Summary of Recent Results from NASA's Space Solar Power (SSP) Programs and the Current Capabilities of Microwave WPT Technology

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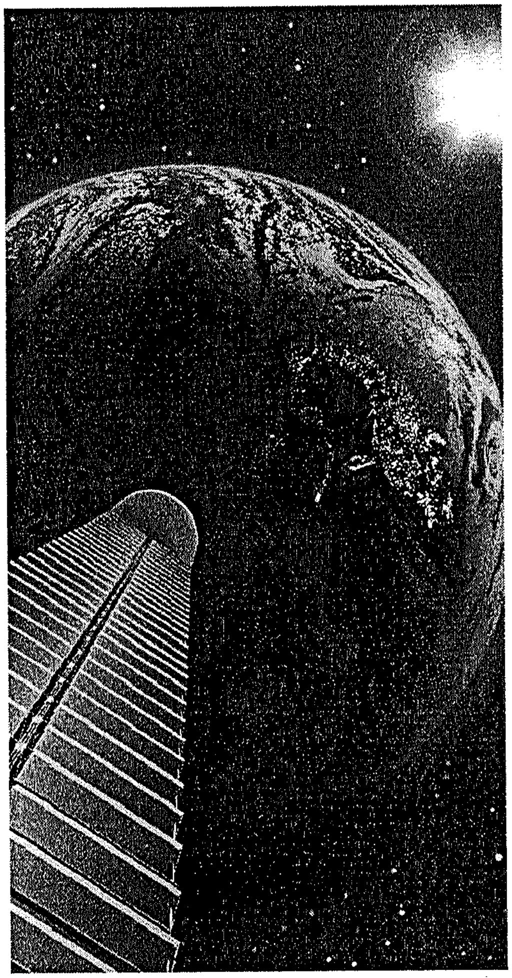


INTRODUCTION

The concept of placing enormous solar power satellite (SPS) systems in space represents one of a handful of new technological options that might provide large-scale, environmentally clean base load power into terrestrial markets. In the US, the SPS concept was examined extensively during the late 1970s by the U.S. Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA). More recently, the subject of space solar power (SSP) was reexamined by NASA from 1995-1997 in the "fresh look" study, and during 1998 in an SSP "concept definition study". As a result of these efforts, in 1999-2000, NASA undertook the SSP Exploratory Research and Technology (SERT) program which pursued preliminary strategic technology research and development to enable large, multi-megawatt SSP systems and wireless power transmission (WPT) for government missions and commercial markets (in-space and terrestrial). During 2001-2002, NASA has been pursuing an SSP Concept and Technology Maturation (SCTM) program follow-on to the SERT, with special emphasis on identifying new, high-leverage technologies that might advanced the feasibility of future SSP systems. In addition, in 2001, the U.S. National Research Council (NRC) released a major report providing the results of a peer review of NASA's SSP strategic research and technology (R&T) road maps.

One of the key technologies needed to enable the future feasibility of SSP/SPS is that of wireless power transmission. Advances in phased array antennas and rectennas have provided the building blocks for a realizable WPT system. These key components include the dc-RF converters in the transmitter, the retrodirective beam control system, and the receiving rectenna. Each subject is briefly covered, and results from the SERT program that studied a 5.8 GHz SPS system are presented.

This paper presents a summary results from NASA's SSP efforts, along with a summary of the status of microwave WPT technology development.

BACKGROUND

The concept of a large "solar power satellite" (SPS) that would be placed in geostationary Earth orbit (GEO) to collect sunlight, use it to generate an electromagnetic beam and transmit the energy to the Earth was invented in 1968 by a Czech-American, Dr. Peter Glaser of Arthur D. Little. In the U.S., a major study of the SPS concept was conducted during 1976-1980 by the DOE with the support of NASA [1]. This effort was funded at a level of more than $55M in FY2002 dollars and resulted in a wide range of useful research.

The DOE-NASA project in the 1970s is best remembered for the "1979 SPS Reference System". The central feature of this concept was the creation of a large-scale power infrastructure in space, consisting of about 60 SPS, each delivering 5 gigawatts (GW) of base load power to the U.S. national grid (for a total delivered power of about 300 GW). However, connections to interim applications of space solar power were tenuous and the space infrastructure requirements were projected to be significant. The "cost-to-first-power" of the 1979 Reference System was expected to be more than $300 billion (in FY 2002 dollars). As a result of the huge price tag, lack of evolutionary approach, and the subsiding energy crisis in 1980-1981, essentially all U.S.

SPS efforts were terminated. In a 1980 report on SSP, the NRC recommended that the concept be re-assessed in about10 years, subsequent to additional technology development and maturation.

During the 1980s, technology development in a range of relevant areas continued – particularly in the area of solar power generation of broad applicability in commercial and scientific spacecraft. Also during the 1980s and early 1990s, low level international interest in the SPS concept emerged, including wireless power transmission flight experiments in Japan and other activities in Europe and Canada. In the U.S., activities were largely limited to generic research and to modest systems studies of potential applications of SSP technology to space science and exploration missions.

RECENT NASA EFFORTS

Fresh Look Study. In 1995, NASA undertook a reconsideration of the challenge of large-scale SSP systems [2], [3]. This goal of this effort–the "Fresh Look Study"– was to determine whether technology advances since the 1970s might enable new, viable SSP systems concepts. The Fresh Look Study examined about 30 SSP concepts (emphasizing systems and architectures for GW-class power in terrestrial markets). The general finding of this preliminary assessment was that there did appear to be a number of promising SSP systems concepts – distinct from those of the 1970s – that were enabled by recent or projected advances in relevant technologies [4]. The Fresh Look Study concluded that the prospects for power from space were more viable technically than they had been at the end of the 1980s–although still exceptionally challenging [5].

SSP Concept Definition Study. During 1998, NASA conducted the SSP Concept Definition Study following the suggestion of the House Science Committee. This study was a focused 1-year effort that tested the results of the previous Fresh Look Study. The 1998 effort engaged a wide range of technologists from outside the Agency as well as within. In addition, NASA funded an independent economic and market analysis study, led by Dr. Molly Macauley of the Washington D.C.-based non-profit, Resources For the Future. The 1998 SSP Concept Definition Study found that SSP did appear more viable than in the past - results that largely validated the findings of the "Fresh Look Study", while invalidating some of the specific systems/architecture concepts that had emerged from the earlier effort. A principal product of the effort was the definition of a family of strategic R&T road maps for the possible development of SSP technologies.

SSP Exploratory Research and Technology Program. Beginning in spring, 1999, and continuing through fall, 2000, NASA conducted the SSP SERT Program. This program, completed in December, 2000, further defined new systems concepts (including space applications), better defined the technical challenges involved in SSP, and initiated a wide range of competitively-selected and in-house R&T activities to test the validity of SSP strategic research and technology road maps [6].

The SERT Program, led by the NASA Marshall Space Flight Center involved technologists from across the U.S. Participants included eight NASA Field Centers, as well as a number of external organizations through a diverse family of some 31 individual, competitively-procured projects created as a result of a 1999 NASA Research Announcement. Funded by NASA at a level of about $22M (approximately $15M in FY1999 and $7M in FY2000), SERT Program participants included large and small companies, other Agencies and laboratories, universities, and several international organizations. The SERT Program involved a focused portfolio of R&D investments, guided by systems studies with the maximum degree of leveraging of existing resources inside and outside NASA; comprised of 3 complementary elements:

- Systems Studies and Analysis: Analysis of SSP systems and architecture concepts (including space applications). Efforts include market/economic analyses to address the potential economic viability of SSP concepts, as well as environmental issue assessments, for various potential terrestrial and space markets.
- SSP Research & Technology: tightly focused exploratory research targeting "tall poles" and rapid analysis to identify promising systems concepts and establish technical viability to "first-order".
- SSP Technology Demonstrations: initial, small-scale demonstrations of key SSP concepts/components using nearer-term technologies, with an emphasis on enabling multi-purpose (space or terrestrial) applications of SSP and related systems/technologies

CURRENT U.S. SSP PROGRAMS

During 2001-2002, NASA is continuing to advance key concepts and technologies for future space solar power applications. In particular, NASA, in Winter 2002 the U.S. National Science Foundation (NSF) and the Electric Power Research Institute (EPRI) issued a joint broad area announcement that is expected to yield a number of high-leverage, high-risk research studies targeting some of the key challenges facing future SSP systems. The solicitation seeks proposals for fundamental, high-risk research that has serious potential to have impact on the larger goals of SSP. The solicitation emphasized projects that would have an impact in one of four key areas:

1. Radical improvements in WPT, with primary emphasis on solid-state device issues central to solid-state transmission by microwaves;
2. More intelligent robotics, to allow assembly of SSP structures in space with minimal use of humans in space;
3. Improved power management and distribution and control (PMAD), with a special emphasis on reducing system mass; and,
4. Understanding of costs and opportunities, and how to optimize them, for the net impact on the environment, health and safety, i.e., to the biosphere, the ionosphere, and to sustainable growth around the world.

NASA is also continuing other activities in support of SSP, including the definition of potential technology flight experiments and the refinement of new analytical modeling tools to enable more effective studies of technology alternatives and resulting economics.

MICROWAVE POWER TRANSMISSION

Due in part to research programs such as those funded by NASA's SERT program and to component improvements resulting from the wireless revolution, the system components supporting microwave WPT have advanced significantly in the past 15 years. Three major WPT conferences held in the 90's highlighted the applications, issues and concerns, environmental assessments, and the technology associated with beaming power via microwaves as well as exposing the international interest [7], [8], [9]. The purpose of this section is to status the key microwave components in a WPT system: the transmitter, beam control, and the receiving rectifying antenna (rectenna). Also, estimates of the end-to-end power transfer efficiency for a solar power satellite as developed in the SERT program are discussed.

The ability to accomplish the task of efficiently delivering electrical power wirelessly is dependent upon the component efficiencies used in the transmitting and receiving apertures and the ability to focus the electromagnetic beam onto the receiving rectenna. Microwave WPT is achieved by an un-modulated, continuous-wave signal with a bandwidth of 1 Hz. The historical frequency of choice for microwave WPT has been 2.45 GHz due to its low cost power components, location in an Industrial, Scientific, and Medical (ISM) band, and extremely low attenuation through the atmosphere. Alternatively, the next higher ISM band centered at 5.8 GHz has drawn WPT interest from the reduction of transmitting and receiving apertures. However, the penalty for increasing the beaming frequency is higher atmospheric attenuation in severe thunderstorms. The solar power satellite configurations studied in the SERT program are based on a 5.8 GHz system. Other frequencies where power beaming demonstrations have been performed include 8.5 GHz [10], 10 GHz [11], and 35 GHz [12]. At the transmitting antenna, microwave power tubes such as magnetrons and klystrons have been extensively studied as the primary RF power sources. However at frequencies below 10 GHz, high-power solid-state devices have the promise as a possible alternative. For beam safety and control, retrodirective arrays are applied in WPT systems due to their inherent self-phasing capability. The mobile communication industries have also shown interest in retrodirectivity to dynamically minimize interference and maximize intended signal reception. Whereas transmitter components and retrodirective phased array antennas have direct applications in the communication industry, the rectenna is a component unique to WPT systems. Conceived by Bill Brown of the Raytheon Company in the early 1960's [13], Brown eventually developed rectennas at 2.45 GHz with conversion efficiencies greater than 90% [14]. Rectenna efficiency records have now been established at the higher frequencies and continue to be broken in research labs across the world. The following sections describe the component performances used in transmitters, beam control systems, and rectennas.

Transmitters. The key transmitter requirement is its ability to efficiently convert dc power to RF power and radiate the power in a controlled and low loss manner. The complexity of the transmitter is dependent on the WPT application. Transmitters in small-scale WPT applications could simply be a single high-power RF source feeding a mechanically steered reflecting antenna. Large-scale WPT applications such as a SPS would require a phased array antenna to distribute the RF power sources across the aperture and to electronically control the power beam. The transmitter's efficiency not only drives the end-to-end efficiency but also the thermal management system that is particularly difficult in space. Any heat generated from inefficiencies in the dc-RF conversion or in the antenna feed system must be removed from the transmitter for long-life and reliable operation. Although operating at elevated temperatures takes advantage of the 4th power relationship between the quantity of heat radiated per unit area to the temperature, it also reduces the lifetime of the RF devices and control electronics. An efficient and reliable transmitter design is not a trivial matter, and many trades must be performed to meet overall system requirements. In space systems, multipactor [15] and passive intermodulation [16] concerns in high power transmitters are areas that deserve critical attention. Filtering of close-in phase noise and suppression of harmonics will be required in most systems to meet regulatory requirements. However, filter implementation involves a trade in their cost, mass, temperature stability and in-band insertion loss to meet specified rejection requirements. For all of these reasons, the specific mass for a space-based transmitter requires an in-depth study.

In the SERT program, a 5.8 GHz, 500 m diameter phased array transmitter was selected as the baseline aperture size for the GEO-based SPS. Common to the 2.45 GHz DOE/NASA Reference System study in the late 1970's, a 10 dB Gaussian amplitude tapered beam was used to efficiently couple the power from the transmitter to the Earth-based rectenna. The transmitter's RF output power is approximately 2 GW to deliver 1.2 GWe to the electric grid. Three dc to RF power converters were considered: klystron, magnetron, and solid-state amplifiers. Since these RF converters are the dominant heat-generating component in the transmitter, efficiency and mass comparisons of the three approaches were developed.

Klystron and magnetron devices were extensively studied in the Reference System study for a 2.45 GHz power beam [17] (Table 1). Although the klystron operated at a higher power level, the magnetron was preferred due to its efficiency, spectral purity, and reliability.

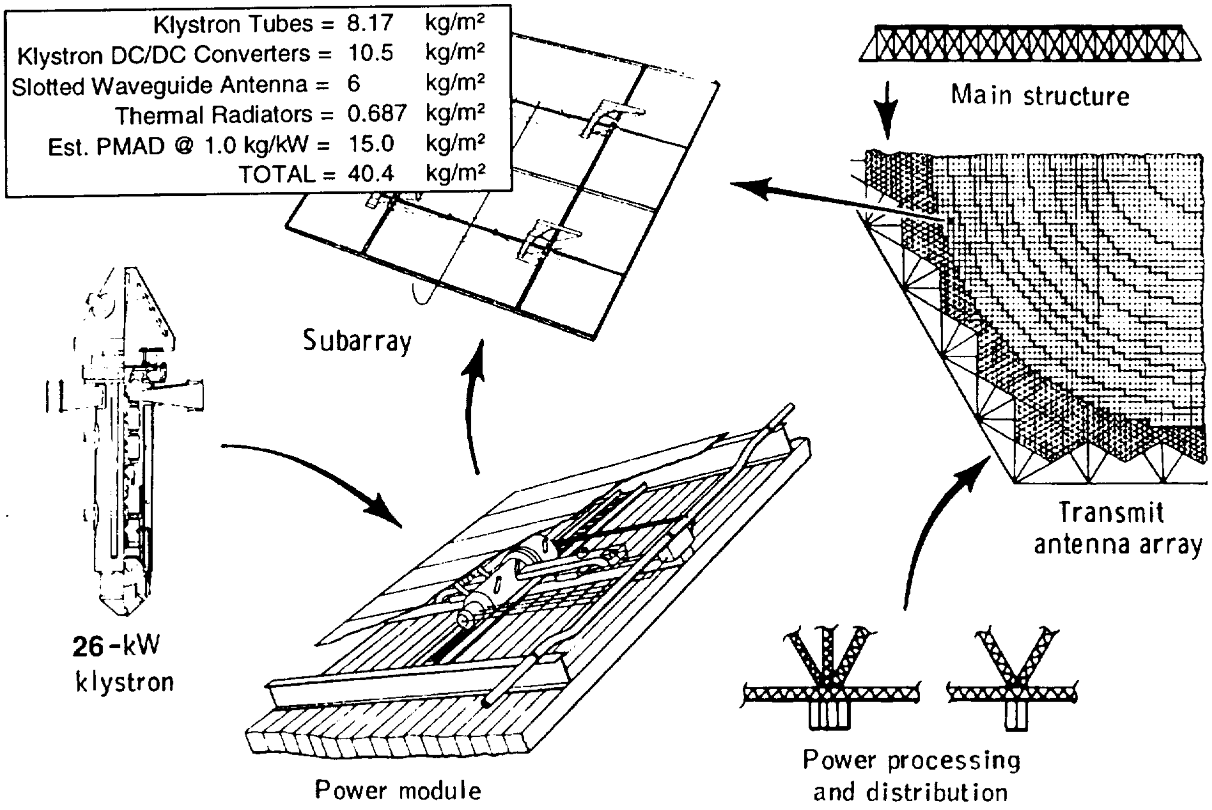
Table 1. 2.45 GHz RF tube comparisons.

Parameter	Klystron [18]	Magnetron [19]
Amplifier Output Power	50 kW	4.39 kW
DC-RF Power Efficiency		87.5%
Overall Efficiency	74%	81.7 %
Carrier to Noise Ratio	120 dB @ 10 kHz	110 dB @ 10 kHz
	135 dB @ 1 MHz	137 dB @ 1 MHz
	140 dB @ 20 MHz	160 dB @ 20 MHz
	160 dB @ 100 MHz	196 dB @ 50 MHz
Lifetime	25 years*	50 years [17]

* Projected

Much progress has been made in vacuum tubes since the Reference System as recently highlighted in this magazine [20]. Efficiency, reliability, and output power continue to increase at ever higher frequencies. Consistent with the Reference System trade, more powerful klystrons were compared to a slightly more efficient magnetron in the SERT program.

In the 5.8 GHz, klystron transmitter, the output power of the most powerful tube located at the array center is 26 kW whose operating voltage and current are 28 kV and 1.12 A, respectively [21]. Although not validated by measured results, the high-efficiency 5.8 GHz klystron design is based on previous built units that have efficiencies over 70%. This modified design uses a multicavity configuration with one of the cavities tuned to the 2^{nd} harmonic and with 5 stages of depressed collectors. The tube body and solenoid operate at 300°C and the collectors operate at 500°C. Preliminary design simulations revealed the overall efficiency (i.e. combined electronic and circuit efficiencies) to be a conservative 76% without the depressed collectors. Including the collector recovery to be 50%, the overall efficiency is 83%. Due to the 10 dB Gaussian amplitude taper, the approach taken with this transmitter design was to place the 26 kW klystrons in the array center and reduce the tube's output power to 2.6 kW at the array's edge in 10 tapered steps. This transmitter configuration is very similar to the Reference System design albeit with a smaller power modules of 1 m^2 (Figure 1).



Klystron Tubes = 8.17 kg/m^2
Klystron DC/DC Converters = 10.5 kg/m^2
Slotted Waveguide Antenna = 6 kg/m^2
Thermal Radiators = 0.687 kg/m^2
Est. PMAD @ 1.0 kg/kW = 15.0 kg/m^2
TOTAL = 40.4 kg/m^2

Figure 1. Klystron transmitter [21].

The second tube approach to the 5.8 GHz transmitter applies a phase-locked magnetron directional amplifier (MDA) whose proposed output power and efficiency are 5 kW and 85.5%, respectively [22]. The MDA operates at 6 kV and dissipates the waste heat at 350°C with a pyrolytic graphite thermal radiator. The MDA is basically a phase injection locked magnetron oscillator with an augmented magnetic bias coil on the permanent magnet for controlling the output power and an output tuning slug for adjusting the frequency. Thus, the phase, amplitude and frequency all could be independently varied. A detailed discussion of the MDA is given in references [19] and [23]. Similar to the klystron transmitter, the MDA is married to a slotted waveguide antenna whose subarray size is 4 m x 4 m (Figure 2).

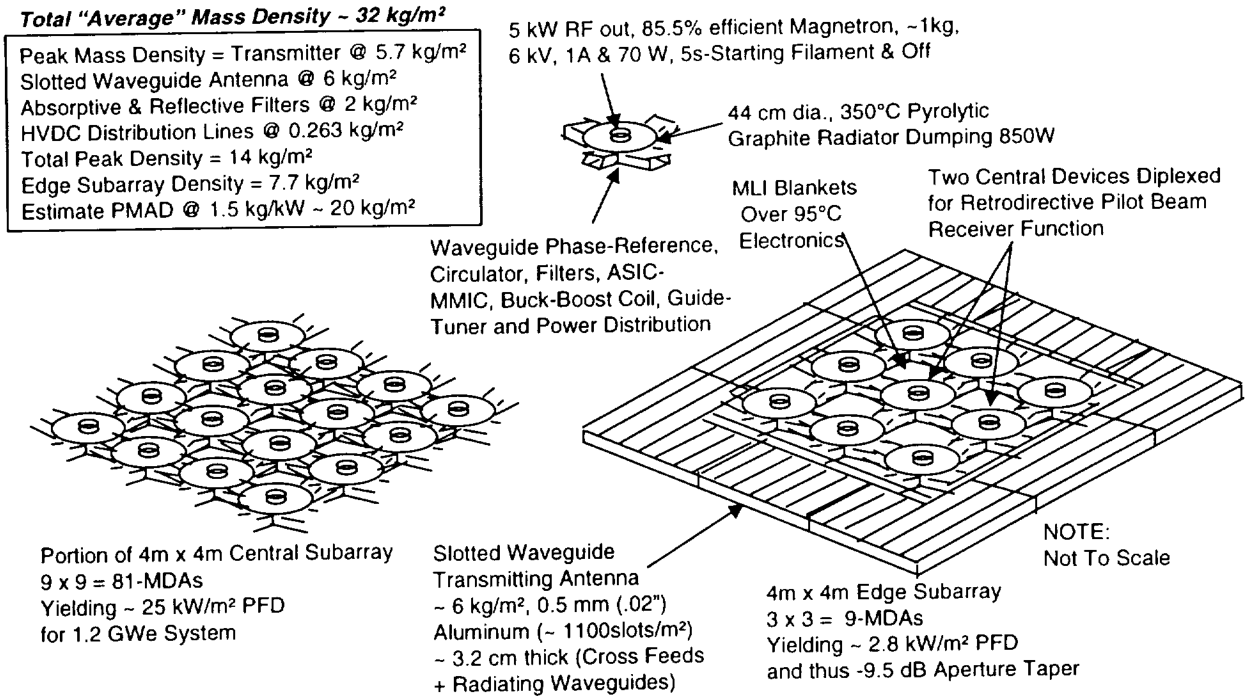


Figure 2. Magnetron directional amplifier transmitter [22].

The third type of transmitter studied in the SERT program uses solid-state devices [24] (Figure 3). Unlike the slotted waveguide array where a tube would feed many radiating slots, the solid-state transmitter places a 5.8 GHz power amplifier and phase shifter behind every radiating element. Because a phase shifter is located at every element, the advantage of this approach over the tube transmitters is the elimination of grating lobes when electronically steering the beam. However, microwave filters are needed on each element to suppress both close-in carrier noise and harmonics generated by the power amplifier. Similar to the klystron approach, the 10-dB Gaussian taper is approximated by 10 distinct power levels where each of the center elements radiate 59 W and the edge elements radiate 5.9 W. The operating voltage and junction temperatures for the power amplifiers are assumed to be 80Vdc and 300°C, respectively.

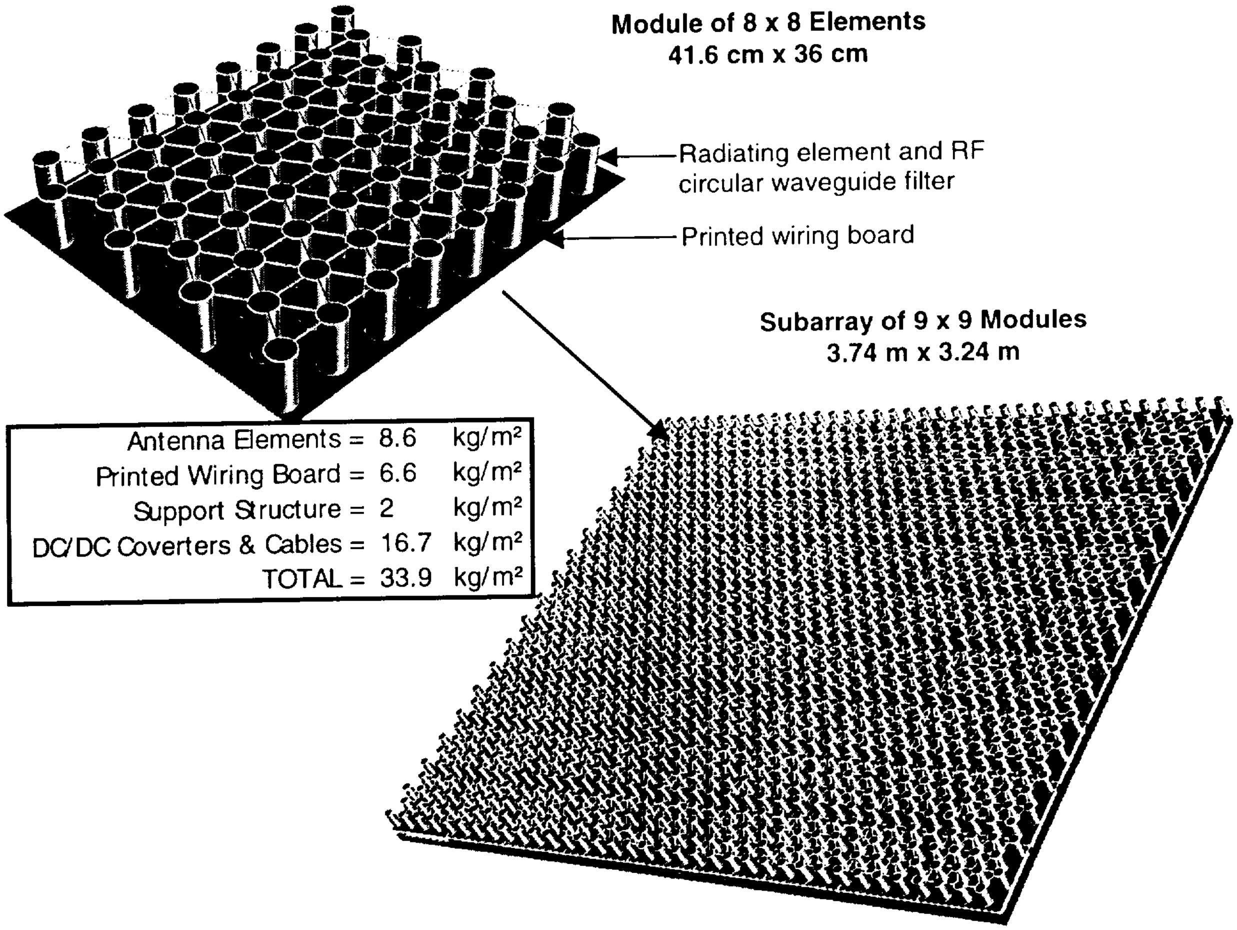


Figure 3. Solid-state transmitter [24].

The device most suited for the power amplification is a GaN-based alloy. This wide bandgap device allows high voltage operation that lessens the impact of many low voltage dc-dc converters that plagued earlier WPT studies based on GaAs devices. Its high breakdown voltage allows high power densities and high junction temperatures which are both desirable for a WPT transmitter. Additionally, predictions on the efficiency indicate an ideal fit for this application. Figure 4 shows predicted power added efficiency (PAE) comparisons of GaN to InGaAs and SiC with harmonic tuning [25].

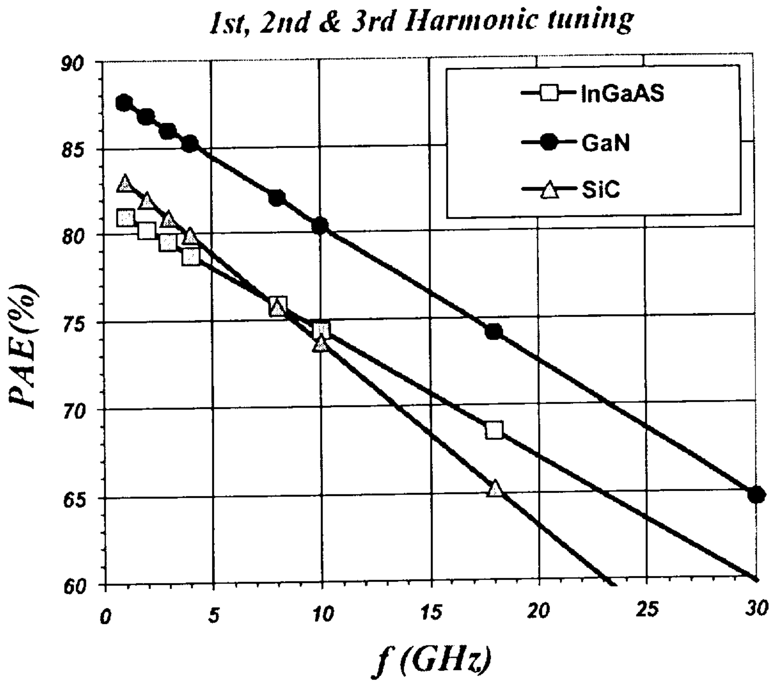


Figure 4. Predicted solid-state device PAE performances [25].

Recently, Class E solid-state power amplifier designs have demonstrated excellent results in the microwave frequency range (Table 2). Class E amplifiers are theoretically possible of achieving 100% efficiency. However, this class of operation is highly nonlinear, and unwanted harmonics generated by their switching action requires RF filtering in the transmitter. To achieve the efficiencies necessary for a SPS transmitter, the output of a GaN power amplifier would have to be combined with either a harmonically tuned circuit (i.e. Class F) or operate as a switch (Class E). A contract was awarded in the SERT program to study AlGaN HFETs on SiC substrates operating in Class E [26]. Using existing AlGaN HFETs in a Class E circuit, simulations revealed that they are capable of achieving PAEs on the order of 70% at 5.8 GHz. The efficiency limitation is due to a fairly large knee voltage where power is dissipated in part of the cycle (Figure 5). Reducing the source and drain contact resistances and reducing the channel access resistances will reduce the knee voltage where considerable improvement is possible. Ideally these devices would operate at junction temperatures as high as possible (ex. 300°C), but the performance and reliability of AlGaN HFETs degrades with increasing temperature. In particular to performance, increasing the temperature decreases electron mobility and velocity and increases the knee voltage that ultimately reduces the efficiency.

Table 2. State-of-the-art microwave Class E power added efficiencies.

Frequency (GHz)	Output RF Power (W)	Drain Efficiency/PAE
2.45 [27]	1.27	- /72%
5 [28]	0.61	81%/72%
8.35 [29]	1.41	64%/48%
10 [30]	0.10	74%/62%

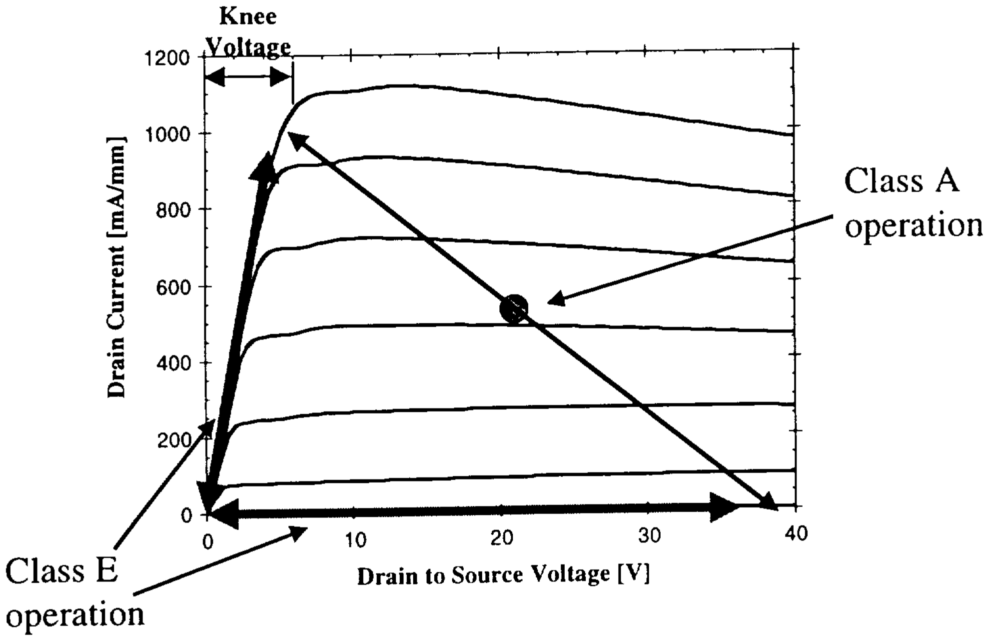


Figure 5. Class E and Class A comparison on an AlGaN HFET IV plot [26].

Although GaN properties appear ideal for a WPT solid-state phased array transmitter, ongoing research may take several years to fully develop its potential as indicated in a recent wide bandgap workshop [31]. In addition to reducing the contact and channel resistances, other GaN limitations and defects include a lack of an inexpensive substrate, surface traps, space charge effects, and interface effects. The goal of achieving a high-efficiency, high-power, and high temperature GaN power amplifier should be reached in the upcoming years.

Finally, the design goals of the three transmitter types for a 5.8 GHz SPS are compared in Table 3. The key difference between the three approaches is the converter's RF output power that drives the quantities and operating voltage. However, the specific masses are relatively the same. The efficiency goals for each dc-RF converter type are ambitious but achievable with sound research and funding.

Table 3. 5.8 GHz, 2 GW transmitter comparisons.

Transmitter Type	Klystron [21]	Magnetron [22]	Solid-State [24]
Maximum Converter P_{out} (W CW)	26,000	5,000	59
Converter Operating Voltage (Vdc)	28,000	6,000	80
Converter dc-RF Efficiency (%)	83	85.5	90
Converter Mass (kg)	14.15	1	0.001
Operating Temperatures	300°C on tube body 500°C on collectors	350°C on radiator	300°C at junction
No. of Converters in 500 m Diameter Antenna	209,863	~400,000	84,001,536
Transmitter Specific Mass (kg/m²)	40.4	32	33.9

Beam Control. A key system and safety aspect of WPT is its ability to control the power beam. Retrodirective beam control systems have been the preferred method of achieving accurate beam pointing. As depicted in Figure 6, a coded pilot signal is emitted from the rectenna towards the SPS's transmitter to provide a phase reference for forming and pointing the power beam. To form the power beam and point it back towards the rectenna, the phase of the pilot signal captured by receivers located at each subarray is compared to an onboard reference frequency distributed equally throughout the array. If a phase difference exists between the two signals, the received signal is phase conjugated and feed back to the phase control circuitry of each dc-RF converter. In the absence of the pilot signal, the transmitter will automatically de-phase its power beam and the peak power density decreases by the ratio of the number of transmitter elements. This aspect of retrodirective beam control is an inherent safety feature of the system.

Today's wireless service industries are continually discovering methods to expand their networks and capacity to accommodate greater volumes of voice and data traffic. To handle the increased demand, smart antenna technology is being deployed globally to reduce signal interference. Retrodirective beam control is one such technique the wireless industry could use to track a mobile phone user [32].

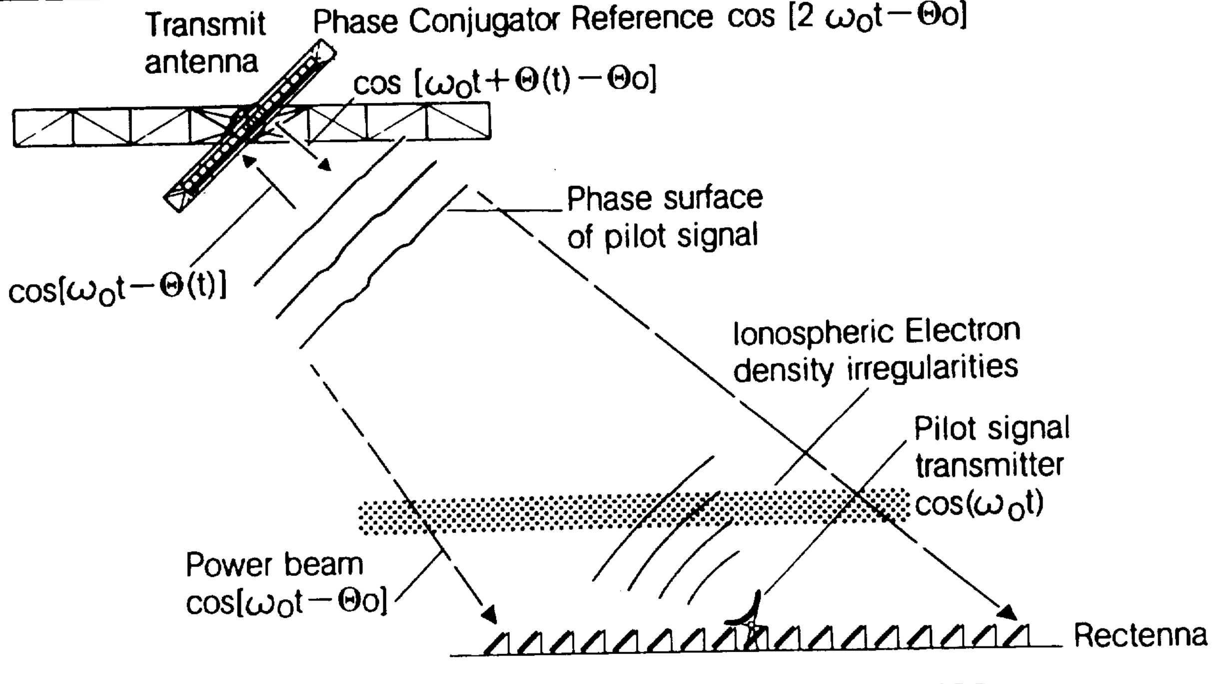


Figure 6. Retrodirective beam control concept with an SPS.

State-of-the-Art Rectennas. Since the early 1960's rectennas have been researched and developed at varying levels of intensity. Bill Brown was a pioneer in developing the first 2.45 GHz rectennas that included the basic circuit components still evident in today's rectenna designs (Figure 7). Measured in 1977, Mr. Brown's aluminum "bar-type" rectenna still holds the highest recorded efficiency of any rectenna in the microwave frequency range at 91.4% [14].

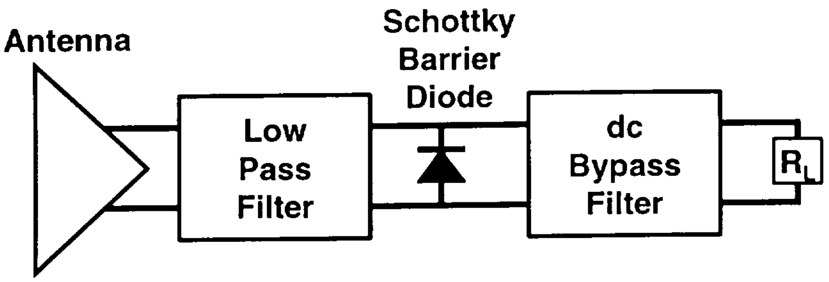


Figure 7. Schematic of rectenna circuit.

Figure 8 shows the highest *measured* conversion efficiencies for 2.45 GHz [14], 5.8 GHz [33] and 35 GHz [12] rectennas as a function of input microwave power density. Also shown are the performance curves for the 2.45 GHz rectenna scaled to 5.8 GHz and 35 GHz for comparison. Due to the substantial amount of research performed at 2.45 GHz over the last 40 years, the efficiency at this frequency is used as a standard for estimating the highest conversion efficiencies attainable at the higher frequencies. This efficiency comparison is made possible by keeping the gain of the 2.45 GHz rectenna (6.4 dBi) constant and scaling in frequency the effective areas of rectennas at 5.8 GHz and 35 GHz. With an effective area of 52 cm^2 for the 2.45 GHz rectenna, the effective areas for the hypothetical 5.8 GHz and 35 GHz rectennas are 8.92 cm^2 and 0.245 cm^2, respectively.

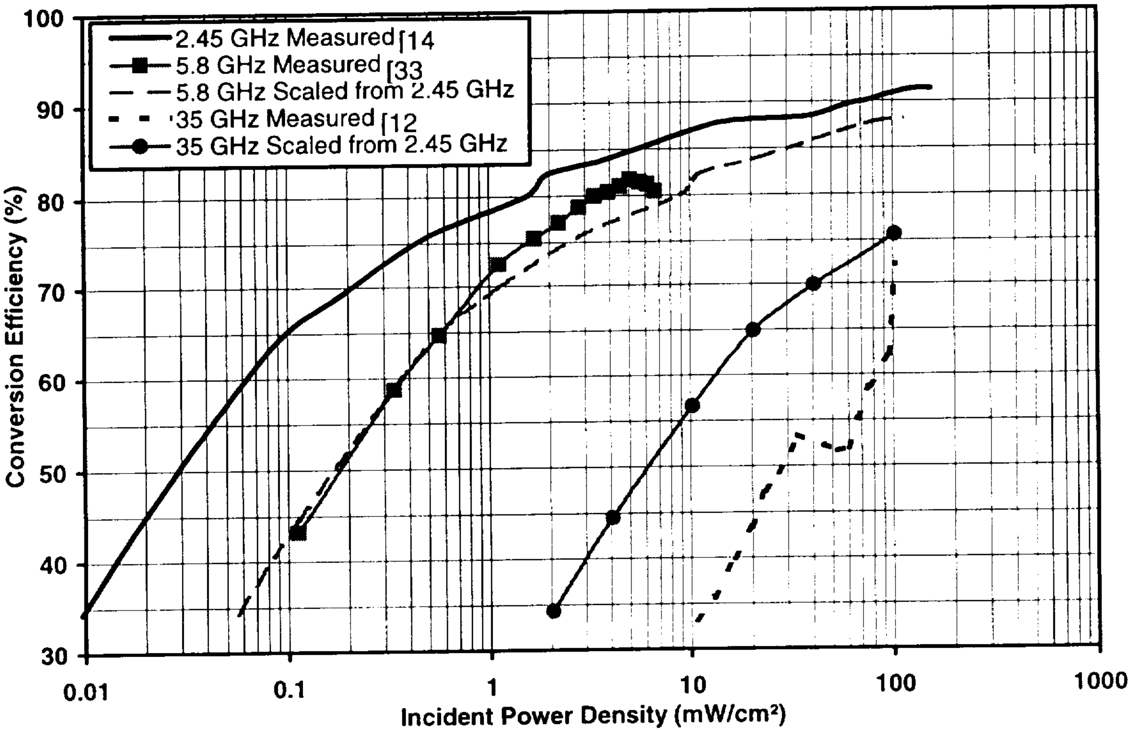


Figure 8. State-of-the-art rectenna efficiencies.

Since the middle to late 1980's, interest in rectenna development has shifted to higher frequencies, dual and circular polarization, and printed circuit formats. Emphasis has been placed on thin, lightweight, and low cost approaches to make power beaming to high-altitude communication platforms more feasible. Table 4 lists some of these printed rectennas and their performances.

Table 4. Printed rectenna performances.

Rectenna Type	Operating Frequency (GHz)	Measured Peak Conversion Efficiency	Peak Output Power per Element (W dc)	Polarization	Mass to dc Output Power Ratio (W/kg)	Specific Mass (kg/m^2)
Printed dipole [34]	2.45	85%	5	Linear	4000	0.25
Circular patch [35]	2.45	81%	5	Dual	263	2.5
Printed dipole [36]	2.45	70%	1	Dual	-	-
Printed Dual Rhombic [37]	5.61	78%	0.084	Circular	-	-
Circular patch [38]	5.8	76%	3	Linear	-	-
Printed Dipoles [39]	2.45 5.8	84.4 82.7	0.094 0.052	Linear Linear	-	-
Square patch [10]	8.51	66%	0.065	Dual	-	-

In the SERT program, a high gain and circular polarized printed rectenna array was developed with over 78% efficiency at Texas A&M University (Figure 9) [37]. Similar to dual polarization, circular polarization adds the flexibility to WPT systems that are mobile such as beaming power to a high altitude communications platform. Because the antenna is a dual rhombic, the element gain was measured to be 11 dBi. High gain allows the rectenna elements to arrayed with wider separations in the effort to lower the number of diodes in a large rectenna array. The rectenna used in the SERT 5.8 GHz system was sized to be 7.5 km in diameter requiring millions of diodes. Also developed at Texas A&M during the same time, a dual frequency rectenna with efficiencies greater than 80% at both 2.45 and 5.8 GHz (Figure 10).

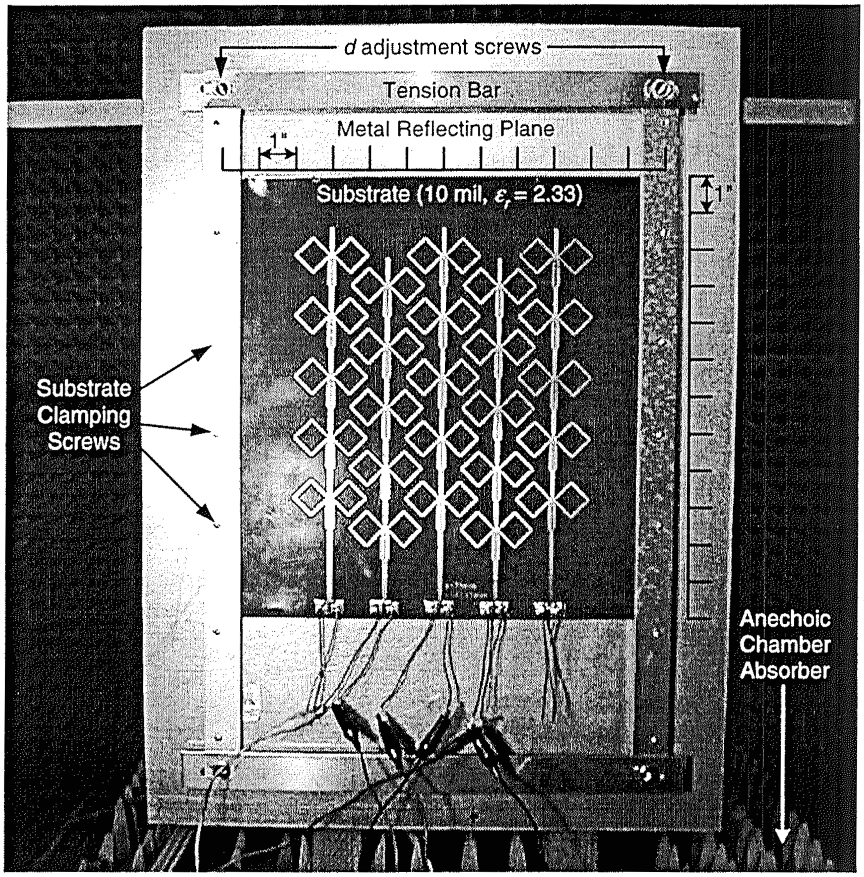


Figure 9. 5.61 GHz circular polarized printed rectenna with over 78% efficiency [37].

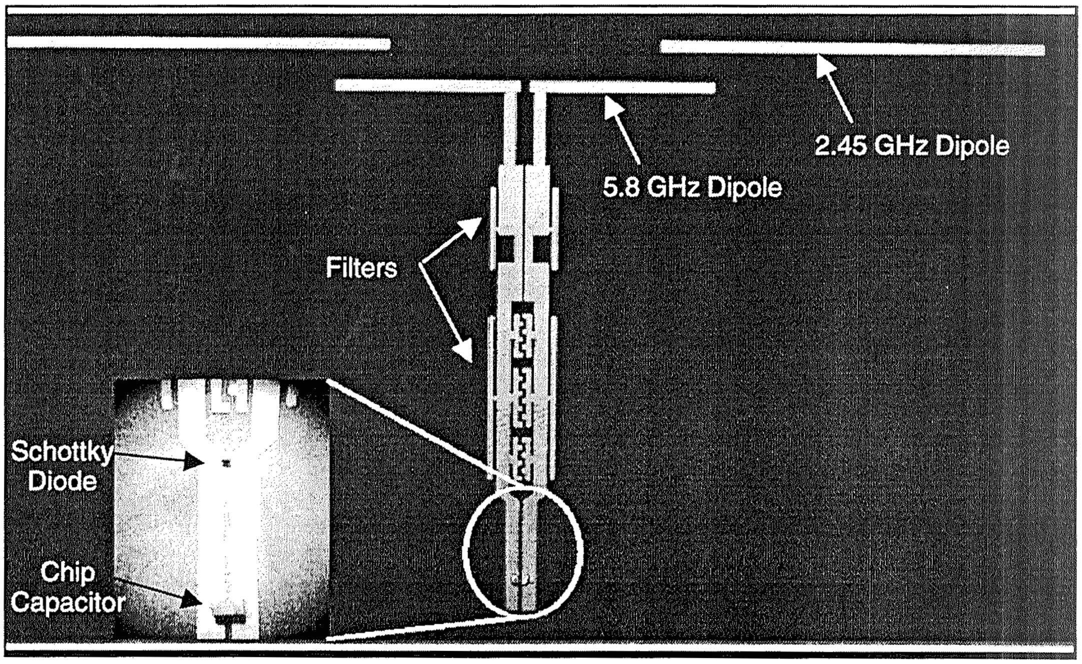


Figure 10. Dual frequency rectenna operating at 2.45 and 5.8 GHz [39].

In well match rectenna arrays, the diode is the most critical component to achieve high efficiencies because it is the main source of loss. Schottky barrier diodes utilizing Si and GaAs have been employed with rectification efficiencies greater than 80%. Although the electron mobility of GaAs is over 6 times greater over Si for high efficiency, Si has a higher thermal conductivity for better reliability. Proper diode selection for a WPT application is dependent on input power levels, and the diode parameters should be chosen carefully for an efficient rectifier at a specified operating frequency. The breakdown voltage (V_{br}) limits the diode's power handling capability and it is directly related to the series resistance and junction capacitance through the intrinsic properties of the diode's material and structure. For instance, increasing the breakdown voltage increases either the series resistance or junction capacitance. Decreasing the series resistance will decrease the power dissipated in the diode, however the breakdown voltage will decrease or the junction capacitance will increase. Increasing the junction capacitance will lower its cutoff frequency. These parameters must be traded in selecting the proper diode for high power applications.

Fortunately, a database of experiments now exists to guide in the diode selection. Table 5 provides a short list of diode parameters (Figure 11) and their measured conversion efficiency. The diode theoretical conversion efficiency is also shown using the closed-form equations in [33]. Operation of rectennas higher than 35 GHz is technically possible. Schottky barrier diodes have been produced with cutoff frequencies up to several THz where the cutoff frequency needs to be approximately 10 times the operating frequency for efficient rectification [40]. Diode cutoff frequency is given by [41]

$$f_c = \frac{1}{2\pi R_s C_{jo}}$$

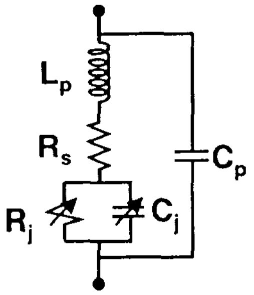
where R_s is the diode's series resistance and C_{jo} is the zero-bias junction capacitance.

Table 5. Diode parameters and their measured and calculated rectenna efficiencies.

Freq. (GHz)	Schottky Diode	C_{jo} (pF)	R_s (Ω)	V_{bi} (V)	V_{br} (V)	RF P_{in} (W)	R_L (Ω)	Measured Eff. (%)	Calculated Eff. (%)
2.45 [14]	GaAs-W	3.7	0.66	0.6	60	7.0	160	92.5	90.5
5.8 [33]*	Si	0.12	8	0.4	8.8	0.05	327	82	78.3
8.51 [10]*	GaAs	0.26	11.2	0.714	9.5	0.10	250	62.5	66.2
35 [42]*	GaAs	0.03	3	0.8	12	0.025	213	60 **	63.6

* Efficiency measured in a rectenna element.

** Reflected power not subtracted.



L_p = Package inductance
C_p = Package capacitance
R_s = Series resistance
R_j = Junction resistance
C_j = Junction capacitance
V_{bi} = Built-in voltage

Figure 11. Schottky barrier diode circuit model.

One of the main concerns about rectennas is their radiation of harmonics generated by the diode. Because it is a highly non-linear circuit, the harmonic power levels are significant and must be suppressed. Harmonic radiation patterns from bar-type rectennas have been measured as a single element and in an array at 2.45 GHz [43]. Although the 2nd harmonic peak power level from a single element was 25 dB down from the fundamental, an array of 42 elements revealed a peak of –11 dBc in the resistively loaded pattern measurements. One method of suppressing harmonics is by placing a frequency selective surface in front of the rectenna that passes the operating frequency and attenuates the 2nd and 3rd harmonics [44], [45]. Experiments have shown 10-15 dB suppression of the 2nd harmonic using this technique. A more powerful technique to suppressing harmonics is locating the rectifying diode and filtering circuits behind the antenna ground plane. A reduction of the 2nd, 3rd, and 4th harmonics by greater than –47 dB from the fundamental has been achieved using this rectenna implementation [38], [46]. In addition to the filter rejection, a circular patch antenna also serves as a harmonic filter due to its non-integer resonance.

End-to-End Power Transfer Efficiency:

Finally, the entire SPS system is linked together to provide an approximation to the dc to dc WPT efficiency (Table 6). Due to the enormous size of the transmit and receive apertures of 500 m diameter and 7.5 km diameter, the power transfer efficiency over 36,000 km is approximately 45%. Although the collection efficiency from the two apertures is sized to be 92%, the cumulative system losses have a large effect on the overall link efficiency.

Table 6. 5.8 GHz SPS dc to dc efficiency calculation.

Sources of Inefficiency	Efficiency	Power (GW)	Notes
Input Power (GW dc)		2.672 dc	
RF Circuit Efficiency			
dc-RF Converter Efficiency	0.860	2.298	Assumes average converter efficiency
RF Filter Insertion Loss (IL)	0.891	2.048	Estimated total IL = 0.5 dB
Transmitting Antenna Efficiency			
Subarray Random Electronic Failures	0.960	1.966	Estimated 2% failures
Meteorite Hit Element Failures	1.000	1.966	100 failures/year
Amplitude Error	0.996	1.957	±1 dB amplitude deviation
Phase Error	0.978	1.914	±15° phase deviation
Phase Quantization	0.997	1.908	5 bit phase shifter
Taper Quantization	0.989	1.886	10 steps
Antenna Aperture Efficiency	0.980	1.849	Conductive losses in aperture
Transmitter Scan Loss	1.000	1.849	Assumes broadside radiation
Mismatch Loss	1.000	1.849	Assumes Array VSWR = 1.0
Beam Coupling Efficiency			
Propagation Loss	0.979	1.809	Rain rate = 4 mm/hr @ 5.8 GHz
Collection Efficiency	0.921	1.666	Gaussian beam taper = 10.14 dB
Polarization Loss	1.000	1.666	Assumes near perfect alignment
Rectenna Efficiency			
Rectenna Random Failures	0.990	1.649	Estimated 1% failures
RF Filter Insertion Loss (IL)	0.891	1.469	Estimated IL = 0.5 dB
Rectenna Scan Loss	1.000	1.469	Rectenna tilted to avoid loss
Mismatch Loss	1.000	1.469	Assumes Array VSWR = 1.0
Rectenna Efficiency	0.860	1.263 dc	Projected optimized average efficiency
dc to Utility Grid Efficiency	0.950	1.200 dc	Assumed dc-dc converter efficiency
System DC-DC Efficiency	45%		

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The U.S. NRC, Aeronautics and Space Engineering Board (ASEB) conducted an independent assessment of the SSP strategic research and technology road maps during 2000-2001 [47]. The general findings of this review were quite positive, although a number of important areas for improvement were also identified. The key findings included the following.

NASA's current SSP technology program is directed at technical areas that have important commercial, civil and military applications for the U.S. Also, that NASA has defined a potential valuable program, but one that will require significantly higher funding and programmatic stability to attain the aggressive performance, mass and cost goals that are required. The NRC also recommended that NASA's SSP efforts should be substantially leverage work ongoing in other Agencies in the U.S., as well as internationally.

CONCLUSIONS

Future large-scale SSP will be a very complex integrated system of systems requiring numerous significant advances in current technology and capabilities. Ongoing technology developments have narrowed many of the gaps, but major technical, regulatory and conceptual hurdles remain. Continuing systems concept studies and analyses will be critical to success, as will following a clear strategic R&T road map. This road map must assure both an incremental and evolutionary approach to developing needed technologies and systems is followed, with significant and broadly applicable advances with each increment. In particular, the technologies and systems needed for SPS must support highly leveraged applicability to needs in space science, robotic and human exploration, and the development of space

Considerable progress has been made in the critical area of microwave power transmission. At 5.8 GHz, dc-RF converters with efficiencies over 80% are achievable today. Rectennas developed at 5.8 GHz have been measured also with efficiencies greater than 80%. With optimized components in both the transmitter and rectenna, a SPS system has the potential of an dc-to-dc efficiency of 45%. Although not considered to be a significant technology barrier, the beam control system based on retrodirectivity needs to be demonstrated in a large scale WPT system.

The decades-long time frame for SPS technology development is consistent with the time frame during which new space transportation systems, commercial space markets, etc. could advance. The question of ultimate large-scale solar power satellite economic viability remains open. However ongoing studies suggest that economic targets may be achievable in the far term, but only if key investments in technology development and infrastructure can be justified on the basis of non-SPS space applications.

GLOSSARY OF ACRONYMS

A	amp
AlGaN	Aluminum Gallium Nitride
ASEB	Aeronautics and Space Engineering Board
CW	Continuous Wave
dB	Decibels
dBi	Decibels referenced to an isotropic radiator
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
FY	Fiscal Year
GaAs	Gallium Arsenide
GaN	Gallium Nitride
GEO	Geostationary Earth Orbit
GHz	Gigahertz
GW	Gigawatts
GWe	Gigawatt electric
HFET	Heterojunction Field Effect Transistor
InGaAs	Indium Gallium Arsenide
ISM	Industrial, Scientific, and Medical
kg	kilograms
kHz	kilohertz
km	kilometer
kV	kilovolts
kW	kilowatts
m	meters
MDA	Magnetron Directional Amplifier
MHz	Megahertz
NASA	National Aeronautics and Space Administration
NRC	U.S. National Research Council
NSF	National Science Foundation
PAE	Power Added Efficiency
PMAD	Power Management and Distribution
R&T	Research and Technology
RF	Radio Frequency

SERT	SSP Exploratory Research and Technology Program
SiC	Silicon Carbide
SPS	Solar Power Satellite
SSP	Space Solar Power
SCTM	SSP Concept and Technology Maturation
Vdc	Direct Current Voltage
W	Watts
WPT	Wireless Power Transmission

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