PROTOTYPE SOLAR POWER SATELLITE OPTIONS

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An optimal path cost minimization problem is presented every time a new system is implemented. A system like the solar power satellite (SPS) is a special challenge because the anticipated development costs are large and, due to optics, the microwave power transmission link can not economically be scaled down to powers of less than a gigawatt. This paper addresses the choice of options for the prototype SPS, which is currently the least well defined of the three major items in the SPS development program. (The other two major items are the construction base and the heavy lift launch vehicle.)

The reason for undertaking any development program is to reduce the risk of failure of subsequent projects. Risk is quantifiable and is basically the program cost multiplied by the reduction in probability of program success due to the risky action. According to Kierolff (Ref. 1) there are four classes of risk. (See Table I) While in an ideal society prototyping would only reduce technical risks, in the real world it may reduce the effects of the other three types of risk by allowing them to be quantified earlier.

In the case of the prototype SPS, the mathematical criterion for when one should prototype is

$$D\, C_f \geq C_p,$$

where D is the difference in program probability of success with and without the prototype option being considered, C_f is the cost of program failure and C_p is the prototype cost. With careful and judicious evaluation of the parameters in this relation (or one very much like it--the one here is very simplified) an objective choice of program plan can be made. (Ref. 2)

Current thinking on requirements for SPS prototypes result in lists like Tables II and III. The generally accepted most difficult technical aspect that the prototype will have to demonstrate is the safe and efficient transmission of commercial amounts (greater than 10 Mw) of power from synchronous orbit to the Earth's surface through all types of atmospheric conditions. The important similarity parameters of the microwave power link are frequency, beam efficiency, desired sidelobe levels and a real atmosphere and ionosphere in the beam path with full scale power density (approximately equal to received power/area) propagating through. Transmitted power/area is not critical for reasonable simulation of full scale beam conditions, although it is an important parameter that should be achieved in in-space subarray tests. For efficient power transmission at S band, the product of the transmitting and receiving areas must be approximately 10^{14} m^4. To realistically test atmospheric and ionospheric effects the received power/area should be that of the full scale satellite (currently 230 w/sq. meter). As a result, the power and aperture area of the transmitting antenna are set once the size of the receiving array is decided. That decision follows from a simple cost minimization exercise.

The most common SPS design, termed "conventional" for purpose of this paper, consists of separate solar and microwave transmitting arrays connected by DC busses and rotary joints. The designer of a prototype of a conventional SPS has a critical choice to make. He may transmit a beam which reaches full scale SPS peak power density on the ground using an oversized, quite nonstandard low power density transmitting array, or he may retain standard subarrays in a smaller than full scale aperture for less than full power density on the ground. Because the former choice results in a design physically larger and quite unlike the full scale SPS the latter option is inevitably chosen. The disadvantage of this is that the operational feasibility of safe and efficient high power microwave beaming and reception is not demonstrated.

A solution to the above problem is to use a large microwave reflector to increase the transmitting aperture. Since reflectors are likely to be less massive than full scale satellite waveguides by almost an order of magnitude the substitution of reflector aperture for waveguide aperture can be favorably made.

The critical technical aspect of reflectors is keeping the proper shape and attitude. By using active control a great reduction in structural stiffening mass and complexity may be achieved. Two basic approaches to implementation of actively controlled microwave reflectors are being considered: mechanical and electrostatic. Both methods show great promise and are currently under study by groups sponsored by Langley Research Center and others. (Refs. 3-5) For reflectors of the size required, a mass per unit area of .5 kg/sq meter or less appears feasible.

Figure 1 and Table IV present a comparison of typical conventional and augmented aperture SPS prototypes. It may be seen that the aperture augmented conventional prototype has a clear mass and cost advantage. For a sandwich type of SPS (where the solar array, microwave power amplifiers and antenna elements form a planar sandwich) this advantage is slight due to the already very low power density at the transmitting aperture.

Because aperture augmentation is not a necessary technology for full scale SPS's (although it does offer some advantages--see Ref. 6) its use on the prototype will increase the risk involved somewhat. However, it is likely to reduce the cost involved to a degree that more than compensates for this. If an aperture augmented prototype meets all the other basic SPS demonstration requirements (and we see no reason why it shouldn't) it will almost surely be possible to construct and operate a conventional SPS because a technically more rigorous test article has been demonstrated.

Space does not allow detailed discussion of several other similar choices between risk and cost on the prototype SPS. They include whether or not to build a full scale heavy lift launch vehicle and construction base for the prototype and whether or not to use full scale production methods on various components. It is recommended that similar quantitative methods be used to make the decisions involved.

References

1) Kierolff, H.E., "Satellite Power System (SPS) Financial/Management Scenario," DOE HCP/R-4024-13, Oct. 1978.
2) Reiffa, Howard, "Decision Analysis," Addison Wesley, Reading MA, 1968.
3) Lang, Gersh and Staelin, "Electrostatically Controlled Wire-Mesh Antenna," Electronics Letters, 14, 655-656, Sept. 28, 1978.
4) Tankersley, B.C., "Maypole (Hoop/Column) Deployable Reflector Concept for 30 to 100 m Antenna," AIAA Paper 79-0935.
5) Ward, J.C., Editor, "Large Space Systems Technology - 1979," NASA Conf. Publication 2118, Nov. 7-8, 1979.
6) Drexler and Sperber, "High-Power Microwave Optics for Flexible Power Transmission Systems," Proc. of 1980 DOE/NASA SPS Program Review, April 1980.

TABLE I. TYPES OF RISK (Reference 1)

"Insurance" Risk

International Conflict Risks (External Conflict)

U.S. Political Variation Risks (Internal Conflict)

Technical Risks

(Lost) Opportunity Costs

Project Engineering Costs

TABLE II. GENERAL PROTOTYPE DEMONSTRATION REQUIREMENTS

(In Order of Importance)

Electromagnetic Power Link Feasibility Demonstration

Component Integration Verification

Construction Technology Verification

Cost Performance Verification

TABLE III. SPECIFIC PROTOTYPE REQUIREMENTS

- Operate at GEO
- Provide meaningful power to a utility grid (tens to hundreds of megawatts)
- Demonstrate reliable control of power beam and its sidelobes
- Provide full scale satellite received microwave power/area
- Demonstrate construction operations
- Demonstrate plant factor >.8
- Demonstrate reliable, repeatable startup and shutdown
- Demonstrate maintainability and repairability
- Provide traceable cost/power performance data

TABLE 4. VARIOUS PROTOTYPING OPTIONS

Type	Conventional w/Small Xmt. Antenna	Reference Conventional	Aperture Augmented Conventional	Reference* Sandwich	Aperture Augmented Sandwich
Transmitting Antenna Dia.	.8 km	1 km	.25 km/2.8 km	1.8 km	1.2 km/2.9 km
Receiver Antenna Dia.	10 km	10 km	3.6 km	4.7 km	2.9 km
Design Procedure	Pick minimum power density for ground tests; zero taper low power subarray and matching solar array.	Build conventional reference SPS	Scale link area to solar array for minimum mass (or cost)	Build reference solid state sandwich SPS	Scale link area to sandwich for minimum mass (or cost)
Peak Transmitted Power/Area	600 W m^{-2}	22 kW m^{-2}	22 kW m^{-2}	550 W m^{-2}	550 W m^{-2}
Peak Received Power/Area	10 W m^{-2}	230 W m^{-2}	230 W m^{-2}	230 W m^{-2}	230 W m^{-2}
Beam Efficiency	.8	.95	.95	.8	.8
Grid Power	.15 GW	5 GW	.70 GW	2x1.21 GW	.59 GW
Masses (No Growth)					
Solar Reflector	0	0	0	} 5,840 MT	} 1,430 MT
Solar Array	2,200 MT	27,900 MT	5,030 MT		
Transmitter	3,300 MT	13,800 MT	1,680 MT	13,030 MT	3,200 MT
μwave Reflector (.5 kg m^{-2})	0	0	6,710 MT	0	4,630 MT
Total w. 25% Growth	6,875 MT	52,100 MT	16,775 MT	23,590 MT	11,580 MT

* Ref: W. Finell
Priv. Comm., 4-16-80

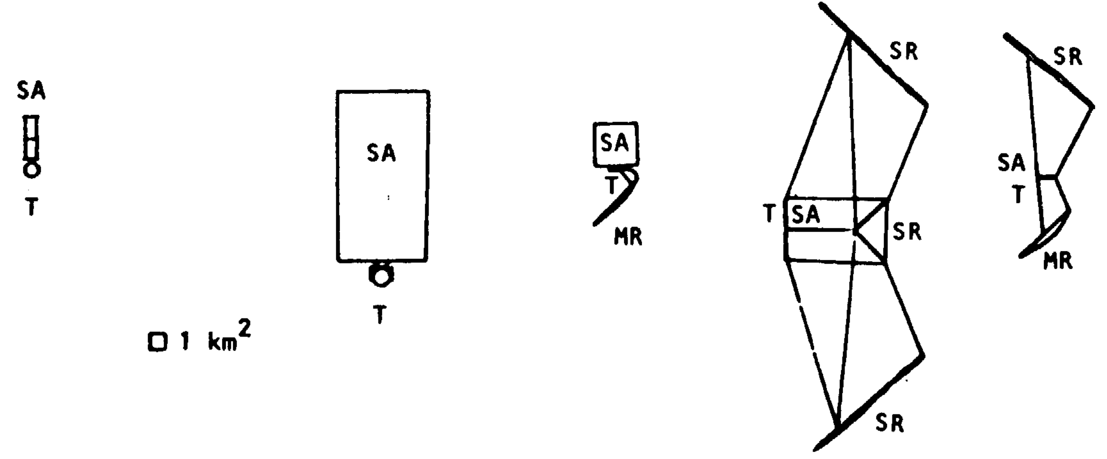

FIGURE 1. THE VARIOUS PROTOTYPE OPTIONS ILLUSTRATED

KEY:
SR - Solar Reflector
SA - Solar Array
T - Transmitting Array
MR - μwave Reflector