments.

Another major design choice to be made involves the stabilization and control of the SPS. The solar panels or collectors must follow the Sun, while the power transmission antenna must be pointed accurately and reliably toward its ground receiver. The selection and integration of systems for stationkeeping and attitude control will be challenging. Possible buildup of static electricity charges and contamination of solar cells and other electronic gear from thrusters and outgassing must be considered. The effects of gravity gradients and solar pressure must either be minimized or be used to help stabilize the spacecraft. A great deal is yet to be learned about the dynamics of such large structures.

The microwave power beam direction must be controlled by electronic steering. One well-defined approach uses a pilot beam from the ground-based rectenna as a phase control reference. This causes the beam to lose coherence in the event of loss of pointing control. A thorough definition and assessment of the beam forming and phase control system will require accomplishment of several high-priority technology investigations.

As great a technological challenge as the SPS is, no reason has so far come to light for concluding that it could not be built and operated successfully. Indeed, there is growing confidence in the technical community that, given the resources for the task, the SPS could be built and would work. How well it would work, for how long, with what societal impact, and at what cost is yet to be determined. The answers to these questions will be different for every combination of options being considered.

Costs. The cost of the total SPS system in dollars, in natural resources, in energy invested, and in possible environmental effects will be great. The same can be said of any large-scale energy system. Whether the energy return of the SPS is sufficient to justify the investment will depend in large measure on the various options indicated above.

The ultimate decision on deployment of an SPS will probably be based largely on the estimated cost of its delivered electricity, in cents per kilowatt-hour, as compared with other candidate energy systems. It is important, therefore, that the SPS version which undergoes this comparison be as cost-efficient as possible, that the best possible basis be developed for reliable cost estimates, and that common cost guidelines and ground rules be established for making comparisons between the various alternatives.

PROGRAM CONSIDERATIONS

Present DOE plans call for the selection during 1979 of a baseline design concept for the SPS. Presumably this selection would be made from paper design concepts developed by two NASA contractors during recent system definition studies.

As the preceding discussion indicates, a wide range of possible design exists--far wider than is represented by the two contracted study results to date. Narrowing the possibilities to two concepts, much less selecting between them, cannot be done without making (explicitly or implicitly) choices for which there is still insufficient experimental or analytical basis. Rather than narrow the options, it is our judgment that they should be further expanded by encouraging creative new concepts, while pursuing an aggressive technology program designed to provide a firm experimental basis for the choices which must eventually be made. *The AIAA therefore feels that to make a baseline selection in 1979 is premature by at least several years.*

In order to minimize investment risk before the feasibility of SPS is demonstrated, a step-by-step approach incorporating multiple go/no-go decision points is suggested. The first decade of the program can be accomplished on the ground and by use of the space shuttle; it is not likely that a responsible decision as to whether or not to proceed with a large-scale demonstration system could be made much before 1990. *It is important to note, however, that a great deal of the technology applicable to SPS systems is needed for other projected space applications.* Only the microwave or other possible power transmission space experiments so essential to determining SPS feasibility are wholly unique to this program.

In addition to the necessary economic, societal, political, and Earth environmental impact analyses now being conducted under the current DOE program, AIAA recommends that a five year ground-based technology verification and advancement program (see Appendix) be pursued to define costs adequately and to select the preferred system. The cost of such a technology program, including the current DOE effort, is estimated to be of the order of $30 million per year.

APPENDIX

Subjects which could be included in a ground-based technology verification and advancement program (in addition to current environmental, economic, societal, and system studies.)

Energy Conversion

Thermal engines and systems
Heat-pipe production
Ceramic heat exchangers
Concentrator construction
Photovoltaic arrays (silicon, gallium arsenide, and new approaches)

Materials

Effect of space environment on plastics and composites
High temperature composites
Special alloys
Coatings
Bonding and fastening processes

Structures

Elastic-plastic stress analysis of thin materials
Joints and fasteners
Integrated structural response to gravity gradients, eclipses (steep thermal gradients), solar wind pressure, maneuvering loads, etc.
Shape control

Electrical Systems
Fast switchgear
Low-mass power processors
Thin-film sheet conductors
Rotary joints
Electric energy storage
High voltage components
Arcing protection

Radio-Frequency (RF)
Klystron and crossed-field directional amplifier performance
Thermal control, including heat-pipe cooling
Phase-control subsystems
Ionospheric heating and RF interference by microwaves
Array hardware
Rectenna diodes, structure, and circuitry Filters

Flight Control
Control of flexible structures (sensing, software, hardware)
Attitude reference sensors
Beam pointing and control
Thruster technology (including contamination experiments)
Gravity-gradient control

Space Transportation
Launch and orbital transfer vehicle concepts
Propellant transfer
Chemical engine development
Electric propulsion

On-orbit servicing
Heat shields
Ground and launch operations

Space Construction Operations
Orbital depot concepts and overall construction strategies
Automated fabrication
Closed life-support systems
Structural integrity/verification
Module docking
Teleoperators

Space Environment Effects
Plasma effects on semiconductors, dielectrics, high voltage equipment
Meteoroid impact prediction, protection, and avoidance
Solar/cosmic radiation effects
Trans-Van Allen-Belt operations

Innovation and Evaluation of Concepts
Alternative SPS concepts
Alternative propulsion and launch vehicle concepts
Feasibility demonstration concepts
Fabrication concepts
Alternative materials supply concepts

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