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Solar Power Satellite System Sizing Tradeoffs

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INTRODUCTION

The initial sizing for the solar power satellite (SPS) was optimized to a 1-km transmitting antenna producing 5 GW of DC power from a receiving antenna (rectenna) approximately 10 km in diameter. There are advantages to a lower power output and a smaller rectenna. Commercial utility companies prefer to integrate lower power levels into their grids. Rectennas smaller than the 10-km diameter in the reference configuration would make more rectenna sites available.

The purpose of this paper is to investigate the tradeoffs of smaller SPS systems. The end result is a comparison between the costs of smaller systems and those of the 5 GW, 10 km diameter rectenna reference system. The microwave system is reoptimized for each antenna/rectenna configuration. Both the 2.45 GHz reference frequency and a higher (5.8 GHz) frequency are used in the candidate systems.

In compliance with the NASA's publication policy, the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). As an aid to the reader, the SI units are written first and the original units are written parenthetically thereafter.

BACKGROUND

The SPS sizing with a 1-km transmitting antenna and 5 GW of DC output power from a rectenna was based on

1. A thermal limitation of 23 kW/m^2 in the transmitting antenna

2. A peak power density of 23 mW/cm^2 in the ionosphere

3. Cost effectiveness (the larger the power system the more cost effective)

The thermal limitation at the center of the antenna is a function of the amount of heat generated by the klystrons (DC-to-RF converters) and of the effective radiator area. The reference configuration has 72 kW klystron tubes operating at 85-percent conversion efficiency and cooled by passive heat pipe radiators. From thermal considerations, larger transmitting antennas are desirable. However, as the antenna size increases, the power density in the ionosphere increases in direct proportion. At some threshold power density level, which is dependent upon the operating frequency, nonlinear interactions between the ionosphere and the power beam could begin to occur. These nonlinear heating effects are of concern because of possible disruptions produced in low frequency communications and navigation systems by radio frequency interference (RFI) and by multipath effects. Theoretical studies of the ionosphere completed during the early phases of the SPS evaluation program indicated the power density should be limited to 23 mW/cm^2 in order to prevent such nonlinear heating effects. This theoretical value was taken

as the SPS design guideline. Subsequent ionospheric heating tests have indicated that this 23 mW/cm^2 threshold may be too low, as will be discussed later. From ionospheric considerations, smaller antennas are desirable. Therefore, from the two opposing requirements, the reference system was sized to produce 5 GW of power with an antenna 1 km in diameter.

The 2.45 GHz downlink power beam frequency is in the center of a 100 MHz wide IMS (Industrial, Medical, and Scientific) band in which users may interfere with other users of that band. This 2400-2500 MHz band is not particularly affected by weather conditions and an SPS system using it should not suffer weather outages. Another IMS band (5800 ± 75 MHz) is also available for possible SPS usage. However, an SPS system operating in this frequency region might have to be shut down under very poor weather conditions, as will be discussed later. Smaller rectennas are more amenable to the higher 5.8 GHz operating frequency as a result of greater antenna focusing.

OPTIMIZED MICROWAVE SYSTEMS - 2450 MHz AND 5800 MHz

To use a smaller rectenna, the antenna must be enlarged and the transmitted power decreased in order to avoid exceeding the 23 mW/cm^2 ionospheric limit. In reoptimizing the microwave system to decrease the rectenna size and reduce the transmitted power, two operating frequencies, 2.45 GHz and 5.8 GHz, were considered. The reference SPS microwave system has an efficiency budget shown in figure 1 (ref. 1).

The rectenna collection efficiency (88 percent) is the percentage of transmitted power from the satellite antenna incident upon the ground rectenna. One of the ground rules for this study was that the rectenna for each configuration be sized to receive 88 percent of the transmitted power. It was assumed that the antenna performance parameters would be the same as those in the present SPS reference configuration. These include 10° root mean squared (rms) phase error, ±0.1 dB amplitude error, 2-percent tube failure rate, 0.63 cm (0.25 in.) mechanical spacing between subarrays, ±1 arc min antenna tilt, and ±3 arc min subarray tilt. A 10-dB Gaussian taper is used for antenna illumination, since this taper maximizes rectenna collection efficiency while minimizing sidelobe peaks (see appendix A). The only constraint on sidelobes is that the first sidelobe peak should have a power density of less than 0.1 mW/cm^2. A buffer strip extends around the rectenna to exclude the general public from 0.1 mW/cm^2 or higher microwave radiation levels.

The procedure to optimize the microwave system for maximum efficiency with different antenna/rectenna configurations is first to use closed-form equations (1) and (2) to obtain the general microwave system characteristics. These characteristics, together with the antenna error parameters listed previously, are then used in microwave simulation programs to obtain the antenna patterns and collection efficiencies.

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63% overall efficiency
(from DC/RF input to RF/DC output)

DC/RF conversion	▶	Transmitting antenna	▶	Average atmosphere
0.85		0.985 I²R		0.98

0.98 - mechanical pointing
and subarray/waveguide tolerances

Rectenna energy collection	▶	RF-DC conversion	▶	DC power interface and DC/DC processing	▶ 5 GW
0.88		0.89		0.97	

(10 km rectenna diameter;
$\sigma = 10°$, ± 0.1 dB, 2% tolerances
on transmitting antenna)
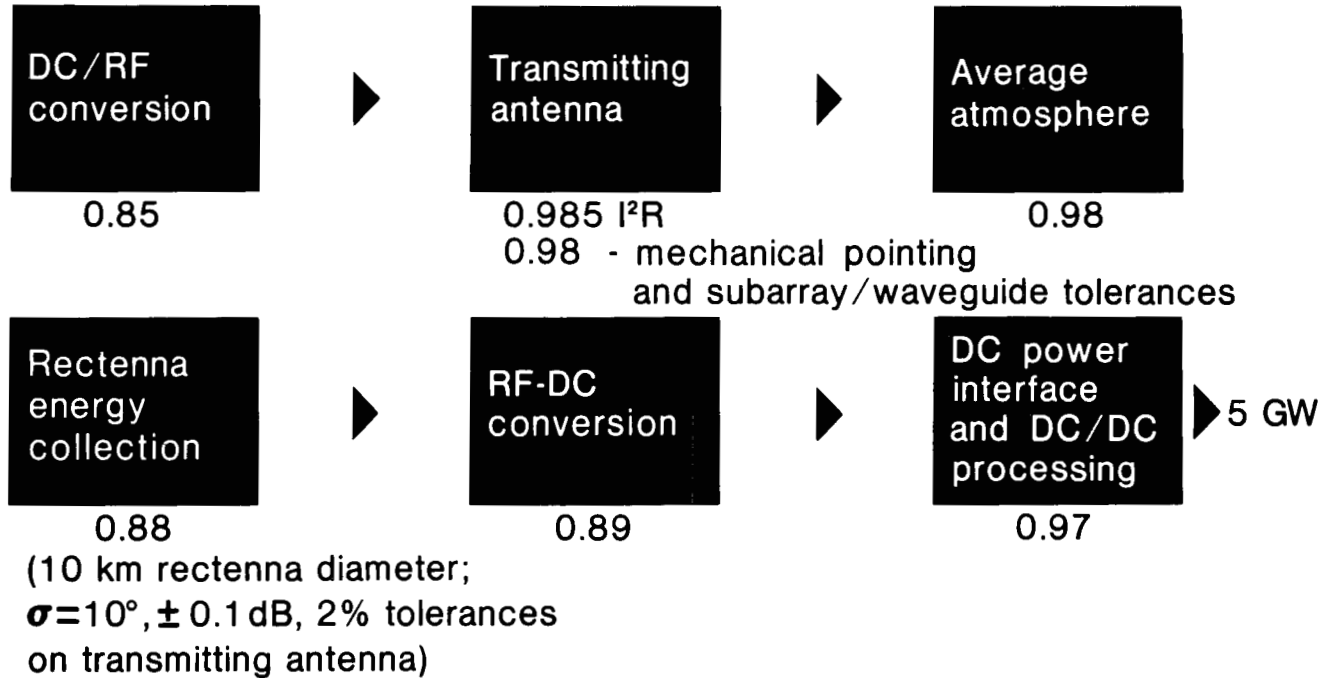
Figure 1.- Microwave transmission efficiency for the 2.45 GHz reference
SPS configuration.

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$$P_{D-GR} = \frac{P_{D-ARRAY}\ A_T^2}{\lambda^2 R^2} \left[\frac{1 - 10^{-dB/20}}{0.115dB} \right]^2 \qquad (1)$$

$$P_{TRANS} = \frac{P_{D-ARRAY}\ A_T \left(1 - 10^{-dB/10}\right)}{0.23dB} \qquad (2)$$

where

P_{D-GR} = peak power density at rectenna boresight

$P_{D-ARRAY}$ = peak power density at center of transmitting antenna

A_T = transmitting antenna area

λ = power beam wavelength (0.1225 m)

R = nominal range from satellite to rectenna (36 000 km)

dB = amount of dB taper for Gaussian antenna illumination (10)

P_{TRANS} = total power radiated from transmitting antenna

For a 2.45 GHz operating frequency, two operating constraints were considered:

1. Retaining the 23 mW/cm^2 ionospheric limit by reducing transmitted power as the size of the satellite antenna increased.

2. Allowing the ionospheric power density limit to increase by retaining the same transmitted power as the size of the antenna increased.

The microwave system characteristics for 2.45 GHz operation may be summarized as shown in table 1.

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TABLE 1.- MICROWAVE SYSTEM CHARACTERISTICS AT 2.45 GHz

Characteristic	Ionospheric limit of 23 mW/cm^2				No ionospheric limit		
Transmitting antenna diameter, km	1	1.36	1.53	2	1.36	1.53	2
Transmitted microwave power, GW	6.5	3.53	2.78	1.64	6.5	6.5	6.5
Power density in ionosphere, mW/cm^2	23	23	23	23	42	54	91
Output DC power from rectenna, GW	5	2.72	2.14	1.2	5	5.05	5.05
Rectenna diameter to capture 88% of energy, km . . .	10	7.6	6.8	5	7.6	6.8	5
Rectenna area relative to reference	1.0	0.56	0.46	0.25	0.56	0.46	0.25

The thermal limit of 23 kW/m^2 is not a constraint for the larger antenna/ smaller rectenna systems operating at 2.45 GHz. The ionospheric limit is the critical parameter in system sizing for 2.45 GHz.

For operation in the 5.8 GHz IMS frequency band, a different set of constraints must be considered. Since the gain of an antenna is proportional to the frequency squared, antennas smaller than 1 km in diameter can be used with rectennas smaller than the 10 km diameter reference rectennas. The antenna thermal limitation is the critical parameter for system sizing at 5.8 GHz. The ionospheric limit of 23 mW/cm^2 is no longer a factor because this threshold is also proportional to frequency squared. That is, the adjusted ionospheric limit for 5.8 GHz is

$$P_{D-5.8 \text{ GHz}} = P_{D-2.45 \text{ GHz}} \left[\frac{5.80}{2.45} \right]^2 = 23 [5.6] = 129 \text{ mW/cm}^2$$

Since the 5.8 GHz antenna will be smaller, or at least no larger, than 1 km in diameter, the adjusted ionospheric limit of 129 mW/cm^2 will not be exceeded. Other factors influencing system sizing include lower efficiencies

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in several of the microwave subsystems operating at the higher 5.8 GHz frequency. The operating constraints at 5.8 GHz are

1. Retaining the 23 kW/m^2 antenna thermal limit by reducing transmitted power as the size of the satellite antenna decreases.

2. Allowing the antenna thermal limit to increase somewhat as the antenna size decreases by redesigning the thermal radiation system.

3. Reducing subsystem efficiencies as follows:

80-percent, rather than 85-percent, DC-RF klystron conversion efficiency

97-percent, rather than 98-percent, efficiency for normal atmospheric transmission

87-percent, rather than 89-percent average RF-DC conversion efficiency in the ground rectenna

The microwave system characteristics for 5.8 GHz operation may be summarized as shown in table 2.

TABLE 2.- MICROWAVE SYSTEM CHARACTERISTICS AT 5.8 GHz

Characteristic	Present thermal limit of 23 kW/m^2	Thermal limit with improved design			
Transmitting antenna diameter, km	0.75	0.5	0.75	1	1.5
Transmitted microwave power, GW	2.84	1.68	3.78	6.5	2.88
Power density in ionosphere, mW/cm^2	30	7.87	40	122	129
Output DC power from rectenna, GW	2	1.17	2.72	4.8	2.12
Rectenna diameter to capture 88% of transmit energy, km	5.8	8.75	5.8	4.3	2.8
Rectenna area relative to reference	0.336	0.765	0.336	0.185	0.078

The candidate configurations have two thermal limits; i.e., the present 23 kW/m^2 limit and that of an improved design, which will be discussed later.

MAXIMUM ANTENNA SIZE CONSIDERATIONS

The relative antenna and rectenna sizes for 2.45 GHz and 5.8 GHz operation are shown in figure 2. Let us now consider the mechanical and electronic constraints on the maximum size for the satellite antenna as a function of frequency.

One limitation on antenna size is the phase control system. An active retrodirective phase control technique is used to point and focus the downlink power beam. In the reference system, a pilot beam signal is transmitted from the ground to the satellite, where it is received and processed at each of the 101 000 power modules (tubes). A phase reference is distributed throughout the antenna to each of the power modules via a Master Slave Returnable Timing System (MSRTS) developed by the LinCom Corporation (ref. 2).

If the antenna is enlarged, additional power modules are needed. The power output from each tube would be reduced, but the number would increase even if the overall transmitted power were lower. The reason is that the antenna mechanical pointing requirement for the attitude control system is determined by grating lobe levels which are dependent on the area of the antenna driven by one tube. Thus, given as an average antenna area associated with one tube as constrained by the antenna attitude control system, a larger antenna requires more power modules.

If the antenna size increases, the phase reference has to be distributed over a larger area, thereby increasing the phase error buildup. The present SPS system has a 10° rms phase error budget, which consists of errors in the phase distribution system, ionosphere-induced perturbations of the uplink pilot beam signal, errors in the RF receiver and processing electronics in each power module, etc. Larger antennas must still adhere to the 10° phase error budget in order to achieve the expected transmission efficiencies. Rectenna collection efficiencies for a 1.5 km diameter antenna with varying amounts of phase error are shown in figure 3. The data indicate that an increase in phase error could easily negate the advantage of a larger antenna; i.e., a smaller rectenna.

Operating at the 5.8 GHz frequency imposes a further constraint on the phase reference distribution system within the antenna. This reference signal is distributed at an intermediate frequency and is then multiplied up to the power frequency, either 2.45 GHz or 5.8 GHz, in the RF receiver electronics in order to perform the phase conjugation of the uplink pilot signal. Because of this multiplication process, the allowable phase error within the reference distribution system is inversely proportional to the output frequency. Thus, operating at 5.8 GHz requires an improvement (reduction) of 5.8/2.45 or 2.37 in the phase distribution system error. A smaller antenna at 5.8 GHz would probably help the phase control system achieve the required performance. In summary, when considering the present reference system phase

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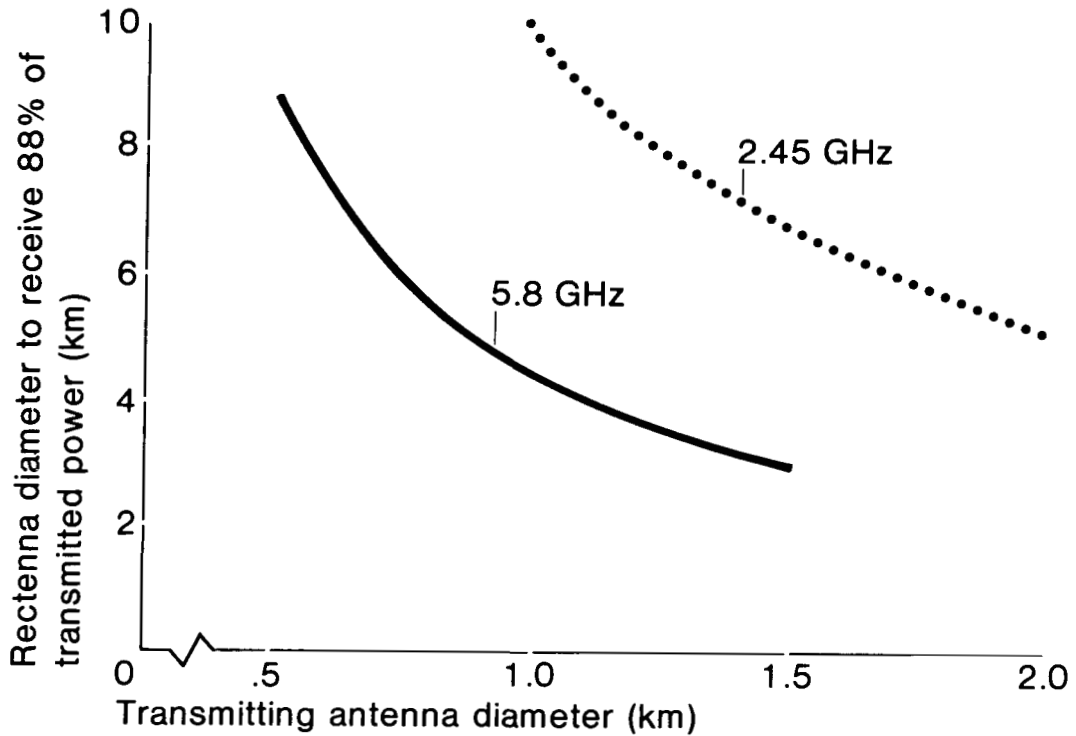
Figure 2.- Antenna and rectenna sizing summary.
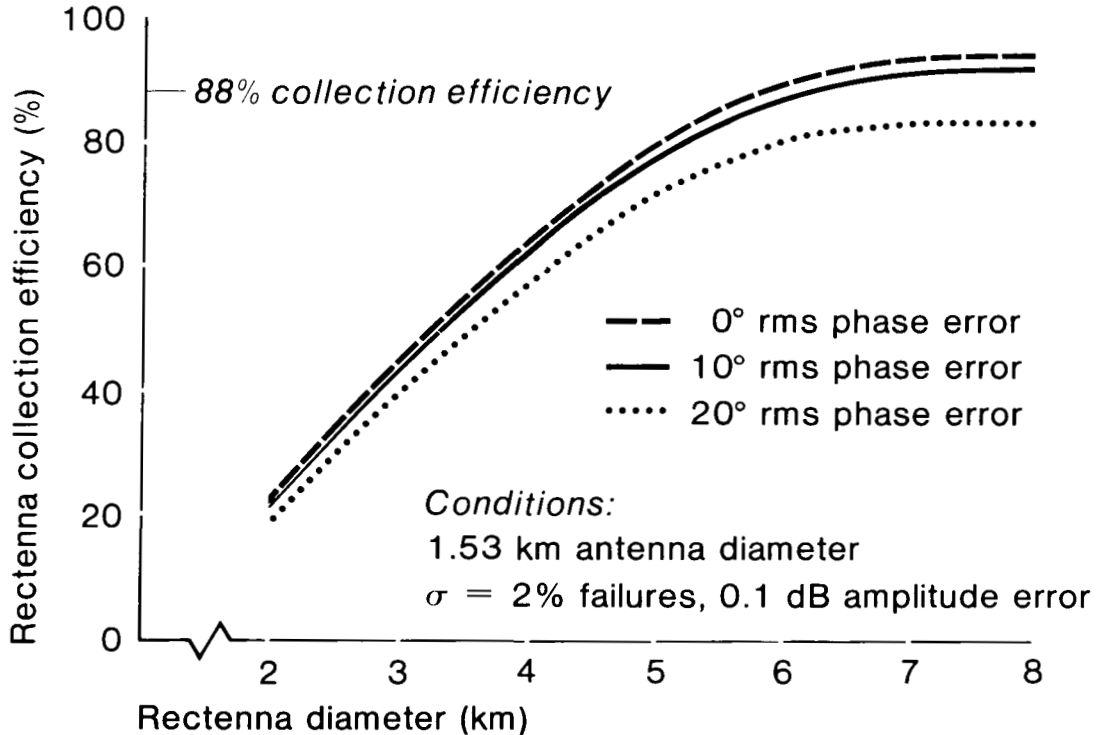
Figure 3.- Rectenna collection efficiency for various phase error budgets.

control and attitude control requirements, reasonable antenna sizes might be a 1.5-km diameter at 2.45 GHz and a 0.75-km diameter at 5.8 GHz.

SYSTEM COST TRADEOFFS

A detailed analysis of subsystem costs and masses for the reference 5 GW solar power satellite with silicon solar cells is given in reference 3. These values are used as a baseline for computing costs for the different antenna/rectenna configurations. Since the purpose of this report is to determine the relative or differential costs for the various configurations, any future changes in the absolute costs for the reference system should not have a great impact on the conclusions stated herein.

The principal elements in the SPS recurring costs are

1. Satellite hardware

2. Transportation (space and ground)

3. Space construction and support

4. Rectenna

5. Program management and integration

6. Cost allowance for mass growth

Some general costing assumptions include

1. 30-year operating lifetime

2. 0.92 plant factor for 2.45 GHz operation

3. 0.90 plant factor for 5.8 GHz operation

4. 15-percent rate of return on investment capital

5. 22-percent mass growth factor to cover potential risks in solar array and microwave system performance estimates

6. 17-percent of net SPS hardware cost factor to account for mass growth

7. 10 GW per year additional power generation capacity

The total mass and cost for the reference SPS system are 59 984 metric tons and \$12 432 million. The cost and mass statements for the individual satellite subsystem are divided into the following categories:

1. Power collection: structure, solar cells, power distribution, and maintenance

2. Rotary joint

3. Power transmission: structure, klystrons and thermal control, waveguides, subarray structure, power distribution (conductors, switchgears, DC-DC converters, thermal control), energy storage, phase control, maintenance systems, and antenna mechanical pointing

4. Information management and attitude control: hardware and propellant

5. Communications

6. Transportation: electric orbit transfer vehicle (EOTV), personnel launch vehicle (PLV), personnel orbit transfer vehicle (POTV), and heavy lift launch vehicle (HLLV)

7. Construction operations: low Earth orbit (LEO) and geosynchronous orbit (GEO)

The cost and mass from each of these subsystems will vary according to total power, antenna size, frequency, etc. of the candidate antenna/rectenna systems. Since the calculations are quite lengthy, only the end results for 2.45 GHz and 5.8 GHz operation are shown in tables 3 and 4. The details are given in appendix B, together with a complete sample calculation for one configuration. In table 3 (2.45 GHz), the microwave system has been sized to conform with the 23 mW/cm^2 ionospheric limit for the first four antenna/ rectenna configurations. This ionospheric constraint has been removed for the last three configurations, resulting in a maximum of 91 mW/cm^2 for the 5 GW, 2 km diameter antenna system.

The electricity costs in mills per kWh and the differential cost increase as compared to the 5 GW, 1-km antenna reference system are shown in figure 4 for 2.45 GHz operation. The top curve, constrained to an ionospheric limit of 23 mW/cm^2, shows a significant increase in electricity cost as the antenna size increases. Microwave power density in the ionosphere is directly proportional to transmitting antenna area and total transmitted power; therefore, if the antenna area is doubled, the power must be reduced by one-half in order to maintain the same power density. The electricity cost rates (mills/kWh) are determined by the total satellite costs divided by the delivered power. As the cost summary in table 3 shows, the total satellite costs decrease at a much slower rate than does the delivered power as the antenna size increases. The cost disadvantage with larger antennas is removed if the total transmitted power remains constant as the antenna size changes. However, the ionospheric power density increases accordingly.

TABLE 3.- SPS SUMMARY COSTS FOR 2.45 GHz OPERATION

(a) Physical parameters

Specification	23 mW/cm^2 ionospheric limit				Increased ionospheric limit		
Antenna diameter, km	1	1.36	1.53	2	1.36	1.53	2
Satellite power output, GW	6.5	3.53	2.78	1.64	6.5	6.5	6.5
Power density at rectenna, mW/cm^2	23	23	23	23	42	54	91
Rectenna diameter, km	10	7.6	6.8	5	7.6	6.8	5
Power delivered, GW	5	2.7	2.1	1.26	5	5.05	5.05

(b) Costs

Cost category	23 mW/cm^2 ionospheric limit				Increased ionospheric limit		
SPS hardware, million dollars	4946	4072	4120	5069	5898	6455	8112
Less amortization of investment, million dollars.	473	257	202	119	473	473	473
Total, million dollars	4473	3815	3918	4950	5425	5982	7639
Mission control, million dollars	10	10	10	10	10	10	10
Transportation, million dollars	3120	2700	2721	3186	3639	3918	4849
Construction operations, million dollars	961	1066	1170	1615	1233	1395	1933
Rectenna, million dollars	2578	1561	1293	835	1852	1646	1283
Program management and integration, million dollars	495	407	412	507	590	645	811
Cost allowance for mass growth, million dollars	760	649	666	841	922	1017	1299
Total, million dollars	12 432	10 243	10 190	11 944	13 671	14 613	17 824
Mills per kWh	47	71.6	90.6	180.1	52	55	67.1
Cents per MJ	1.3	2.0	2.5	5.0	1.4	1.5	1.9
% increase in electricity costs compared to cost of 1.3¢/MJ (47 mills/kWh) for the reference SPS system	--	52.4	92.7	283	10.6	17	42.7

TABLE 4.- SPS SUMMARY COSTS FOR 5.8 GHz OPERATION

(a) Physical parameters

Specification	Present thermal design	Improved thermal design			
Antenna diameter, km	0.75	0.5	0.75	1.0	1.5
Satellite power output, GW	2.84	1.68	3.78	6.5	2.88
Power density at rectenna, mW/cm^2	30	7.87	40	122	129
Rectenna diameter, km	5.8	8.75	5.8	4.3	2.8
Power delivered, GW	2	1.17	2.72	4.8	2.12

(b) Costs

Cost category	Present thermal design	Improved thermal design			
SPS hardware, million dollars	1452	3038	5366	4777	2494
Less amortization of investment, million dollars	122	275	473	209	206
Total, million dollars	1330	2763	4893	4568	2288
Mission control, million dollars	10	10	10	10	10
Transportation, million dollars	1288	2070	3120	2720	1794
Construction operations, million dollars	444	734	1057	1270	663
Rectenna, million dollars	4925	2672	2003	1063	2578
Program management and integration, million dollars	145	303	536	477	249
Cost allowance for mass growth, million dollars	226	470	832	777	389
Total, million dollars	8368	9022	12 451	10 885	7969
Mills per kWh	138	64	50.3	99	76.1
Cents per MJ	3.8	1.8	1.4	2.7	2.1
% increase in electricity costs compared to cost of 1.3¢/MJ (47 mills/kWh) for the reference SPS system at 2.45 GHz	193	36	7	111	62

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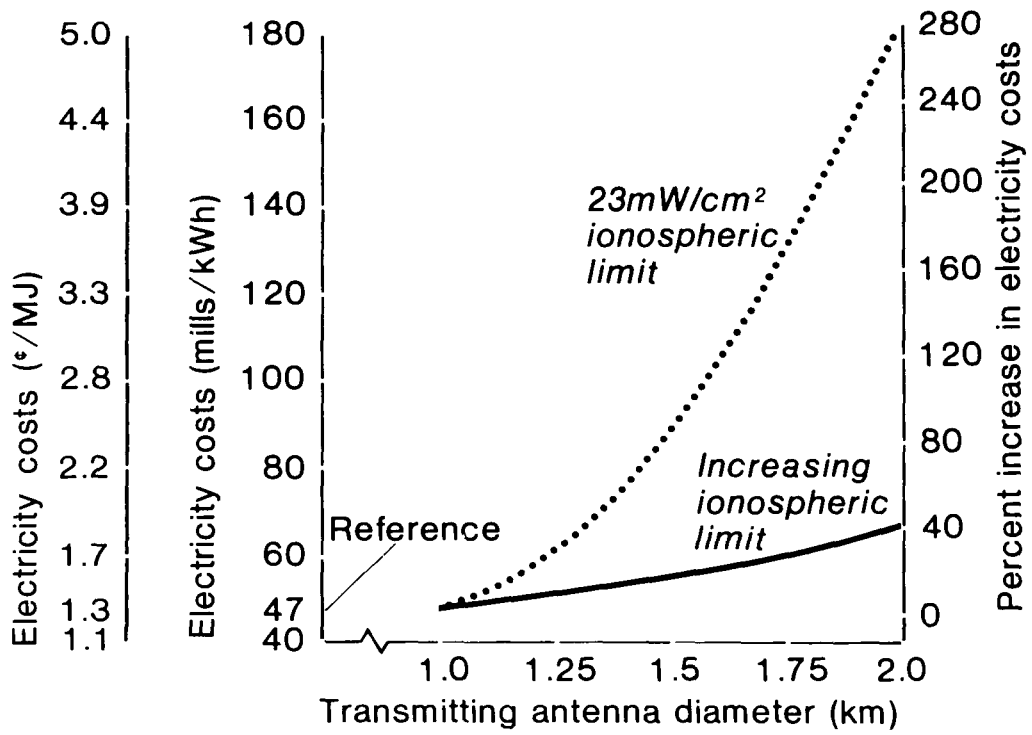
Figure 4.- Electricity costs for 2.45 GHz systems.

The 5.8 GHz systems described in table 4 have thermal limitations in the transmitting antenna rather than ionospheric limitations as the dominant constraint. The 5.8 GHz systems are inherently smaller (antenna, transmitted power, and rectenna) as compared to the 2.45 GHz configurations as a result of the increased antenna gain at higher frequencies.

The electricity costs for the 5.8 GHz systems are compared to the reference 2.45 GHz system in figure 5. The data indicate that a significant reduction in costs can be achieved with a modest improvement in thermal radiator design. Since the increase in differential cost is reduced from 64 percent to 36 percent for the 0.75 km diameter antenna by using a new thermal radiator configuration, improvements in thermal design are considered mandatory. Details of the thermal design estimates are given in a later section.

In summarizing the costing results and the microwave system tradeoffs, several options should be considered further:

2.45 GHz

Increase ionospheric limit -- to 54 mW/cm^2

1.53-km antenna; 6.8-km rectenna with 5 GW grid power; differential cost increase is 17 percent (to 1.5¢/MJ (55 mills/kWh))

Retain 23 mW/cm^2 -- as ionospheric limit

1.36-km antenna; 7.6-km rectenna with 2.7 GW grid power; differential cost increase is 50.2 percent (to 2.0¢/MJ (70.6 mills/kWh))

5.8 GHz

Increase antenna -- thermal limit by 33 percent

0.75-km antenna; 5.8-km rectenna with 2.72 GW grid power; differential cost increase is 36 percent (to 1.8¢/MJ (64 mills/kWh))

The microwave radiation patterns for the 1.53-km antenna operating at 2.45 GHz and the 0.75-km antenna operating at 5.8 GHz are compared in figure 6 with the 1-km antenna, 5 GW reference SPS system.

IONOSPHERIC, ATMOSPHERIC, AND THERMAL LIMITATIONS

The relative electricity costs from the various antenna/rectenna configurations are heavily dependent upon the ionospheric, atmospheric, and thermal constraints imposed on the microwave systems. The validity of these constraints is under review and may be revised pending the results of a number of studies.

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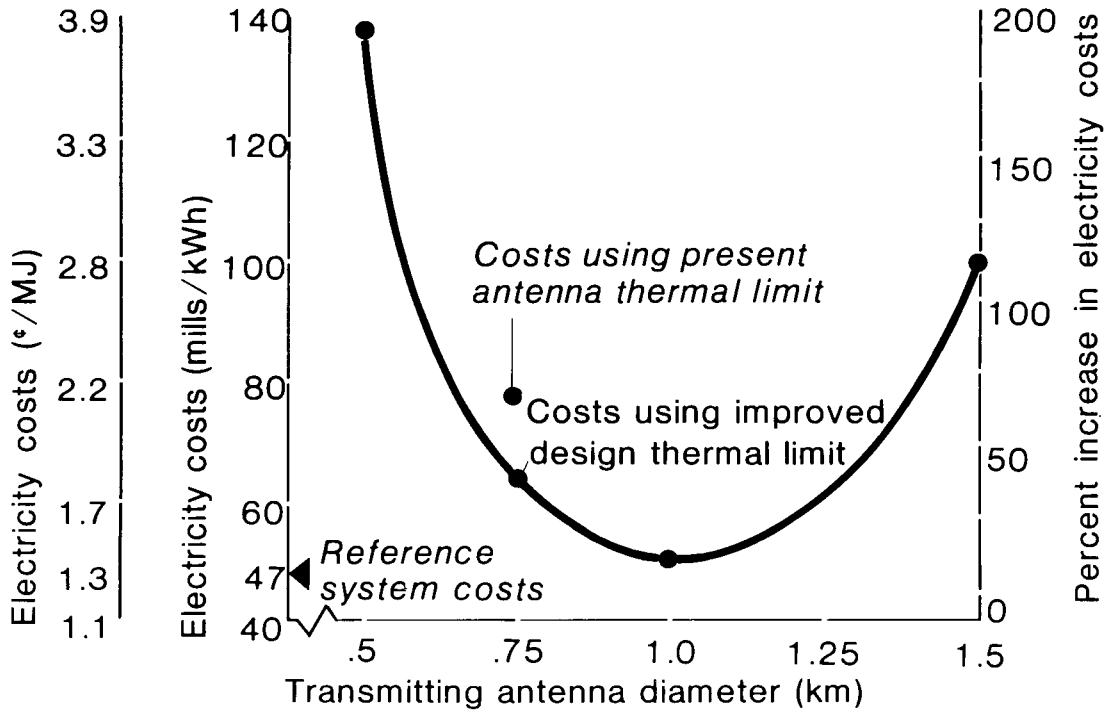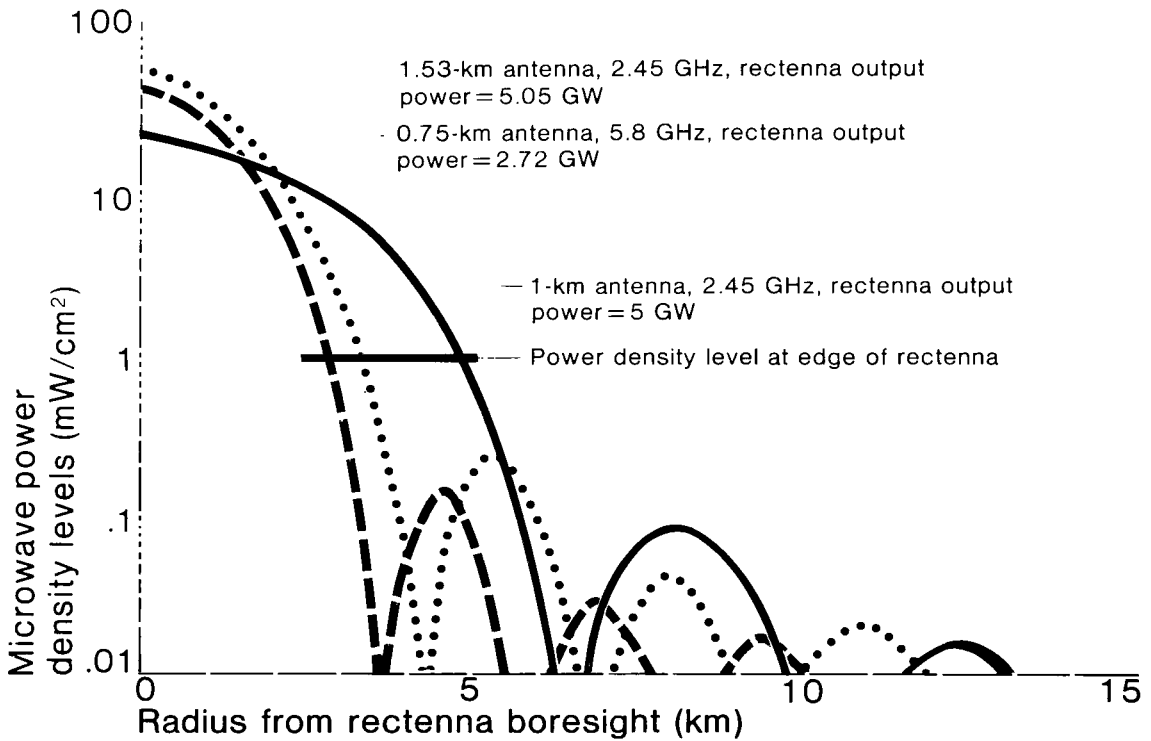Figure 5.- Electricity costs for 5.8 GHz systems.

Figure 6.- Antenna patterns for three SPS configurations.

IONOSPHERIC LIMITATIONS

Resistive (ohmic) heating effects by the power beam may produce nonlinear instabilities such as enhanced electron heating in the lower ionosphere (D and E regions) and thermal self-focusing effects in the upper ionosphere (F region). The Department of Energy (DOE) has recently sponsored a number of ionospheric studies which include (1) theoretical and experimental analyses of the effects of underdense heating upon ionospheric physics, performed in part at the Arecibo, Puerto Rico, observatory; (2) experimental studies by the Institute for Telecommunication Sciences (ITS) into heated ionospheric effects upon low frequency communication and navigation systems (loran, OMEGA, WWV, and AM broadcasting stations). This ITS work is being performed under the direction of Charles Rush using the Platteville, Colorado, heating facility.

The results of the tests performed to date at Arecibo and Platteville show no evidence to support 23 mW/cm^2 as an upper limit. The electron temperature increases due to underdense heating are a factor of 2 or 3, rather than the order of magnitude predicted in the early analyses (ref. 4). The theory is now being revised and initial results predict a $1/f^3$ heating rather than $1/f^2$. The $1/f^3$ heating would increase the power density limit. In addition, there are no indications of irregularities being formed in the lower ionosphere during underdense heating. Effects produced by simulated SPS heating are many times less than natural ionospheric disturbances created by solar flares (private communication from C. Rush, Dec. 1979).

An ionosphere power density level of 50-60 mW/cm^2 may be a reasonable limit and would accommodate the 54 mW/cm^2 level produced by the 1.5-km antenna, 5 GW satellite system. More ionospheric studies with upgraded facilities at Arecibo and Platteville to produce 50-60 mW/cm^2 equivalent heating levels in the upper ionosphere (F region) are needed to verify the higher limits.

ATMOSPHERIC LIMITATIONS

The efficiency budget for the 2.45 GHz reference configuration has 98-percent transmission (2-percent loss) through the atmosphere. This signal attenuation is primarily due to rain and atmospheric absorption. The 2-percent attenuation, or 130 MW loss, represents a bad case (but not the worst possible condition) for the 2.45 GHz frequency. The 5.8 GHz frequency has approximately the same transmission efficiency as has the 2.45 GHz through a nonrainy atmosphere, but the 5.8 GHz frequency is severely degraded under rainy conditions. The losses for two systems providing 5 GW of ground grid power may be summarized as follows (refs. 5 and 6):

| | Attenuation losses | |
Medium	2.45 GHz	5.8 GHz
Ionosphere	0.25 kW	1 kW
Neutral atmosphere at mid-United States latitude (water vapor and oxygen absorption)	90 MW	100 MW
Rain		
Heavy (15 mm/hr over 15-km path)	148 MW	1.8 GW
Central/Eastern U.S. - 9 hr/yr		
Southern U.S. - 3 hr/yr		
Western U.S. - 3 hr/yr		
Moderate (5 mm/hr over 10-km path)	34 MW	405 MW
Central/Eastern U.S. - 45 hr/yr		
Southern U.S. - 85 hr/yr		
Western U.S. - 10 hr/yr		
Wet hail	2.6 GW	4.99 GW

The 2.45 GHz frequency has very minimal losses due to nonideal weather conditions; the 5.8 GHz frequency operates satisfactorily in the dry climates of the southwestern United States but would suffer outages in wetter regions.

The impact on a commercial utility grid of a 5.8 GHz microwave system that may have to be shut down on an unscheduled basis because of weather effects is not known. If a 5.8 GHz microwave system is to be seriously considered as an alternative to a 2.45 GHz system, then an indepth study of this question is required.

THERMAL LIMITATIONS

Since antenna thermal radiation is a major constraint for a 5.8 GHz system, an investigation into the upper thermal limit was undertaken. The initial design for the thermal radiators in the reference SPS system (given in reference 7) was found to be quite conservative and improvements (increases) in the amount of waste heat rejection are possible. The major improvement is due to using graphite composite materials with a high emissivity coating for the radiator, as was proposed several years ago by Grumman in the system design for crossfield amplifiers.

It is first necessary to estimate the RF losses and determine where they occur in a 5.8 GHz klystron tube. A preliminary estimate, as provided by

E. Nalos of the Boeing Company, of the waste heat sources for a 70 kW tube operating at 80-percent efficiency is given below:

Collector: 9.7 kW at 773 K (500° C)

Cavity: 4.3 kW at 573 K (300° C)

Solenoid: 3.5 kW at 573 K (300° C)

Total losses   17.5 kW

Using the Stefan-Boltzmann equation for heat radiation, with a fin efficiency of 80 percent and 85-percent efficiency for the emissivity of the coatings, the required radiator areas are

2.22 m^2 - for collector radiators at 773 K (500° C)

.76 m^2 - for cavity and solenoid radiators at 573 K (300° C)

.22 m^2 - 7 percent additional area for mechanical spacings

3.2 m^2 - total radiator area per tube

The waste heat radiated per unit area is 17.5 kW/3.2 m^2 = 5.46 kW/m^2, an increase of 33 percent over the reference SPS design, which radiates 4.1 kW/m^2. The corresponding RF radiated power per unit area is 70 kW/3.2 m^2 = 21.9 kW/m^2. The total transmitted power from a 0.75 km diameter antenna radiating at 5.8 GHz with 70-kW klystrons operating at 80-percent efficiency may be calculated using equation (2):

$$P_{TRANS} = \frac{\left(21.9 \text{ kW/m}^2\right) \pi (750)^2 \left(1 - 10^{-dB/10}\right)}{4(0.23dB)} = 3780 \text{ MW}$$

where dB = amount of dB taper for Gaussian antenna illumination (10).

This transmitted power of 3780 MW has been used in tables 2 and 4 to calculate system performance and electricity costs. Corresponding transmitted power values are calculated for the other antenna/rectenna configurations using the same technique. It appears that an increased thermal limit is feasible for the 5.8 GHz systems (and also for the 2.45 GHz systems). In general, operating at the higher frequency makes the thermal radiation problem more difficult since the tubes are physically smaller and present a larger heat load.

MULTIPLE ANTENNAS

The present SPS scenario has 60 satellites separated 1° (700 km) in geosynchronous orbit, each delivering 5 GW of rectenna DC grid power. Because

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of increased demands for geosynchronous slots by other users, it may become necessary to reduce the number of SPS satellites. Multiple antennas on one SPS satellite are recommended. It has been shown that SPS antennas can operate in close proximity with negligible interference from each other.[1] An example of a multiple antenna system would be a 5 km by 20 km solar array (twice the size of the present solar array for one antenna) feeding two 5 GW antennas, one at each end. It may be advantageous to have four or more antennas on a single satellite especially if a larger antenna/smaller rectenna configuration or a higher frequency (5.8 GHz) system is chosen. The relative sizes for a number of antenna/rectenna configurations are shown in figure 7.

CONCLUSIONS

The satellite and associated microwave system have been reoptimized with larger antennas (at 2.45 GHz), reduced output power, and smaller rectennas. Four constraints were considered: (1) the 23 mW/cm^2 ionospheric limit, (2) a higher (54 mW/cm^2) ionospheric limit, (3) the 23 kW/m^2 thermal limit in the antenna, and (4) an improved thermal design for the 5.8 GHz systems allowing 33 percent additional waste heat. The differential costs in electricity for seven antenna/rectenna configurations operating at 2.45 GHz and five satellite systems operating at 5.8 GHz have been calculated. The conclusions are

1. Larger antenna/smaller rectenna configurations are economically feasible under certain conditions.

2. Transmitting antenna diameters should probably be limited to 1-1.5 km for 2.45 GHz operation and 0.75-1.0 km for 5.8 GHz because of phase control, construction costs, and attitude control.

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[1]G. D. Arndt and J. W. Seyl: RF Interference/Orbital Spacing Analysis for Solar Power Satellites. Lyndon B. Johnson Space Center (Houston, Tex.), to be published.

Single antenna configurations

	2.45 GHz			**5.8 GHz**		
Relative satellite size	5 km × 10 km					
Transmitting antenna diameter	1 km	1.36 km	1.53 km	0.75 km	1 km	1.5 km
Relative rectenna size	10 x 13 km	7.6 x 9.9 km	6.8 x 8.8 km	5.8 x 7.5 km	4.3 x 5.6 km	2.8 x 3.6 km
Ground power output	5 GW	2.7 GW	5.05 GW	2.72 GW	4.78 GW	2.12 GW
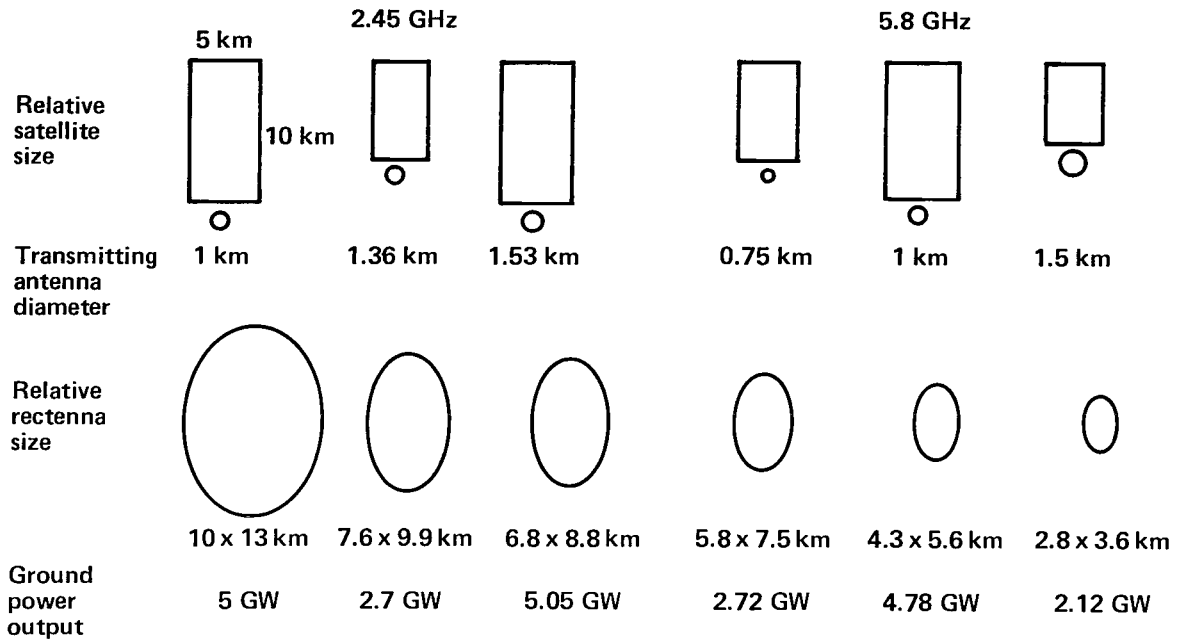
Multiple antenna configurations

Two - 5 GW, 1 km dia. systems at 2.45 GHz

Four - 5.05 GW, 1.53 km dia. systems at 2.45 GHz

Four - 2.72 GW, .75 km dia. systems at 5.8 GHz

10 x 13 km

6.8 x 8.8 km

5.8 x 7.5 km
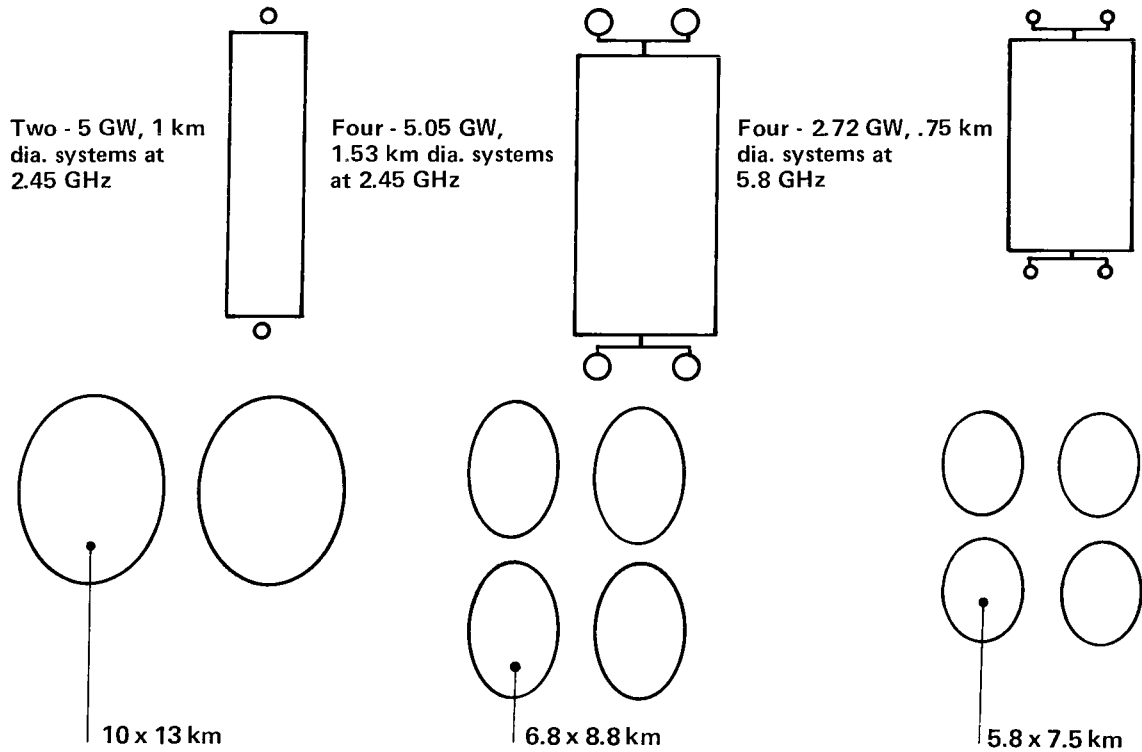
Figure 7.- Relative sizes for several antenna/rectenna configurations.

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3. Two 2.45 GHz configurations are selected, dependent upon the ionospheric power density limit.

	23 mW/cm^2 limit	54 mW/cm^2 limit
Antenna diameter, km	1.36	1.53
Rectenna DC grid power, GW	2.76	5.05
Rectenna diameter, km	7.6	6.8
Relative rectenna area, %	56	46
Electricity cost increase, %	50.2	17
Electricity cost, mills/kWh	70.6	55
Electricity cost, ¢/MJ	2.0	1.5

Note: The rectenna areas and electricity costs are in comparison to those for the reference SPS system.

4. The present ionospheric limit of 23 mW/cm^2 is too low and should be raised after the ionospheric heating tests and studies are completed. Because of SPS cost considerations, it is very important to ascertain the true upper limit.

5. The 5.8 GHz configurations are constrained by antenna thermal limitations rather than ionospheric limits. A reasonable configuration based on a 33-percent improvement in waste heat rejection is

Antenna diameter, km	0.75
Rectenna DC grid power, GW	2.72
Rectenna grid, km	5.8
Relative rectenna area, %	33
Electricity cost increase, %	36
Electricity cost, mills/kWh	64
Electricity cost, ¢/MJ	1.8

6. The impact on commercial utility grids of a 5.8 GHz system that has to be shut down on an unscheduled basis due to localized weather conditions should be investigated.

7. Multiple (two to four) antennas on a single solar satellite are definitely recommended regardless of the particular antenna/rectenna configuration chosen. This is a means of maintaining the same amount of power supplied to the ground while reducing the number of geosynchronous slots (spacings) required for the satellites.

Lyndon B. Johnson Space Center
    National Aeronautics and Space Administration
        Houston, Texas, December 5, 1980
            986-15-89-00-72

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APPENDIX A

ANTENNA TAPERS

The antenna illumination taper for the reference SPS system was optimized to provide maximum rectenna collection efficiency while minimizing sidelobe levels. Previous simulation results for a 1-km antenna indicated that a 10-dB Gaussian taper maximized the rectenna collection efficiency in the 85-90 percent range while satisfying the antenna thermal constraints. These data, taken for an antenna operating with the specified error parameters (i.e., $\sigma = 10°$ phase error, ±0.1 dB amplitude error, and 2 percent tube failures) yield an 88-percent collection efficiency over approximately a 10 km diameter rectenna. This appendix addresses the question of whether other tapers would be more efficient with larger antennas.

The results are given in figure A-1 for a 1-km antenna operating with no errors and a 2-km antenna transmitting with the specified error parameters. As the amount of taper increases, the main beam peak intensity decreases and the beam width increases. There is more power in the main beam and less power in the near sidelobes. This condition increases the rectenna collection efficiency. Both systems achieve good performance, with rectenna collection efficiency in the 85-90 percent range using a 10-dB taper. All the SPS configurations in this report have a 10-dB taper.
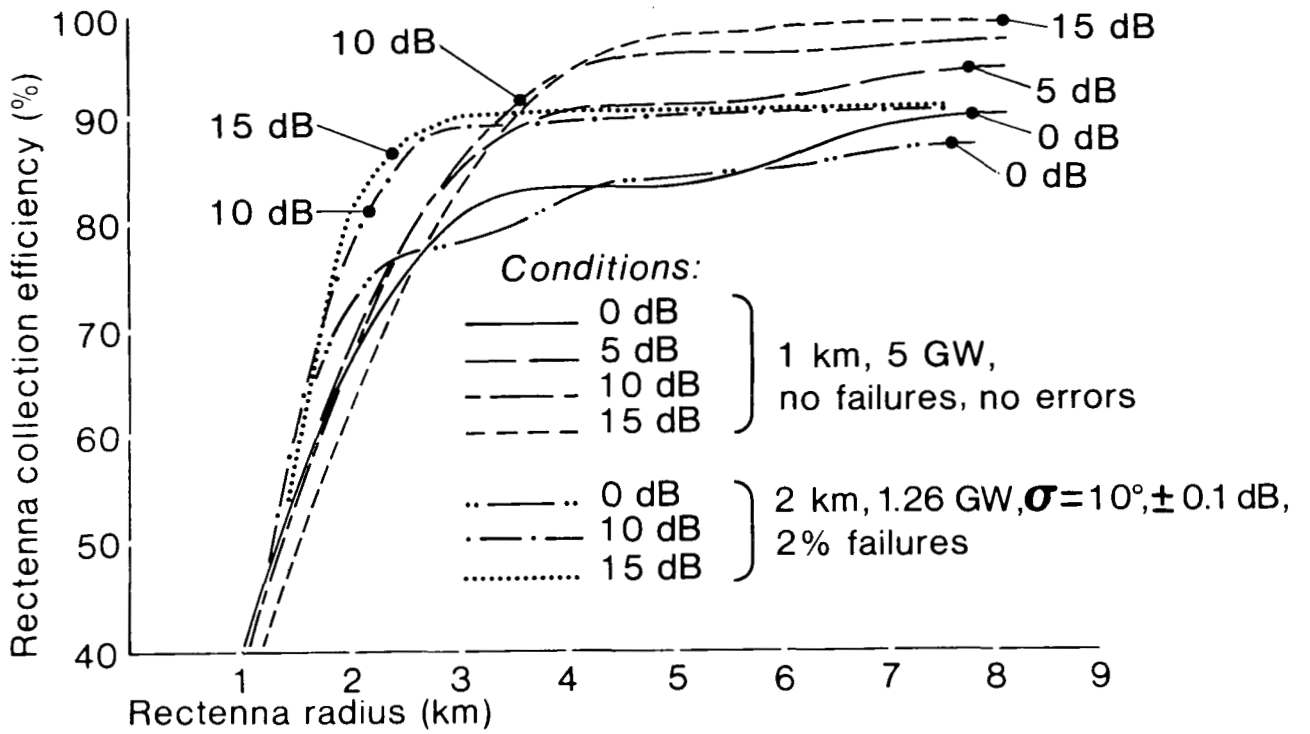
Figure A-1.- Rectenna collection efficiency vs. array taper.

APPENDIX B

EXAMPLE CALCULATIONS

The purpose of this appendix is to review the assumptions, methods, and steps by which cost and mass were calculated for various SPS configurations. The rationale is explained in the body of the text. The Boeing-JSC reference design cost and mass numbers were used as the basis for all comparative calculations in this study. Where applicable, these numbers are included as case L. Study assumptions are defined in table B-1, and cost and mass (C/M) factors are included in table B-2. The factors referred to in table B-1 are defined in table B-2. They were used to estimate new costs and masses for the various alternative configurations.

Factor values are presented in table B-3. In case A, the satellite RF power output is 1.68 GW. Factor 1 is calculated by dividing this number by 6.5 GW, as explained in table B-2. The resulting value of factor 1 is 0.258. The antenna diameter in case A is 0.5 km. Therefore, factor 2 is calculated $(0.5)^2/(1)^2 = 0.25$. The reference rectenna diameter (case L) excluding the buffer zone is 10 km. In case A, the rectenna diameter is 8.75 km. Factor 3 is then given by $(8.75)^2/(10)^2 = 0.76$. Factor 4 is the relative land area including the buffer zone out to 0.1 mW/cm^2. For case A, major and minor diameters are found in table B-4 (12.9 km and 9.2 km). Factor 4 is thus calculated π (12.9) (9.2) $\div$ 4 (158.3) = 0.589. The buffer zone area for the reference configuration is given in table B-5. Before factor 5 can be calculated, the total mass of the transmitting antenna in question must be estimated. Factor 6 is required for maintenance system mass. It is determined by extracting the square root of factor 2. In this case factor 2 was 0.25, so factor 6 is $\sqrt{0.25} = 0.5$.

Factors 7, 8, 9, and 10 are simple calculations based on factors 1, 2, and 3. Factor 11 is used for calculating HLLV costs as a portion of factor 13. In the reference case, 208 launches are required - 94 for solar power systems, 46 for the transmitting antenna, and 68 for other purposes. Factors 1 and 2 are used in scaling factor 11 for HLLV costs, as is shown in table B-2. Because of the simplicity of factors 12-16, a detailed explanation of their calculation is not necessary (see table B-2).

In table B-5, the values for reference system mass and cost are listed in the last two columns. The first two columns (case F) are derived by multiplying the last two columns, respectively, by the appropriate factor value from table B-3. The mass of the power collection structure, for example, is found by multiplying 4654 $\times$ 0.543 = 2527. In this manner, values are found for all costs and masses until antenna mechanical pointing is reached. This requires the use of factor 5, which has not been determined. To overcome this obstacle, the mass for mechanical pointing is assumed to be the same as the reference. Using this value, an interim total power transmission mass is found. Factor 5 is determined using this mass, and a new mechanical pointing value is calculated using the factor 5 value. Then a more accurate power transmission mass is totaled.

As can be calculated from the first mass column in table B-5, the subtotal of all power transmission masses except that for mechanical pointing is 12 679 t. Adding 134 t to this from the last mass column (reference case) results in 12 813 t for the interim total. The power transmission mass total for the reference case is 13 628 t. From the definition in table B-2, factor 5 (for case F) turns out to be

$$(12\ 813) \times (1.36)^2/(13\ 628)(1)^2 = 1.74$$

This value of factor 5 is then used to determine a new value for the mechanical pointing mass: $134 \times 1.74 = 233$ t. The power transmission mass may then be retotaled to provide 12 912 t for the 1.36-km case.

The equations presented as factor 17 are used to determine the cost of electricity in mills per kWh. For a 15-percent rate of return (R) over a 30-year period (y), the equation

$$\frac{R}{1 - \left(\dfrac{1}{R + 1}\right)^y} \times 10^3$$

produces 152.3 as a constant multiplying factor. In the denominator of the equation for 2.45 GHz, the hours per year of operation with a 92-percent plant factor were 8050. Because of brownout during rainstorms at 5.8 GHz, the plant factor was reduced to 90 percent, resulting in 7875 annual hours of operation. Using these constants, system cost, and plant capacity for 2.45 and 5.8 GHz cases, the cost of electricity was calculated for each scenario. Results are presented in table B-6. For case A, in which power delivered is 1.17 GW and total system cost is $8368 million, factor 17 results in a cost of

$$\frac{(152.3)(8368)}{(7875)(1.17)} = 138 \text{ mills/kWh} = 3.8 \text{¢/MJ}$$

In each instance, factors are used to determine the amount of variation from the reference case. Tables B-4 and B-5 present the results obtained after applying the equations and factors as described above. Totals for the various satellite configurations are listed in table B-6.

B-2

TABLE B-1.- STUDY ASSUMPTIONS

1. Each scenario will have the same total electrical capacity (10 GW) installed per year.

2. For the following subsystems of the solar power collection system, cost and mass (C/M) vary linearly with power (factor 1).

    - Structure
    - Solar cells
    - Power distribution
    - Maintenance

3. The cost and mass of the rotary joint are related to antenna mass and diameter squared (factor 5).

4. Cost and mass of the following subsystems of the microwave power transmission system vary as indicated.

    - Structure - C/M vary linearly with area (factor 2)
    - Klystrons and thermal control - C/M vary linearly with power (factor 1)
    - Waveguides - C/M vary linearly with area (factor 2)
    - Subarray structure - C/M vary linearly with area (factor 2)

    - Power distribution

        - Conductors - C/M vary linearly with area and power (factor 9)
        - Switchgears, DC-DC converters, thermal control - C/M vary linearly with power (factor 1)

    - Energy storage - remains constant
    - Phase control - C/M vary linearly with area (factor 2)
    - Maintenance systems - C/M vary with square root of antenna area (factor 6)
    - Antenna mechanical pointing - C/M vary linearly with factor 5

5. The information management and control systems have cost and mass variations as follows.

    - Mass varies with antenna area (factor 2).
    - Cost varies with square root of antenna area (factor 6).

6. The cost and mass of the attitude control system vary linearly with factor 5.

7. Communication systems remain constant.

8. The mass growth allowance for the satellite remains constant at 22 percent of the total satellite mass.

9. The cost of the rectenna is dependent upon the following items:

- Buffer zone out to 0.1 mW/cm^2 - factor 4
- Structure and installation - varies with rectenna area (factor 3)
- Ground plane and RF assemblies - vary with rectenna area (factor 3); RF assemblies also vary with frequency squared
- Distribution buses - vary with rectenna area and power according to factor 8
- Command and control center - remains constant
- Power processing and grid interface - varies with square root of power (factor 7)

The area of the rectenna is always sized to collect 88 percent of the transmitted energy.

10. The amortization of satellite investment costs varies with power (factor 1).

11. The costs of the transportation system for personnel and materials are divided into four categories:

- EOTV - varies with power (factor 1)
- PLV - varies with power (factor 1) and antenna diameter
- POTV - varies with power (factor 1) and antenna diameter
- HLLV - varies with power and antenna area according to factor 11

12. Program management and integration requires 10 percent of the hardware costs.

13. The construction operation costs for the satellite are divided into low Earth orbit staging costs and geosynchronous orbit construction costs.

- LEO - varies with square root of power (factor 7)
- GEO - varies with square root of power and the transmitter area according to factor 10

TABLE B-2.- COST AND MASS FACTOR DEFINITIONS

1. Power/reference power

2. Antenna area/reference area

3. Rectenna area/reference area

4. Rectenna buffer area out to 0.1 mW/cm^2/reference buffer area

5. Antenna mass $\times$ diameter^2/reference antenna $\times$ diameter^2

6. Square root of antenna area (factor 2)

7. Square root of power (factor 1)

8. Rectenna area (factor 3) $\times$ power (factor 1)

9. Antenna area (factor 2) $\times$ power (factor 1)

10. Construction operation costs = $0.5 \times$ square root of factor 1 $+ 0.5 \times$ factor 2

11. Relative number of HLLV launches = $\dfrac{68 + 94 \times \text{factor 1} + 46 \times \text{factor 2}}{208}$

12. End-to-end microwave power transmission efficiency at 5.8 GHz

13. Satellite material and personnel transportation costs ($)

    - EOTV = $652 million $\times$ factor 1
    - PLV = $286 million $\times$ factor 1 $\times$ antenna diameter
    - POTV = $14 million $\times$ factor 1 $\times$ antenna diameter
    - HLLV = $2167 million $\times$ factor 11

14. Amortization of investment = $473 million $\times$ factor 1

15. Program management and integration expenses = 10% of hardware costs

16. Construction costs ($), for 2.45 GHz operating frequency

    - LEO = $313 million $\times$ factor 7
    - GEO = $648 million $\times$ factor 10

    For 5.8 GHz operating frequency

    - LEO = $344 million $\times$ factor 7
    - GEO = $713 million $\times$ factor 10

17. Electricity costs in mills per kWh

$$\text{For } 2.45 \text{ GHz} = \frac{152.3 \times \text{system cost } (\$10^6)}{8050 \times \text{plant capacity (GW)}}$$

$$\text{For } 5.8 \text{ GHz} = \frac{152.3 \times \text{system cost } (\$10^6)}{7875 \times \text{plant capacity (GW)}}$$

TABLE B-3.- PREDEFINED COST AND MASS FACTORS FOR ANTENNA/RECTENNA CONFIGURATIONS

Microwave characteristic	Satellite configuration											
	A	B	C	D	E	F	G	H	I	J	K	L
Transmitting frequency, GHz . . .	5.8	5.8	5.8	5.8	5.8	2.45	2.45	2.45	2.45	2.45	2.45	2.45
Antenna diameter, km	0.5	0.75	1.0	1.5	0.75	1.36	1.53	2	1.36	1.53	2	1
Satellite power output, GW	1.68	3.78	6.5	2.88	2.84	3.53	2.78	1.64	6.5	6.5	6.5	6.5
Power density at rectenna, mW/cm^2	7.87	40	122	129	30	23	23	23	42	54	91	23
Rectenna diameter, km	8.75	5.8	4.3	2.8	5.8	7.6	6.8	5	7.6	6.8	5	10
Power delivered, GW	1.17	2.72	4.8	2.12	2	2.7	2.1	1.26	5	5.05	5.05	5
Power delivered per km^2 of land, kW/km^2	12.5	53.6	67.9	65.8	39.8	30.3	29.9	30.9	53.6	67.5	110.6	31.6
Factor												
1	0.258	0.581	1	0.443	0.436	0.543	0.427	0.252	1	1	1	1
2	0.25	0.562	1	2.25	0.562	1.85	2.34	4.0	1.85	2.34	4.0	1
3	0.76	0.336	0.185	0.078	0.336	0.58	0.462	0.25	0.58	0.462	0.25	1
4	0.589	0.320	0.445	0.203	0.320	0.562	0.445	0.258	0.589	0.468	0.286	1
5	0.07	0.33	1	2.36	0.278	1.74	2.34	5.4	2.32	3.3	7.7	1
6	0.5	0.75	1	1.5	0.75	1.36	1.53	2.0	1.36	1.53	2.0	1
7	0.508	0.762	1	0.666	0.660	0.736	0.653	0.50	1	1	1	1
8	0.196	0.195	0.185	0.034	0.146	0.314	0.197	0.063	0.58	0.462	0.25	1
9	0.0645	0.326	1	1	0.245	1	1	1	1.85	2.34	4.0	1
10	0.378	0.662	1	1.46	0.611	1.29	1.49	2.25	1.42	1.67	2.5	1
11	0.5	0.72	1	1.03	0.65	0.98	1.037	1.325	1.19	1.30	1.66	1
12	0.698	0.720	0.735	0.735	0.713	--	--	--	--	--	--	--

TABLE B-4.- COST AND MASS STATEMENTS FOR 5.8 GHz SYSTEMS

(a) SPS

Component	A (0.5 km, 1.68 GW)		B (0.75 km, 3.78 GW)		C (1 km, 6.5 GW)		D (1.5 km, 2.88 GW)		E (0.75 km, 2.84 GW)
	Mass, t	Cost, $	Mass, t	Cost, $	Mass, t	Cost, $	Mass, t	Cost, $	Cost, $
Power collection									
(1) Structure	1 201	116×10^6	2 704	260×10^6	4 654	448×10^6	2 062	198×10^6	195×10^6
(1) Solar cells	5 455	513	12 285	1155	21 145	1988	9 367	881	867
(1) Power distribution	321	39	724	87	1 246	150	552	66	65
(1) Maintenance	160	71	361	159	621	274	275	121	119
Total	7 137	[a]783	16 074	[a]1762	27 666	[a]3032	12 256	[a]1343	[a]1321
(5) Rotary joint	17	7	78	34	236	102	557	241	28
Power transmission									
(2) Structure	81	7	182	15	324	26	729	59	15
(1) Klystrons and thermal control	1 808	123	4 071	277	7 007	477	3 104	211	208
(2) Waveguides	701	53	1 576	120	2 804	213	6 309	479	120
(2) Subarray structure	314	70	705	158	1 254	281	2 822	632	158
Power distribution									
(9) Conductors	23	1	116	6	356	18	356	18	4
(1) Switchgears, DC-DC converters, thermal control	482	78	1 086	175	1 869	301	828	133	76
Energy storage	313	5	313	5	313	5	313	5	5
(2) Phase control	5	23	10	51	18	90	41	203	51
(6) Maintenance systems	115	252	173	378	230	504	345	756	378
(5) Antenna mechanical pointing	14	1	66	7	200	21	471	50	6
Total	3 856	613	8 298	1192	14 375	1936	15 318	2546	1021
Information management and control									
Computers - (2) Mass (6) Cost	1	15	3	23	4.5	30.7	10	47	31
Cabling - (2) Mass (6) Cost	23	9	51	13	91.1	17.3	205	26	17
Attitude control									
(5) Hardware	14	17	5	6	204	240	481	566	67
(5) Propellant	8	0	3	0	114	0	259	0	0

[a]These cost totals have been adjusted by 0.85/0.80 = 1.06 to account for reduced klystron DC-RF conversion efficiency.

(a) Concluded

Component	A (0.5 km, 1.68 GW) Mass, t	Cost, $	B (0.75 km, 3.78 GW) Mass, t	Cost, $	C (1 km, 6.5 GW) Mass, t	Cost, $	D (1.5 km, 2.88 GW) Mass, t	Cost, $	E (0.75 km, 2.84 GW) Cost, $
Communications	0.2	8×10^6	0.2	8×10^6	0.2	8×10^6	0.2	8×10^6	8×10^6
Mass growth (22% of total satellite mass)	2 435	–	5 393	–	9 340	–	6 401	–	–
Satellite total	13 506	1452	29 905	3038	51 795	5366	35 497	4777	2494
Transportation									
(13) EOTV		168		379		652		289	284
PLV		37		125		286		190	94
POTV		2		6		14		9	5
HLLV		1081		1560		2167		2332	1409
Total		1288		2070		3120		2720	1794
Construction operations									
(16) LEO		175		262		344		229	227
GEO		269		472		713		1041	436
Total		444		734		1057		1270	663
Mission control		10		10		10		10	10

TABLE B-4.- Concluded

(b) Rectenna

Component	A (0.5 km, 1.68 GW)	B (0.75 km, 3.78 GW)	C (1 km, 6.5 GW)	D (1.5 km, 2.88 GW)	E (0.75 km, 2.84 GW)
Cost, million dollars					
(4) Land	57	31	44	20	31
(3) Structure and installation	263	116	64	27	116
(3) Ground plane and RF assemblies	4081	1804	993	419	1804
(8) Distribution buses	60	60	57	11	45
Command and control center	70	70	70	70	70
(7) Power processing and grid interface	394	591	775	516	512
Total	4925	2672	2003	1063	2578
Land required out to 0.1 mW/cm^2, km^2	93.2	50.7	70.4	32.2	50.7
Rectenna diameter, km	8.75	5.8	4.3	2.8	5.8
Buffer diameter out to 0.1 mW/cm^2 (minor axis), km	9.2	6.8	8	5.4	6.8
Buffer diameter out to 0.1 mW/cm^2 (major axis), km	12.9	9.5	11.2	7.6	9.5

TABLE B-5.- COST AND MASS STATEMENTS FOR 2.45 GHz SYSTEMS

(a) SPS

Component	F (1.36 km, 3.53 GW) Mass, t	Cost, $M[a]	G (1.53 km, 2.78 GW) Mass, t	Cost, $M	H (2 km, 1.64 GW) Mass, t	Cost, $M	I (1.36 km, 6.5 GW) Mass, t	Cost, $M	J (1.53 km, 6.5 GW) Mass, t	Cost, $M	K (2 km, 6.5 GW) Mass, t	Cost, $M	L (1 km, 6.5 GW) Mass, t	Cost, $M
Power collection														
(1) Structure	2 527	243	1 987	192	1 173	113	4 654	448	4 654	448	4 654	448	4 654	448
(1) Solar cells	11 481	1079	9 029	849	5 329	501	21 145	1988	21 145	1988	21 145	1988	21 145	1988
(1) Power distribution	677	81	532	64	314	38	1 246	150	1 246	150	1 246	150	1 246	150
(1) Maintenance	337	149	265	117	156	69	621	274	621	274	621	274	621	274
Total	15 023	1553	11 813	1221	6 972	721	27 666	2860	27 666	2860	27 666	2860	27 666	2860
(5) Rotary joint	420	181	553	238	1 273	550	547	237	778	336	1 817	785	236	102
Power transmission														
(2) Structure	600	48	758	61	1 296	104	600	48	758	61	1 296	104	324	26
(1) Klystrons and thermal control	3 805	259	2 992	204	1 766	120	7 007	477	7 007	477	7 007	477	7 007	477
(2) Waveguides	4 323	329	5 469	417	9 348	712	4 323	329	5 469	417	9 348	712	2 337	178
(2) Subarray structure	1 933	433	2 445	548	4 180	936	1 933	433	2 445	548	4 180	936	1 045	234
Power distribution														
(9) Conductors	356	18	356	18	356	18	559	33	833	42	1 424	72	356	18
(1) Switchgears, DC-DC converters, thermal control	1 014	163	798	129	471	76	1 869	301	1 869	301	1 869	301	1 869	301
Energy storage	313	5	313	5	313	5	313	5	313	5	313	5	313	5
(2) Phase control	22.2	22.2	28	28	48	48	22	22	28	28	48	48	12	12
(6) Maintenance systems	313	685	352	771	460	1008	313	685	352	771	460	1008	230	504
(5) Antenna mechanical pointing	233	24	314	33	722	75	310	32	442	46	1 032	108	134	14
Total	12 912	1986	13 825	2214	18 960	3102	17 250	2364	19 516	2658	27 038	3771	13 628	1769
Information management and controls														
Computers - (2) Mass (6) Cost	8	42	10	47	18	61	8	42	10	47	18	61	4.5	30.7
Cabling - (2) Mass (6) Cost	169	24	213	26	364	35	169	24	213	26	364	35	91.1	17.3

[a]$M = million dollars.

(a) Concluded

Component	F (1.36 km, 3.53 GW)		G (1.53 km, 2.78 GW)		H (2 km, 1.64 GW)		I (1.36 km, 6.5 GW)		J (1.53 km, 6.5 GW)		K (2 km, 6.5 GW)		L (1 km, 6.5 GW)	
	Mass, t	Cost, $M	Mass, t	Cost, $M	Mass, t	Cost, $M	Mass, t	Cost, $M	Mass, t	Cost, $M	Mass, t	Cost, $M	Mass, t	Cost, $M
Attitude control														
(5) Hardware	236	278	318	374	734	600	315	371	449	528	1 047	600	136	160
(5) Propellant	135	0	177	–	411	–	177	–	251	–	586	–	76.1	0
Communications	.2	8	.2	8	.2	8	.2	8	.2	8	.2	8	.2	8
Mass growth (22% of total satellite mass)	6 358	–	5 920		6 321		10 149		10 754		12 878		9 146	–
Satellite total	35 261	4072	32 830	4120	35 053	5069	56 281	5898	59 637	6455	71 414	8112	50 984	4946
Transportation														
(13) EOTV		354		278		164		652		652		652		652
PLV		211		187		144		389		428		572		286
POTV		10		9		7		19		21		28		14
HLLV		2125		2247		2871		2579		2817		3597		2167
Total		2700		2721		3186		3639		3918		4849		3120
Construction operations														
(16) LEO		230		204		157		313		313		313		313
GEO		836		966		1458		920		1082		1620		648
Total		1066		1170		1615		1233		1395		1933		961
Mission control		10		10		10		10		10		10		10

(b) Rectenna

Component	F	G	H	I	J	K	L
	(1.36 km, 3.53 GW)	(1.53 km, 2.78 GW)	(2 km, 1.64 GW)	(1.36 km, 6.5 GW)	(1.53 km, 6.5 GW)	(2 km, 6.5 GW)	(1 km, 6.5 GW)
Cost, million dollars							
(4) Land	67	53	30	71	56	34	120
(3) Structure and installation	201	160	86.5	201	160	86.5	346
(3) Ground plane and RF assemblies	556	443	240	556	443	240	959
(8) Distribution buses	97	61	20	179	142	77	308
Command and control center	70	70	70	70	70	70	70
(7) Power processing and grid interface	570	506	388	775	775	775	775
Total	1561	1293	835	1852	1646	1283	2578
Land required out to 0.1 mW/cm^2, km^2	89.01	70.33	40.88	93.2	74.06	45.2	158.3
Rectenna diameter, km	7.6	6.8	5	7.6	6.8	5	10
Buffer diameter out to 0.1 mW/cm^2 (minor axis), km	9	8	6.1	9.2	8.2	6.4	12
Buffer diameter out to 0.1 mW/cm^2 (major axis), km	12.6	11.2	8.54	12.9	11.5	9.0	16.8

TABLE B-6.- COST SUMMARY

(a) Physical parameters

Microwave characteristic	Satellite configuration											
	A	B	C	D	E	F	G	H	I	J	K	L
Frequency, GHz	5.8	5.8	5.8	5.8	5.8	2.45	2.45	2.45	2.45	2.45	2.45	2.45
Antenna diameter, km	0.5	0.75	1.0	1.5	0.75	1.36	1.53	2	1.36	1.53	2	1
Satellite power output, GW	1.68	3.78	6.5	2.88	2.84	3.53	2.78	1.64	6.5	6.5	6.5	6.5

(b) Costs

Cost category	Satellite configuration											
	A	B	C	D	E	F	G	H	I	J	K	L
SPS hardware, million dollars	1452	3038	5366	4777	2494	4072	4120	5069	5898	6455	8112	4946
Less amortization of investment (see factor 14), million dollars	122	275	473	209	206	257	202	119	473	473	473	473
Total, million dollars	1330	2763	4893	4568	2288	3815	3918	4950	5425	5982	7639	4473
Mission control, million dollars	10	10	10	10	10	10	10	10	10	10	10	10
Transportation, million dollars	1288	2070	3120	2720	1794	2700	2721	3186	3639	3918	4849	3120
Construction operations, million dollars	444	734	1057	1270	663	1066	1170	1615	1233	1395	1933	961
Rectenna, million dollars	4925	2672	2003	1063	2578	1561	1293	835	1852	1646	1283	2578
Program management and integration (see factor 15), million dollars	145	303	536	477	249	407	412	507	590	645	811	495
Cost allowance for mass growth, million dollars	226	470	832	777	389	649	666	841	922	1017	1299	760
Total, million dollars	8368	9022	12 451	10 885	7969	10 243	10 190	11 944	13 671	14 613	17 824	12 432
Mills per kWh (see factor 17)	138	64	50.3	99	76.1	71.6	90.6	180.1	52	55	67.1	47
Cents per MJ	3.8	1.8	1.4	2.7	2.1	2.0	2.5	5.0	1.4	1.5	1.9	1.3
% increase in electricity costs compared to cost of 1.3¢/MJ (47 mills/kWh) for the reference SPS system	193	36	7	111	62	52.4	92.7	283	10.6	17	42.7	--

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15. Supplementary Notes

16. Abstract

The present reference configuration for a solar power satellite system provides 5 GW of electrical power at the ground using a 1 km diameter antenna transmitting at 2.45 GHz and a 10 km diameter receiving antenna (rectenna). This paper considers technical and economic tradeoffs of smaller solar power satellite systems configured with larger antennas, reduced output power, and smaller rectennas. These systems are reoptimized by changing the guidelines of the sizing studies; that is, the ionospheric power density limit, the operating frequency, and the antenna thermal limit.

The differential costs in electricity for seven antenna/rectenna configurations operating at 2.45 GHz and five satellite systems operating at 5.8 GHz are calculated. Two 2.45 GHz configurations dependent upon the ionospheric power density limit are chosen as examples. If the ionospheric limit could be increased to 54 mW/cm^2 from the present 23 mW/cm^2 level, a 1.53 km antenna satellite operating at 2.45 GHz would provide 5.05 GW of output power from a 6.8 km diameter rectenna. This system gives a 54-percent reduction in rectenna area relative to the reference solar power satellite system at a modest 17-percent increase in electricity costs. At 5.8 GHz, a 0.75-km antenna providing 2.72 GW of power from a 5.8 km diameter rectenna is selected for analysis. This configuration would have a 67-percent reduction in rectenna area at a 36-percent increase in electricity costs. Ionospheric, atmospheric, and thermal limitations are discussed. Antenna patterns for three configurations to show the relative main beam and sidelobe characteristics are included. Multiple antenna satellites can effectively reduce the number of geosynchronous slots (spacings) required for the solar power satellites.

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