RECTENNA SYSTEM DESIGN

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1.0 INTRODUCTION

The function of the rectenna in the solar power satellite system is to convert the downcoming microwave power beam to electrical grid power. Due to its large physical size (a typical rectenna site is a 10 KM x 14 KM ellipse) and element composition (many repetitive components), the projected cost savings of automatic mass production are of prime importance. Control of the satellite power beam and its distribution also takes place at facilities on the rectenna site. These critical functions have minor cost impacts and are not treated in this document.

The fundamental processes at the rectenna consist of rectifying the incident r.f. field into d.c. current using Schottky barrier diodes, filtering the rectified output, combining it and processing it to higher voltages for distribution. Hierarchial combination and processing of currents is done several times to integrate the relatively low power per diode to electrical grid power magnitudes. Provisions for power control for equipment protection and load management exist at each step in the hierarchy.

2.0 RECEIVING ANTENNA OPTIONS

Figure 1 illustrates the basic design choices based on the desired microwave field concentration prior to rectification and on the ground clearance requirement for the rectenna structure. For an optimized system, these parameters depend on positions within the site, local terrain and incident r.f. field. For purposes of the present study, a non-concentrating inclined planar panel with a 2 meter minimum clearance configuration was selected as representative of the typical rectenna.

3.0 RECEIVING ELEMENT OPTIONS

Figure 2 illustrates some of the options that have been considered for receiving antenna elements. Dipoles in various implementations represent the most straightforwar way of receiving a linearly polarized incident field compatible with the slotted waveguide transmitting array, and are relatively easy to analyze. However, other options, including elements that receive circularly polarized fields, have been considered.

Figure 3 shows capture area as a function of element width and length for a number of different types of elements. A trade study of diode power for maximum rectification efficiency (5-10 watts per diode) as opposed to long life with passive cooling (<5 watts per diode) suggests a power level per diode of somewhere between 1 and 5 watts. (See Table 1).

TABLE 1: SINGLE DIODE RECTENNA (DIPOLE) ELEMENT

Element Power Level (Watts)	Equivalent Power* Density mW/CM^2	Achieved Element Efficiency %	Projected Element Efficiency %
8	160	91	91
1	20	88	90
0.5	10	86	88
0.2	4	84	86
0.1	2	82	85

*Proposed Power Density at SPS Rectenna Center - 23 mW/CM^2

Proposed Power Density at SPS Rectenna Edge - 1 mW/CM^2

The baselined modified half-wave dipole, with a capture area of 70 CM^2 (typical) will provide between 1-2 watts of power per diode at the center of the rectenna (23 mW/CM^2) indicating good efficiency. More directional elements or dipole arrays must be used as we go out to the rectenna edge ($\approx$1 mW/CW^2); for instance, a 4 x 4 dipole array would again provide 1 watt per diode. Care must be exercised not to select too large an array which would pose problems of directional reception and increased losses in the r.f. collection lines. The design chosen integrates the dipoles and their associated power and microwave circuitry inside an aluminum environmental shield and support structure which readily lend themselves to mass production methods.

4.0 BASELINE RECTENNA DESCRIPTION

A representative rectenna design at a 35° latitude is described, characterized by a 5 GW Gaussian tapered beam with a peak incident microwave power of 23 mW/CM^2. Power is collected out to the point where the interception efficiency is 95%. The basic receiving element of the baseline rectenna is a dipole above a ground plane. The dipole assembly also contains a filtering and matching circuit to match the dipoles to the incoming wave with a reflection coefficient of better than -20 db. It is assumed that all dipoles are identical throughout the rectenna. The number of dipoles in the rectenna is approximately 1.3 x 10^{10} in a 7.9 CM = .64 λ triangular array format.

Component designs for the rectenna are varied to most effectively match the incident power flux in ten rings. Basically, all microwave system components of a given type are similar within a ring. However, power bussing and control segmentation at the 5-10 mW power level and above extends across ring boundaries. Local d.c. voltages on the panels are designed not to exceed $\pm$3.25 KV.

Due to the power density variation over the rectenna aperture, a single type of radiating element or a single type of rectifier cannot provide optimum conversion efficiency. Either a number of radiating element types or a number of diode types must be provided. Presently, one single type of diode is assumed which is operated with four different types of antenna elements. It is assumed that besides the dipole element already described, these antenna elements are formed by using the basic dipoles in arrays containing 2, 4, or 8 dipoles. The corresponding assemblies are called Type 1,2,3, and 4 receiving arrays. There are approximately 7.654 x 10^9 arrays (diode assemblies) in the overall antenna.

The array assemblies are combined into panels which are the smallest assembly units from the fabrication point of view. 10 m^2 was selected for the panel area, with a N-S plane dimension of 3 m and E-W plane dimension of 3.33 m. Figure 4 shows a typical panel assembly in the center of the rectenna. It is assumed that all panel sizes are identical. This requires 7,060,224 panels in the rectenna. There are four different types of panels, corresponding to the four different types of receiving arrays. Although the dipoles and diodes are identical for all panels, the combining-matching-filtering circuits and the diode wiring represent four types. Table 2 summarizes the characteristics of the panels.

TABLE 2: RECTENNA PANEL CHARACTERIZATION

Ring	P $\frac{mW}{cm^2}$	P_{RF} $\frac{W}{Panel}$	P_{DC} $\frac{W}{Panel}$	Dipoles	Diodes	V_{DC} $\frac{V}{Diode}$	P_{DC} $\frac{W}{Diode}$	V_{DC} $\frac{V}{Panel}$	I_P $\frac{A}{Panel}$	R_{DC} $\frac{ohm}{Panel}$
1	23.33	2333	1738.8	43 x 43 = 1849	1849	17.96	.9398	772.3	2.25	1100
2	18.76	1876	1375.2	1849	1849	16.11	.7437	692.7	1.98	1100
3	14.38	1438	1043.3	1849	1849	14.11	.5642	606.7	1.72	1100
4	11.42	1142	828.1	2x30x31 = 1860	930	17.73	.8904	545.6	1.50	1136
5	8.67	867	625.6	1860	930	15.44	.6727	478.6	1.31	1136
6	6.72	672	468.1	1860	930	13.59	.5033	421.3	1.11	1136
7	5.34	534	365.4	1860	930	12.12	.3929	375.7	.973	1136
8	4.24	424	292.1	4x21x22 = 1848	462	15.32	.6322	337.0	.866	1152
9	3.49	349	236.5	1848	462	13.90	.5119	305.8	.773	1152
10	3.14	314	214.0	8x15x15 = 1800	225	18.90	.9511	283.3	.755	1100

Units are combined from panels in such a manner that nominally 1,000 panels are in one unit and the N-S dimension of a unit is always 32 x 3.662 = 117.18 m, which means that the number of panel rows in the N-S plane is always 32. This allows a standardization of the unit layouts to a minimum of seven types. Figure 5 shows the overall layout of the rectenna with the ring boundaries and the number of units within each ring. Note that the N-S dimension of the units are standardized to 117.18 m everywhere within the rectenna and only the E-W dimension of the units varies from ring to ring.

The last assembly which is formed at DC is called "group". This brings the power output into the 5-10 MW range. In order to keep the voltage levels relatively low, groups are formed from the units by parallel connections only. The power from the unit output is brought to group centers, or blocks, where the DC to AC inverters are located, by relatively long transmission lines that are parallel-connected at the group centers only. Blocks handle approximately 70 MW of power each.

Selection of the layout for the rectenna AC system between the individual DC/AC converters and the bulk power transmission system depends on the location and the power levels of the DC/AC converters as well as on the needs of the bulk power transmission system. A one-line diagram for the rectenna AC system in which the DC output from the dipoles is collected into 40 MW DC/AC converter stations is shown in Figure 6. The 40 MW converter station output is transmitted by underground cable to 200 MW transformer stations where the voltage is stepped up to 230 kV, then collected in 1,000 MW groups and transformed to 500 kV for interphase with the bulk transmission system. The switchyards are shown arranged as reliable "breaker and a half" schemes where single contingency outages may be sustained without loss of power output capability. The selection of the voltage level for the ultimate bulk power transmission interface with the utility grid, as well as the possibility of interconnecting two or more of the 1,000 MW switching stations together should be optimized based on detailed information about the connecting utility system. The solution, shown in Figure 6, integrated in a utility system with a control structure, as indicated in Figure 7, is one of several possible choices.

Availability calculations for the baseline rectenna design (Figure 8) were performed, the results of which are that 80% of the rated satellite power is available 96.8% of the time, and that scheduled no-power periods total only 208 hours per year.

To define the requirements for a given specific situation, load flow and system stability studies are required. It is likely, however, that the SPS power system would be far more stable than a conventional power plant of the same rating. This would mean that the transmission distances could be increased for a given line loading without need for as much series compensation as in conventional power plants.

When substantial amounts of power are to be transported for distances of 400 miles or more, the consideration of a high-voltage DC (HVDC) as the transmission load is often indicated. The HVDC system is ideally suited for long distance bulk power transport since it does not suffer from stability effects and can even be used to improve the stability of the AC system to which it is connected. The DC system is asynchronous and can easily transmit power between independent power systems such as those of the Eastern and the Western United States. HVDC technology is advanced and the systems have been well received. A 6,300 MW system in Brazil is currently in the proposal stages with full scale operation scheduled for 1985. It appears that a DC system or a combination of DC and AC systems could be applied to the Solar Power Satellite system with few difficulties.

5.0 SCATTERING AND RADIO FREQUENCY INTERFERENCE

The microwave transmission link must meet a stringent standard of electromagnetic cleanliness which states that out-of-band power must be more than 150 db down from the link power. Even though stray power reflected from and/or radiated by the rectenna generally travels in an upward direction, there are enough scattering mechanisms for harmonics from the diode rectifier and associated noise to warrant the serious question of meeting this requirement. Some of the approaches and their implications are summarized in Raytheon data of Table 3 below.

TABLE 3: APPROACHES TO DECREASE HARMONIC RECTENNA RADIATION

Approach	Expected Improvement in 2nd, 3rd and 4th Harmonics	Implications
o More filter sections of current design	Approx. 14 db per section	o No physical room, 1% loss for each section. o Mechanical tolerance problem.
o Stub lines to short higher harmonics at dipole terminals	∿30 db	o 2nd harmonic reduction easily added. o 3rd and higher harmonics require added width to core section. o Less than 1% decrease in circuit efficiency. o Could degrade the electronic efficiency
o Incorporate stub lines as part of filter sections	∿60 - 80 db	o Mechanical tolerance problem. o Requires additional width of core section. o Some circuit efficiency degradation. o Could degrade the electronic efficiency.
o Full wave rectification	∿15 db	o Doubles or quadruples number of diodes. o Greatly complicates electrical circuit and mechanical construction.

In the baseline design, two low pass filter sections which attenuate the second and higher order harmonics by over 25 db separate the rectifier from the outside world. More filter sections add approximately 17 db more suppression, each at a cost of approximately 1% efficiency loss. Other alternatives, also with an efficiency penalty, are to use stub line filters or full wave rectification. All of these approaches have mechanical configuration problems that, while solvable, will increase rectenna diode array assembly costs. Given these difficulties, it may become necessary to seek SPS-assigned bands at the first few harmonic frequencies.

Another type of scattering which affects system design is Fresnel edge diffraction from the rectenna panel edges. A slight overlapping of panels can reduce these losses but does increase total panel area and cost. The expected capture loss and resultant efficiency loss is estimated at between 1 to 2%.

6.0 RECTENNA SYSTEM OPTIMIZATION

Optimization of a rectenna system design to minimize costs is carried out at several levels. It is always desirable from the cost per unit power standpoint to transmit as much power through the transmission link as the ionospheric medium and beam pattern constraints will allow. The rectenna should be increased in size until the incremental rate of return from sales of the intercepted power are marginal. Such a procedure is illustrated in Figure 8 where the incremental revenue per square meter is balanced by the incremental cost per unit rectenna area at the optimum.

Much of the cost of the rectenna is in the structural support material required to support it against wind drag and snow loads. Different types of rectenna panels were considered. The baseline design chosen is an intermediate between the inexpensive but draggy flat panels and the more expensive, low drag panels which have circuit topology problems. The present rectenna panel support structure evolved from stiff edge-supported panels to a hierarchial more centrally supported frame which uses much less material.

7.0 RECTENNA CONSTRUCTION

Construction of the rectenna is, by necessity, highly automated. Starting with prefabricated dipole assembly components, a dipole machine (Figure 9), manufactures completed dipole/diode assemblies at a high rate. These are then combined with other prefabricated parts to manufacture receiving element sticks. The sticks, metal frame and ground plane are then tack-welded together to form panels (Figure 10).

The completed panels are then taken to the rectenna site where specialized equipment, shown on Figure 11, prepares the site through the emplacement of panel support arches. The panels are then lowered on the support arches, fastened and connected electrically.

There must, of necessity, be some rather conventional construction at the rectenna for the grid power system and the pilot beam transmitter(s), but these constitude only a small fraction of the construction cost.

8.0 RECTENNA COST

The rectenna investment and maintenance cost breakdown for the baseline design is indicated in Table 4.

TABLE 4: SPS RECTENNA COST BREAKDOWN PER MAJOR TASK

Task	Labor	Eqmt.	Material	Freight	Total
Initiate Site Preparation	503	301	4,479	255	3,402
Complete Site Preparation	1,400	1,047	18,780	884	15,446
Foundation and Supporting Structure	24,550	64,093	182,842	32,181	303,666
Manufacture and Install Panels	24,296	145,134	928,664	3,455	1,101,549
TOTAL ($'s in Thousands)	50,752	210,575	1,088,247	36,775	1,386,349

Land costs are excluded, but are typically less than 5% of the anticipated cost for typical sites considered. If desired, the land underneath the rectenna may be used for factories or intensive agriculture.

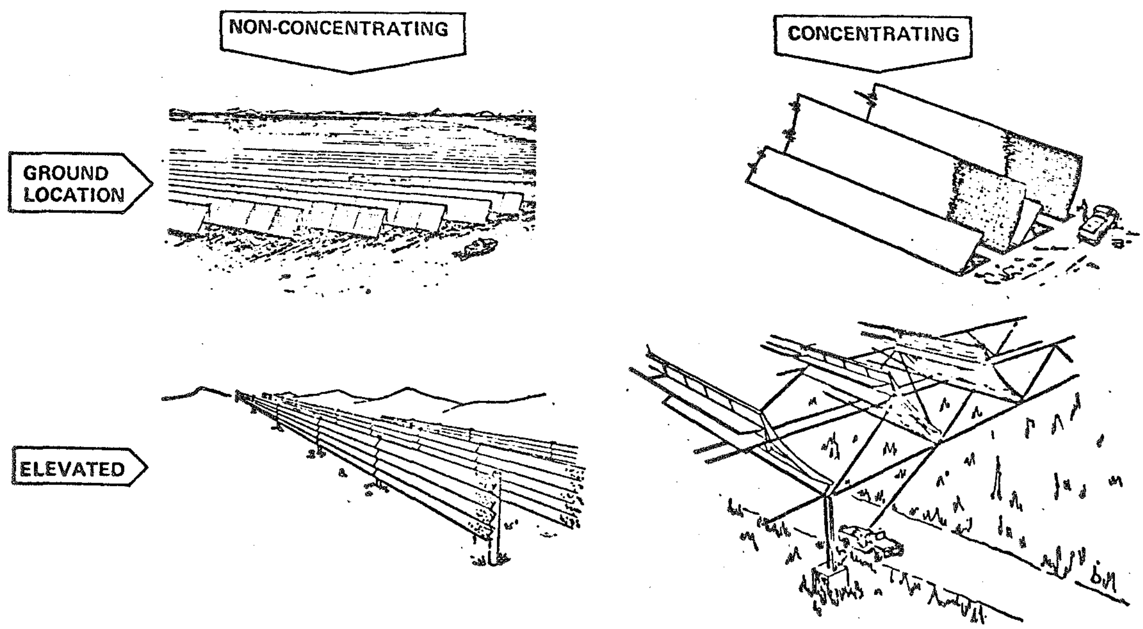


Figure 1: Potential Rectenna Configurations

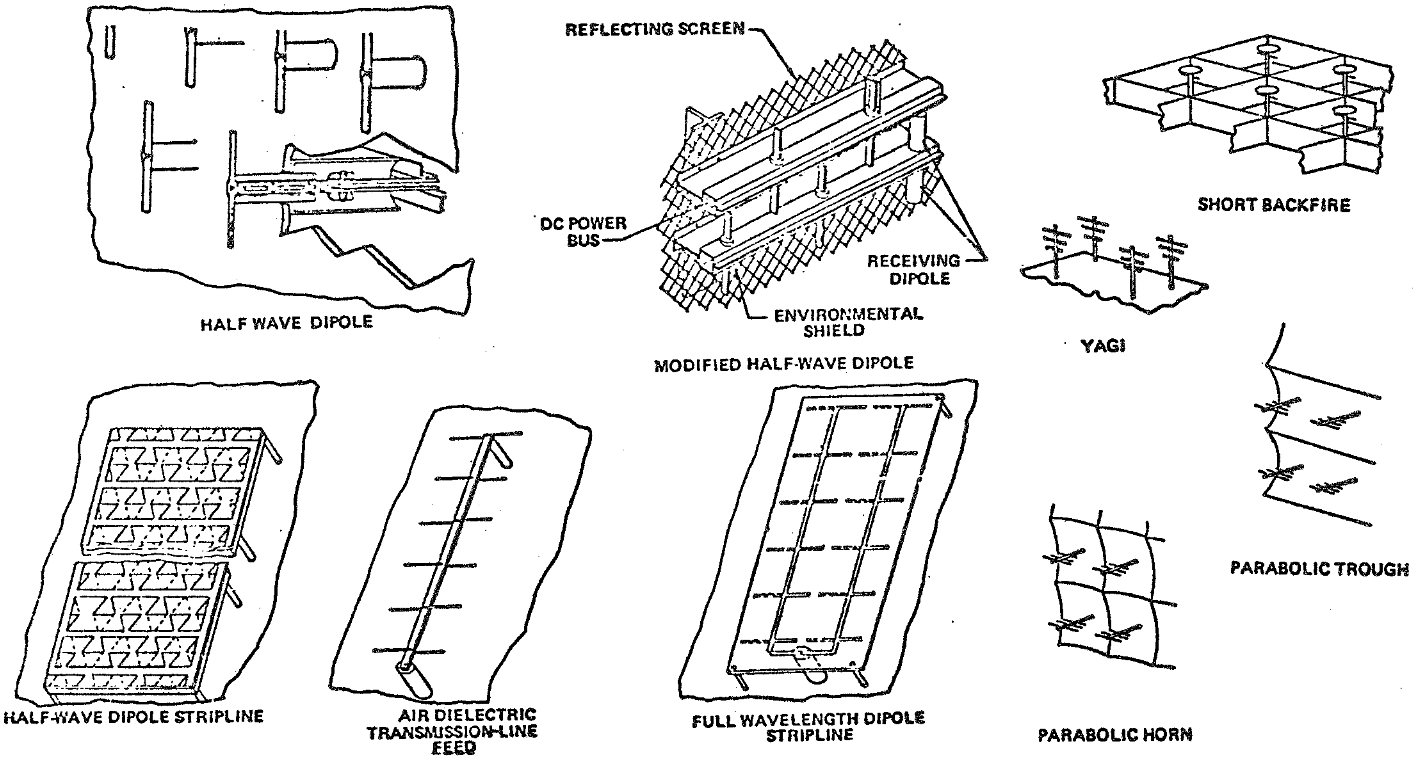


Figure 2: Rectenna Receiving Element Options

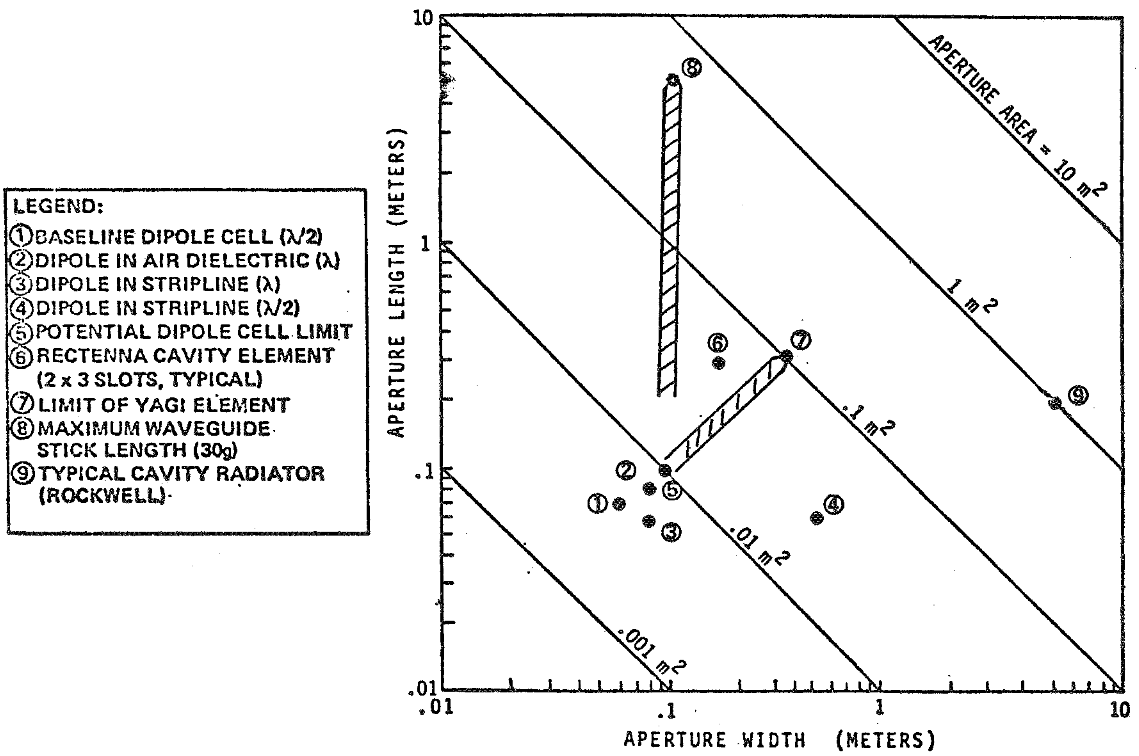


Figure 3: Rectenna Element Capture Areas

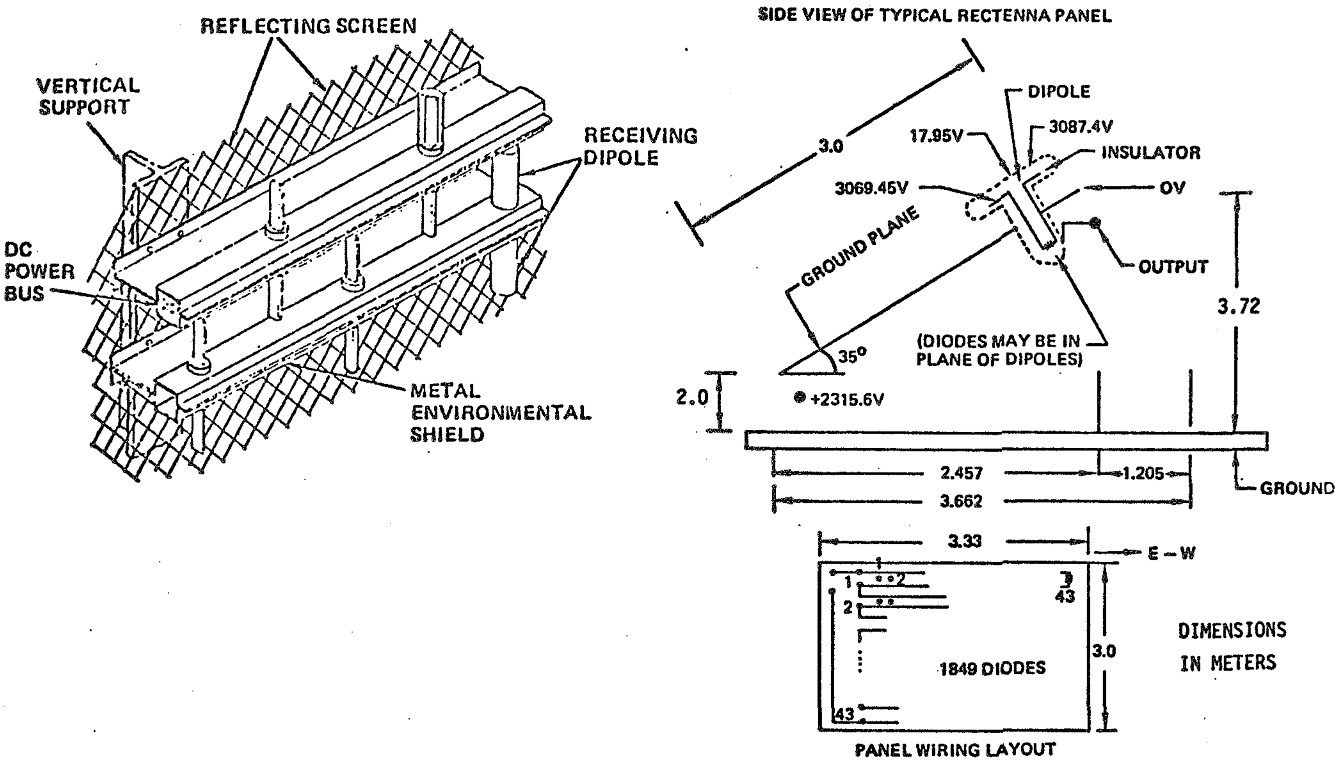
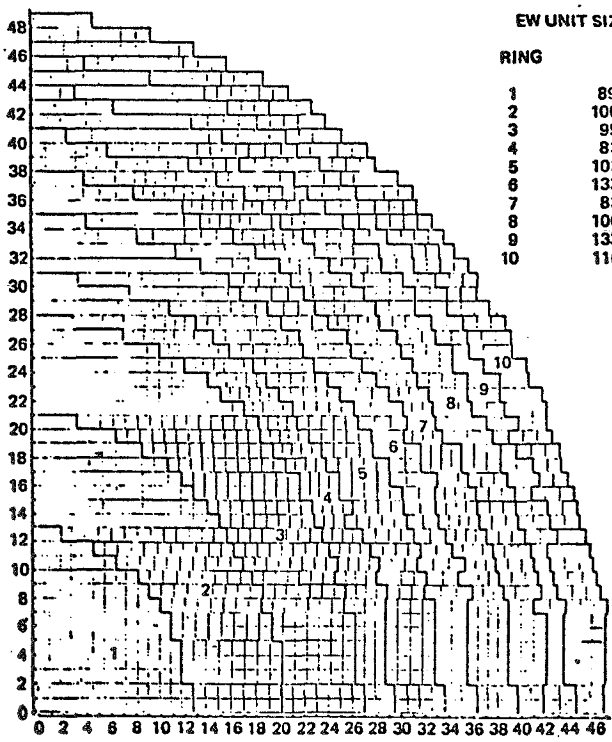


Figure 4: Typical Panel Configuration at Rectenna Center



EW UNIT SIZES

RING	m
1	89.991
2	106.656
3	99.99
4	83.325
5	103.323
6	133.320
7	83.325
8	106.656
9	133.320
10	116.665

Figure 5: Rectenna Ring and Unit Boundary Map

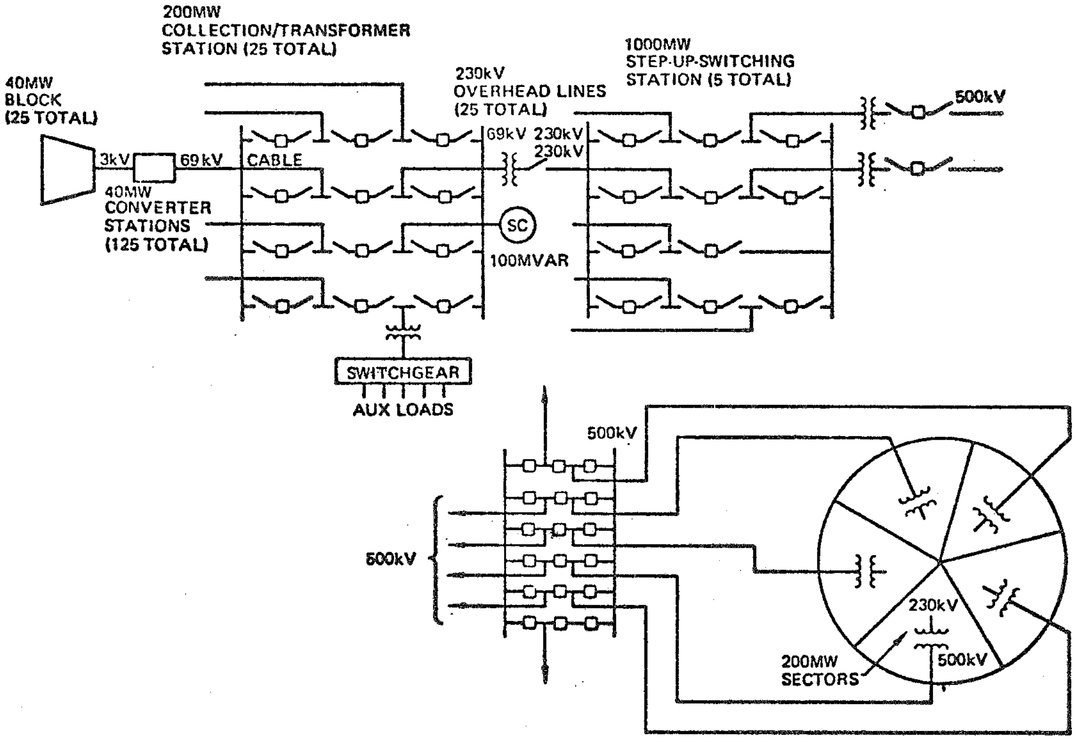


Figure 6: Grid Connection Approach

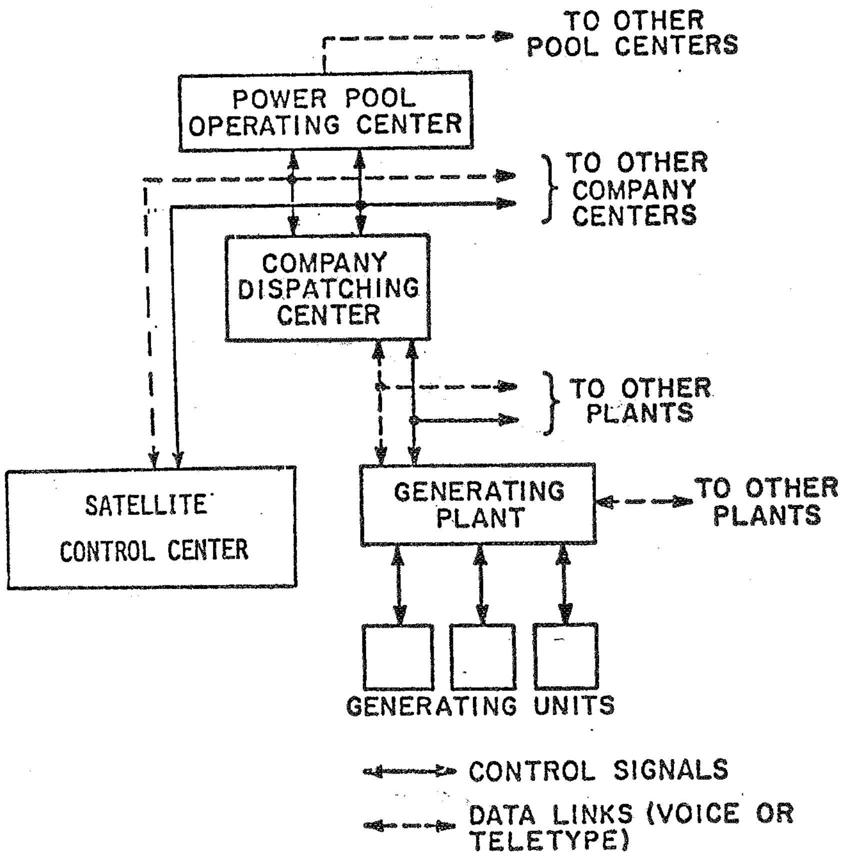


Figure 7: Utility System Control Structure

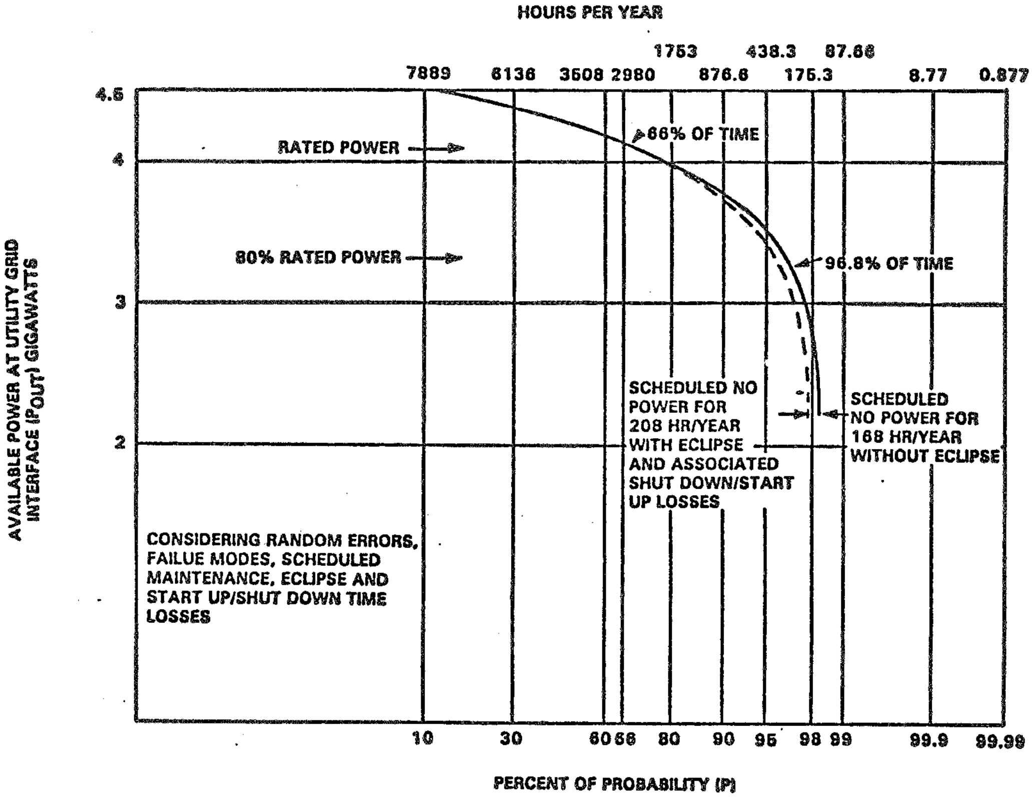
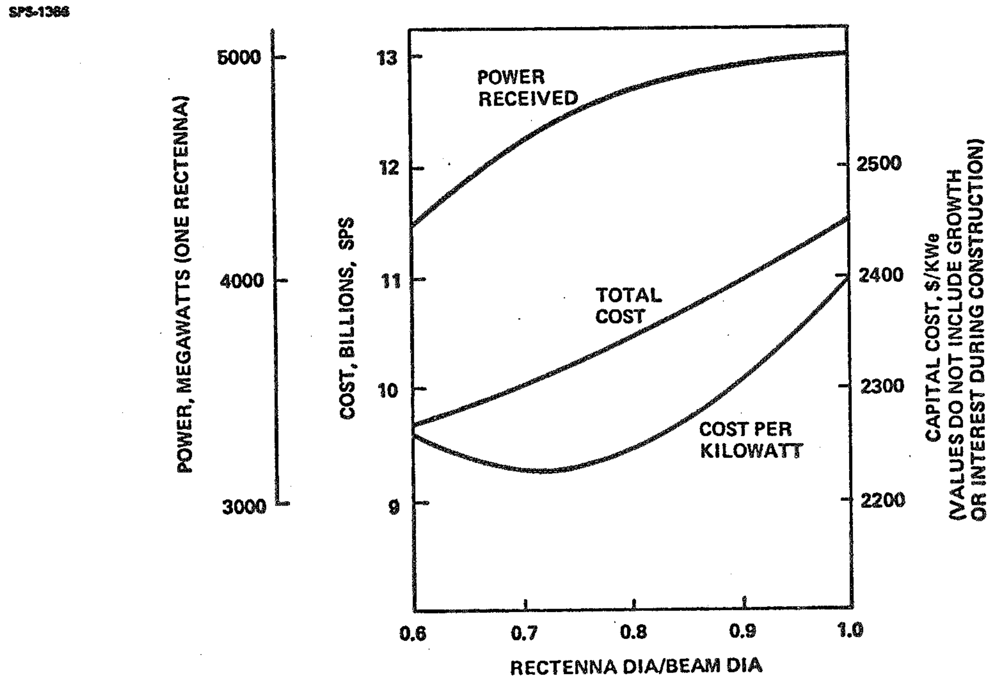


Figure 8: SPS Power Availability



(Note: Beam diameter is the entire main lobe to the first null.)

Figure 9: Rectenna Size Optimization

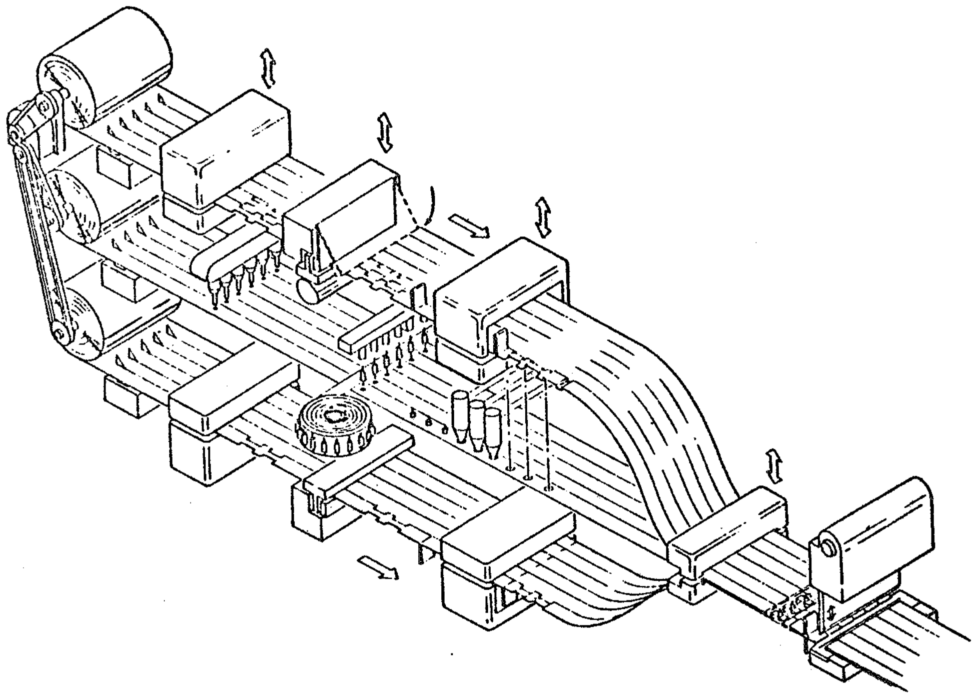


Figure 10: Dipole Machine

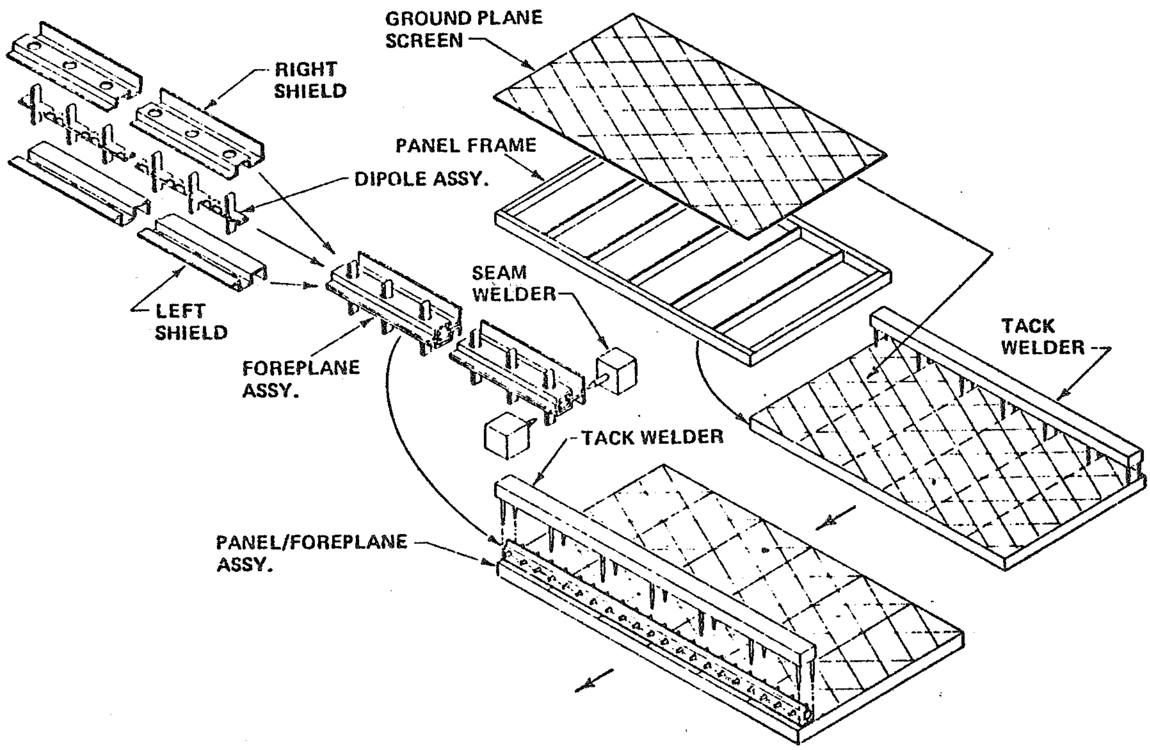


Figure 11: Rectenna Panel Fabrication Sequence