EMERGING SPS CONCEPTS

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Four new technologies have recently been evaluated to determine their effect on Satellite Power System (SPS) concepts. Two of these technologies, solid-state power amplifiers and magnetrons, are replacements for the klystrons used for dc to RF conversion on the satellite. A third technology, laser power transmission, transmits the energy at laser frequencies rather than microwave frequencies. The fourth technology, multibandgap solar cells, has the promise of significantly increased solar to dc conversion efficiency as compared to the reference-concept silicon and gallium arsenide solar cells. This paper summarizes the design characteristics of concepts resulting from application of these technologies.

One of the solid-state microwave concepts, shown in Figure 1, has a configuration similar to the reference concept, although this concept has two end-mounted antennas rather than one. Solar energy is collected in the same manner as it is on the reference satellite and is conducted to the attached microwave antenna using a modified power distribution system. Because of a lower operating temperature requirement for the solid-state amplifiers (compared to klystrons), larger antennas are needed that produce less power at the utility interface than the reference concept (2.6 GW per antenna compared to 5.0 GW). Although the concept shown in Figure 1 uses a concentrated GaAs solar array, a nonconcentrated silicon solar array also could be employed and would have a similar collector area. The antenna configurations for this concept are quite different from the reference klystron design because of the large number of solid-state power amplifiers needed to provide the RF power compared to klystrons (5-10 watts per amplifier for solid state compared to 50-70 kilowatts for klystrons). The major problem, however, is distribution of power from the solar array to each of the power amplifiers. Feed voltages for the solid-state amplifiers is ten volts compared to voltages for the klystron that vary from 8,000 volts to 40,000 volts. One approach proposed by Rockwell to alleviate this problem employs a combination of series/parallel strings of power amplifiers to achieve higher module voltages along with two-step dc/dc power conversion on the antenna to transform from high voltage from the solar array (40,000 volts) to the string voltage (640 volts). The resulting system requires advanced technology dc/dc converters with masses of 0.27 kg/kW. An alternate approach proposed by Boeing utilizes parallel/series strings up to very high voltages (e.g., 5500 volts) with direct power from the array.

A solid-state sandwich concept, shown in Figure 2, overcomes the power distribution problems of the previously described solid-state concept by putting the microwave antenna and power amplifiers directly behind the solar array in a "sandwich" configuration. Since the antenna must constantly be pointed at a receiving site on the ground, the sun must be reflected onto the array with a two-reflector

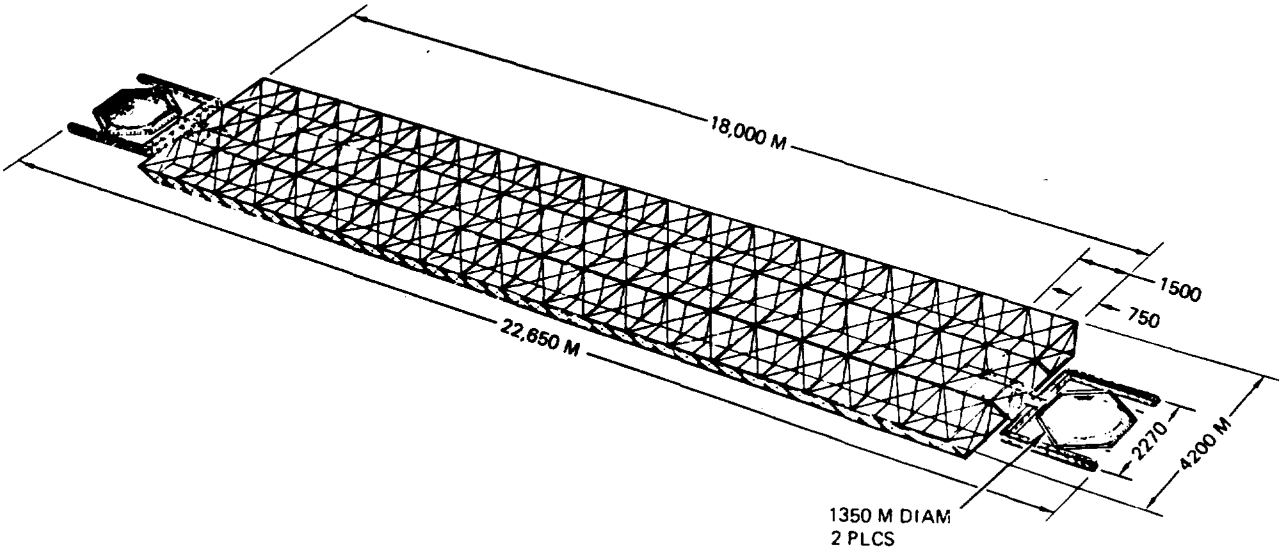

Figure 1. Solid-State End-Mounted Antenna Satellite Concept

system. The secondary reflector is fixed to the sandwich array, while the primary reflectors point at the sun continuously. Although the reflector area is large, the reflector mass is low since it is fabricated from 1/2 mil aluminized kapton. The concept as illustrated in Figure 2 has two microwave antennas, each of which transmits 1.2 GW of power to the utility interface on the ground. This concept is not practical with silicon solar cells because it is necessary to have concentrated sunlight (5.2 suns in this concept) on the solar cells to provide adequate power density to the transmitters. Either GaAs or multibandgap solar arrays are feasible under these conditions.

The sandwich panel concept designed by Rockwell is shown in Figure 3. The solar array is bonded to a fiber honeycomb core. The back of the solar array serves as a ground plane for the power amplifier drive distribution system located midway through the honeycomb core. Another ground plane is located on the other side of the sandwich. This ground plane serves both the amplifier drive system and the transmitter. The honeycomb core assembly is attached to a truss structure that supports the antenna and power amplifiers. The power amplifiers are shown mounted at the front of the truss structure to beryllium oxide wafers that dissipate waste heat from the amplifiers. A single amplifier drives each dipole. The total mass per unit area of the sandwich is only 1.68 kg/m^2

Magnetrons appear to have significant advantages compared to klystrons, including increased lifetime (up to 30 years compared to ten years for klystrons between replacements), a single rather than multiple operating voltages (thus eliminating dc/dc conversion), a simpler waste heat rejection system (use conduction/radiation of heat rather than heat pipes and radiators), and possible a higher dc/RF conversion efficiency (e.g., 90 percent compared to 85 percent). The resulting design concept is shown in Figure 4. Although the satellite appears very similar to the klystron reference concept, there are some significant differences. Power at the utility interface is 5.6 GW compared to 5.0 GW for the reference concept. The mass is only 26.7 million kg compared to 31.6 million kg for the reference concept.

Table 1 compares some of the most significant characteristics of the above described concepts. As indicated, the magnetron concept has much lower specific mass compared to the reference concept, the solid-state end-mounted antenna concept has higher specific mass, and the solid-state sandwich concept, using multibandgap solar cells, has a specific mass that is similar to the reference concept using multibandgap solar cells. The multibandgap solar cells significantly reduce specific mass. They are particularly effective on the sandwich concept in this regard.

Laser power transmission concepts have not yet been defined to the level of detail of microwave concepts. The Boeing Company is currently conducting initial studies of this concept. Three approaches are being considered: electric discharge, solar pumped, and free-electron lasers.

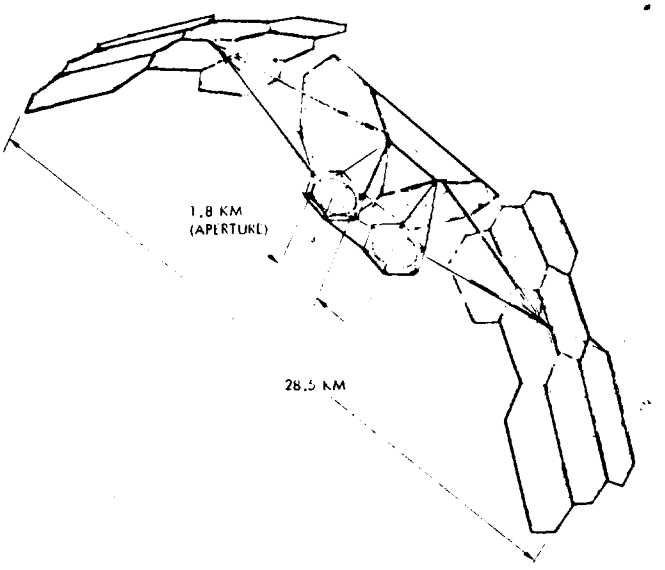

Figure 2. Solid-State Sandwich Satellite Concept

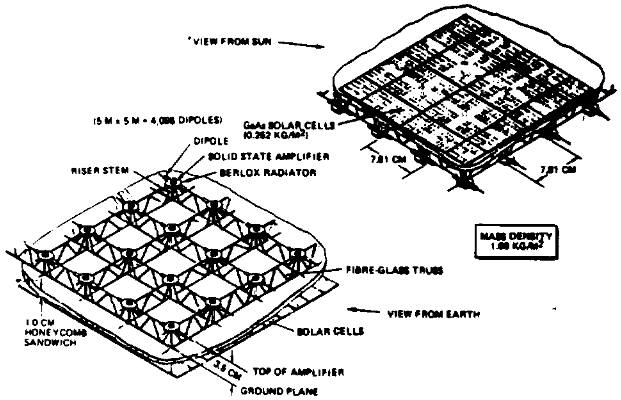

Figure 3. Solid-State Sandwich Design

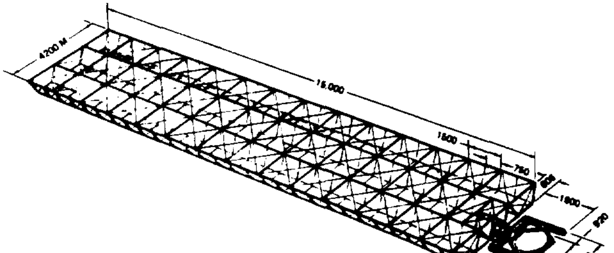

Figure 4. Magnetron-Antenna Satellite Concept

Table 1. Concept Comparisons

	REFERENCE CONCEPT		MAGNETRON CONCEPT		SOLID-STATE END-MOUNTED CONCEPT		SOLID-STATE SANDWICH CONCEPT	
TYPE OF SOLAR ARRAY	GaAs	MBG	GaAs	MBG	GaAs	MBG	GaAs	MBG
EFFECTIVE CONCENTRATION RATIO	1.83	1.83	1.83	1.83	1.83	1.83	5.2	5.2
MAXIMUM TRANSMITTED POWER DENSITY (kW/m^2)	21	21	28	28	6.6	6.6	0.70	1.1
ANTENNA POWER TAPER (dB)	10	10	10	10	10	10	0	0
TRANSMITTING ANTENNA APERTURE (km)	1.0	1.0	0.92	0.92	1.4	1.4	1.8	1.6
RECTENNA BORESIGHT DIAMETER (km)	10.0	10.0	11.0	11.0	7.5	7.5	4.8	5.4
POWER AT UTIL. INTERFACE/SATELLITE (GW)	5.0	5.0	5.6	5.6	5.2	5.2	2.4	3.0
POWER AT UTIL. INTERFACE/ANTENNA (GW)	5.0	5.0	5.6	5.6	2.6	2.6	1.2	1.5
SATELLITE MASS (10 kg)	31.6	26.0	26.7	21.5	40.0	35.6	20.5	16.4
SATELLITE SPECIFIC MASS (kg/kW)	6.2	5.1	4.8	3.8	7.7	6.8	8.5	5.40

Electric discharge lasers require electric power to drive a high-voltage discharge that pumps the laser medium to an excited discharge state and to circulate the lasant through a cooling loop to remove waste heat. For this type of system, a solar array may be employed to produce the power. This type of system is extremely inefficient, resulting in a large solar array and large radiators. The result is a system mass and cost that is not competitive with microwave power transmission systems.

Direct solar-pumped lasers also are inefficient because of the narrow lasant spectral band and the broad spectral characteristics of solar energy. For this reason, an indirect solar-pumped approach is used to achieve more compatible spectral characteristics. Solar energy is focused by reflectors into a cavity collector (Figure 5). A temperature is achieved in this cavity that releases thermal radiation in the spectral region that excites the lasant. Efficiencies of this system are considerably improved.

The final laser system, the free-electron laser, is shown in Figure 6. In this concept, an electron beam is formed (using a klystron as the electron source, which is accelerated in an RF accelerating cavity) that produces laser frequency energy upon passing through a magnetic field that causes lateral electron movement. The beam is directed to mirror assemblies on each end of the satellite that form a laser beam which is directed to a receiving station on the earth. The solar array provides the energy that powers the system. The system on the ground for conversion of laser to electrical energy uses optical diodes that are analogous to the microwave rectenna. Conversion efficiencies are similar to the rectenna system. This system appears to provide the highest efficiency and lowest mass of all laser systems studied.

Figure 7 compares the specific masses of the laser concepts and the reference silicon solar array concept that uses klystrons for dc/RF microwave conversion. Current estimates made by the Boeing Company indicate that the lowest mass laser concept (free-electronic laser) is about twice the specific mass of the reference concept.

Additional effort remains to be accomplished to evaluate and compare these concepts. Even lower mass and cost solid-state antennas need to be developed because of the importance of antenna mass on the cost of these concepts. Device development also must proceed to ensure that the requirements can be met. Magnetron concepts appear to have the best combination of characteristics, but development is needed to determine whether predicted lifetime and efficiency goals can be obtained. Because of the obvious advantages of multibandgap solar arrays in improving system

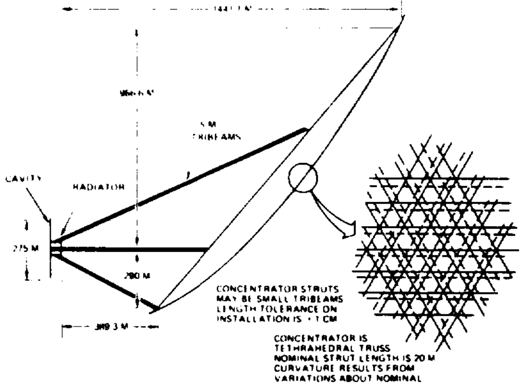

Figure 5. Indirectly Optically Pumped Laser SPS General Arrangement

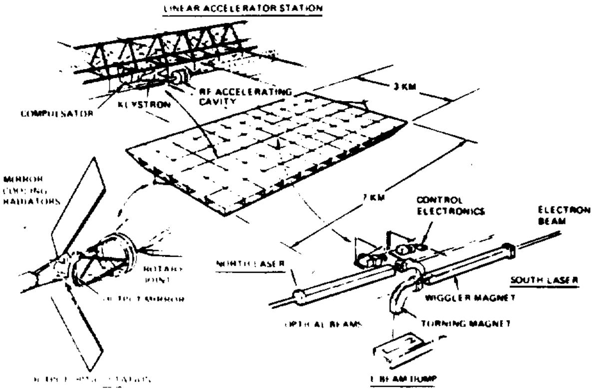

Figure 6. 1-GW Single-Pass Free Electron Laser SPS

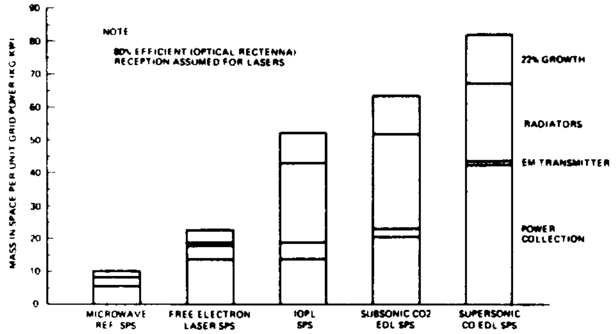

Figure 7. Comparison of Laser Options and Reference SPS Concept

efficiency, research leading to cells with the desired high efficiencies with little increase in cost and mass is needed. Additional laser systems studies are needed to determine approaches that may lead to reduced mass and cost to make them more competitive with the microwave SPS concepts. In addition, because of the problems related to penetrating heavy cloud layers, total power system integration studies are needed to determine the degree to which a laser system might penetrate the utility network.