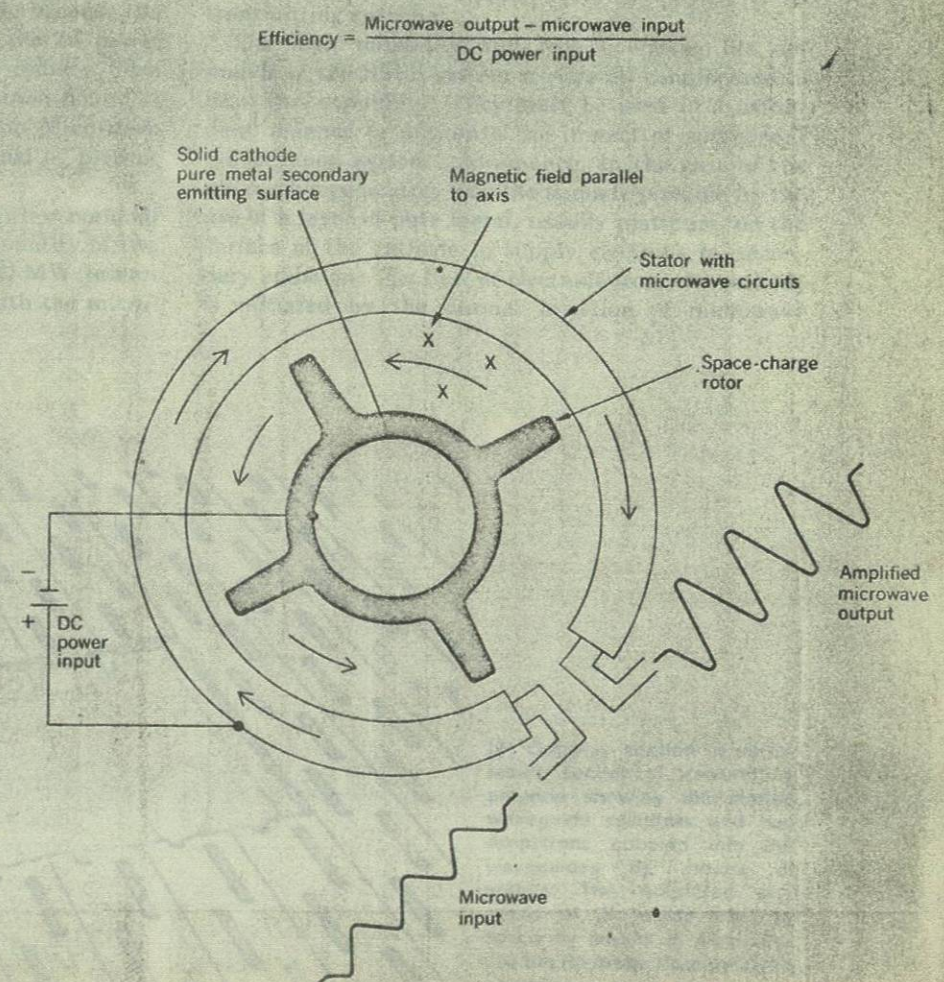
SSPS, these self-phasing concepts would require that the transmitting antenna be subdivided into a large number of smaller arrays so that the phase of the radiated output from each subarray could be controlled independently. The reference phase front, with which the output phase of each subarray is compared, would be established by an independent transmitter located on earth at the center of the receiving location for the power beam.

The overall efficiency of a microwave power transmission system depends upon the conversion efficiencies at both ends of the system as well as upon the launching and beam efficiencies. Conversion devices have already exhibited highly efficient operation and even greater efficiencies are possible if advantage is taken in device design of newly available materials.

Conversion of dc to microwave power. In the SSPS system, the space environment imposes unusually severe requirements upon the conversion of dc power to microwave power. Waste heat disposal, the need for extremely long life and high reliability, and the demand for light weight assume an importance far above that encountered in a terrestrial environment. In the base-line design, one promising device, the crossed-field electron tube, was selected for examination to see how well it would meet the stringent requirements if integrated into the overall system. It will not necessarily be the final choice.

The crossed-field device is the most efficient converter of dc power to microwave power in the wavelength range of interest. In both its oscillator form (magnetron) and amplifier form (Amplitron) it has exhibited overall conversion efficiencies of between 85 and 90 percent.[24] With the aid of the recently developed permanent magnet material, samarium cobalt, the device can also be made very light in weight.

In both the magnetron and the Amplitron, as shown schematically in Fig. 5 for the Amplitron, there is a rotor consisting of spokes of space charge that induce high-frequency alternating currents in a stator composed of a microwave circuit. The electric fields from the energy in the microwave ci cuit, in turn, exert a force against the spokes of space charge. The torque required to spin the rotor comes not from external mechanical torque, as in the 60-Hz alternator, but from the motion of charged particles in static electric and magnetic fields oriented at right angles to each other. Unlike the mechanical rotor of the alternator, the space-charge rotor of the crossed-field device has very little mass and rotates at extremely high speed—perhaps 100 000 000 times that of a 60-Hz alternator. Since the power generated by any device is



[5] Principle of operation of the Amplitron. Rotating spokes of space charge induce currents into the microwave circuit and provide efficient amplification of the microwave input signal. DC to microwave conversion efficiencies of over 85 percent have been obtained from the cross-field device.

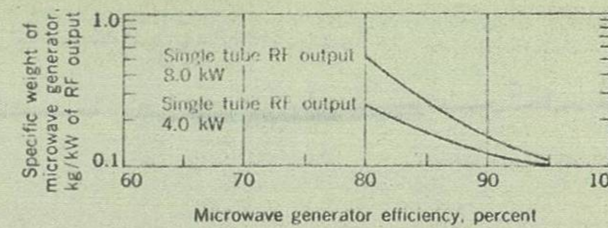
proportional to the product of torque and angular velocity, the capability of the small, lightweight microwave device to generate large amounts of microwave power becomes evident. This inherently lightweight mechanism, in normal practice, is highly disguised in conventional tubes because of the mass of the magnet required for operation and the mass of the glass and metal envelope required in the terrestrial environment. In space, the envelope is not required and the new samarium-cobalt magnet material can reduce the magnet weight by a factor of at least ten.

In the SSPS system, the power-handling capability of the device and its weight are directly related to disposal of the waste heat that results from any inefficiency in operation. Weight and reliability considerations require that waste heat be disposed of by direct radiation into space so the generator must have an efficient radiator fin attached to it. Fortunately, the large area of the transmitting antenna allows these radiators to dispose of a large amount of waste energy if the generators are uniformly distributed over the antenna's area. At 300°C, for example, a disk 1 km in diameter has a black-body radiation capability of 4.46×10^6 kW from each of its faces.

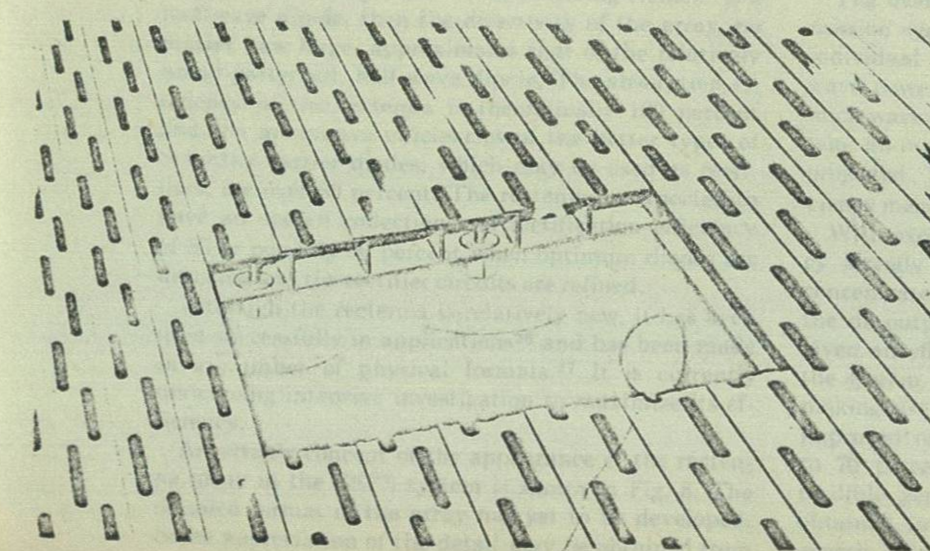
A study has been made of the specific weight of the crossed-field generator together with its permanent magnet and its pyrolytic graphite radiator as a function of Amplitron efficiency and power-handling capability. The results are given in Fig. 6. The specific weight of the combined generator and cooling fin, as measured in kg/kW of output power, is sensitive to both efficiency and power level primarily because the weight of the cooling fin approximates the 2.5 power of the quantity of waste heat it must radiate. This consideration places a practical upper power bound of about 10 kW on the microwave generator. Microwave tubes with power ratings that are nominal by present standards would be used in the SSPS.

Use of microwave power amplifiers with a nominal power rating of 5 kW would require a quantity of two million such tubes to produce a 10 000-MW microwave beam. The problems associated with the microwave excitation of such a large number of tubes, and the efficient coupling of them into a phased array, are resolved by a cascade arrangement of tubes and slotted waveguides, as suggested by the artist's rendering in Fig. 7. The output of each Amplitron flows into a section of slotted waveguide where most of the power is coherently radiated and becomes part of the microwave beam. Enough power is left over to excite the next Amplitron. The cycle is then repeated for the next section of waveguide and the next Amplitron, etc. Not within the scope of this discussion are the methods of phase correction and other controls that integrate the cascaded arrangement into the antenna subarray and insure proper overall behavior of the transmitting antenna.

The high reliability and long operating life demands of the SSPS system require all components to have this capability. They must be used in a redundant manner to minimize the impact of component failure upon system performance. In the case of the microwave generator, long life is made possible by the use of a layer of pure metal, usually platinum, on the surface of the cathode to supply electrons by secondary emission. The flow of electrons from the cathode is initiated by the normal injection of microwave

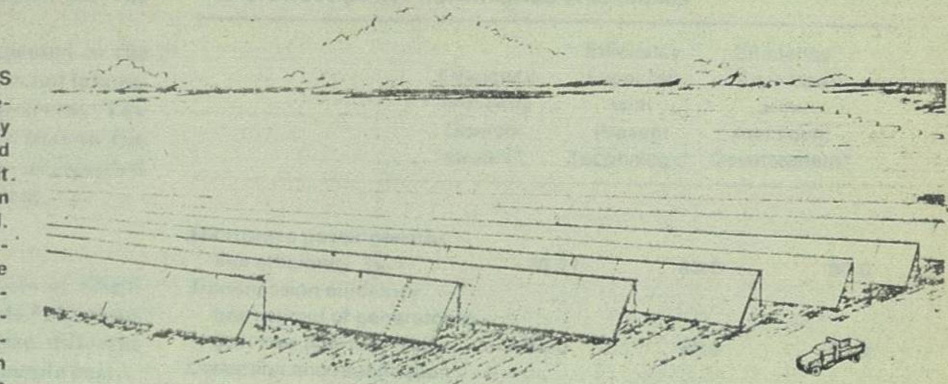


[6] Specific weight of microwave generator and associated magnet and cooling radiator as a function of generator efficiency and power rating of tube. Radiation from both sides. Average fin temperature is 300°C, temperature rise in fin is 50°C, temperature of tube edge is 325°C, radiator material is pyrolytic graphite, and heat sink is space 0°K.



[7] Cutaway section in earth-facing section of transmitting antenna showing the slotted waveguide radiators and two Amplitrons coupled into the waveguides by means of probes. The Amplitron disposes of its waste heat to space by means of a circular cooling fin made from pyrolytic graphite.

[8] Artist's sketch of the SSPS rectenna, the electronic device that captures the energy from the microwave beam and simultaneously converts it into dc power for distribution on a conventional power grid. The rectenna need not be accurately pointed toward the transmitting antenna for efficient operation and its operation is independent of any distortion of the microwave beam as it passes through the earth's atmosphere.



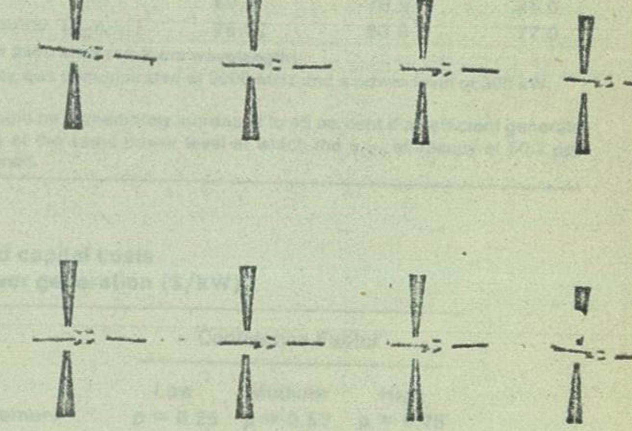
energy (see Fig. 5) into the microwave input terminal of the tube so that no initiation of electron flow by thermal means is needed. This technique eliminates the need for a cathode heater that not only has a limited life but, in this application, would impose an additional complication because of its separate power supply requirement. There is no known life limitation to the secondary emission process from a pure metal cathode other than erosion from sputtering, and this is expected to be negligible in the high vacuum of space. The use of pure metal cathodes, and starting them with RF injection, is a standard procedure in many terrestrial applications.

The efficient capture and rectification of the microwave power over such a large receiving area would probably not be practical if it were not possible to combine these two functions in the rectenna[25] and thereby simultaneously achieve high collection and rectification efficiency, insensitivity of the array to amplitude and phase perturbations of the incoming beam caused by atmospheric phenomena, insensitivity to the direction of the incoming radiation over a considerable angle, economical construction, and disposal of waste heat by passive radiation.

Structurally, the rectenna consists of many independent receiving elements, each of which is terminated in a rectifier. The dc outputs of the rectifiers feed into a common load. If the receiving element is a half-wave dipole, then the directivity of the array, no matter how large, approximates that of the relatively broad-patterned, half-wave dipole. The absorption efficiency of the rectenna is theoretically 100 percent and the microwave efficiencies of the better types of Schottky-barrier diodes, which may be used as rectifiers, are over 80 percent. The rectenna is expected to have an overall collection and rectification efficiency of 85 or possibly 90 percent when optimum diodes are designed and the rectifier circuits are refined.

Although the rectenna is relatively new, it has been used successfully in applications[26] and has been made in a number of physical formats.[27] It is currently undergoing intensive investigation to maximize its efficiency.

An artist's concept of the appearance of the rectenna array in the SSPS system is shown in Fig. 8. The detailed format of the array has yet to be developed. Some appreciation of the detail may be obtained from a laboratory model of the rectenna shown in Fig. 9. Printed circuit techniques would undoubtedly be used in production designs.



[9] Laboratory model rectenna made of elements consisting of a half-wave dipole and solid-state rectifiers. Elements are mounted in a plane one quarter wavelength above a reflecting metal surface. Overall capture and rectification efficiency, experimentally achieved, is 63 percent. Potential overall efficiency is 85 to 90 percent.

Microwave power transmission efficiency

The overall efficiency of a microwave power transmission system is defined as the product of the three individual efficiencies associated with dc-to-microwave power conversion, microwave transmission, and microwave-to-dc power conversion. In the SSPS system, an overall efficiency of 65 to 70 percent has been projected. How does this compare with various efficiency measurements in the laboratory?

With excellent dc-to-microwave conversion efficiency already well established,[24] laboratory effort has concentrated on output of the microwave generator to the dc output of the rectenna. Recent results[18] have given an efficiency of 60.2 percent for this portion of the system. Recent improvements in rectenna design, making use of improved Schottky-barrier diodes and improved rectifier circuits, will soon raise this figure to 70 percent. If this efficiency is multiplied by a credible generator efficiency of 85 percent, already obtained in some magnetrons and Amplitrons,[24] an overall efficiency of 59 percent is obtained, which is approaching the 65 to 70 percent projected for the SSPS.

The achieved efficiencies and those expected in the future are given in Table I. It shows an eventual laboratory overall dc-to-dc efficiency of 77 percent. The principal reason for this high efficiency is that in the laboratory nearly all of the beam can be intercepted whereas in practice this may be uneconomical.

Projected costs for the SSPS system

Table II gives the estimated capital costs of SSPS power generation in dollars per kilowatt.[8] Various confidence levels are reflected in the three different estimates of total cost and principal-components cost.

The estimates for the solar array were based on a straightforward extrapolation of existing manufacturing techniques into a highly automated format justified by the huge production volume. They did not take into account possible breakthroughs in manufacturing techniques, such as those already discussed.

The cost for the microwave transmitting antenna (designated "microwave" in Table II) and the rectenna were arrived at by a consideration of the basic materials involved and a highly automated production line, again justified by the huge number of identical units to be produced. The cost of the microwave generators was based on the very low cost of already mass-produced electronic-oven magnetrons whose material and assembly labor content is similar to the proposed generator. The cost of the Schottky-barrier diodes in the rectenna was projected on the basis of the basic material content and the use of experience curves typical of the semiconductor device industry.[28]

The estimate of transportation costs is based upon a completely reusable space shuttle to transport material from the ground to near-earth orbit and the use of space tugs equipped with high-specific-impulse electric propulsion to transport material from near-earth to synchronous orbit. The estimate given in the "low" column of the table is associated with a second-generation earth-to-near-earth-orbit system.

All component and system costs are assumed to be an average cost associated with the tooling for and the manufacture of 20 or more nearly identical systems. The development costs of the first prototype cannot now be estimated accurately but it is assumed that this cost spread over a production of 20 or more systems represents only a small fraction of the costs listed in Table II.

Number of SSPS systems and land use

The number of SSPS systems that might be deployed is dependent upon their economic viability. Any discussion of the number deployed and land use must be placed in the context of the year 2000 or thereabouts. At that time, the projected requirement is for two million megawatts of electric power generation.[1] This requirement is staggering but it still does not take into account such distinct possibilities in that time period as electric propulsion of automobiles or forced abandonment of fossil fuels for heating purposes. If the requirement were to be met by conventional generating stations rated at 1000 MW each, a quantity of 1600 such plants would be required. If these were all located offshore so as to minimize impact upon the land environment, there would be an average of one generating station approximately every 5 km along the entire U.S. coastline, exclusive of Alaska and Hawaii. This absurd example illustrates not only the magnitude of the requirement but the necessity of a variety of approaches to the energy problem.

The terrestrially based portion of the SSPS system, by virtue of its low pollution and no need for a coolant, is well suited to the inland areas of a country. There is, then, a desire to find land areas that are either wasteland, or at least marginal from an economic use point of view. To such land areas may be added low-cost land that may be located within a reasonable distance of even our most populous areas. Without some drastic reversal of the present declining birth rate and the present flow of the population from rural regions to urban centers, many sparsely populated land regions will remain available as sites for rectennas in the year 2000. This is particularly true of the arid regions of the Southwest and the Great Plains.

To be an important factor in supplying the base-load requirements in the year 2000, the SSPS system

I. Microwave power transmission efficiencies

	Efficiency Presently Demonstrated*	Efficiency Expected with Present Technology*	Efficiency Expected with Additional Development*
Microwave power generation efficiency (η_g)	76.7†	85.0	90.0
Transmission efficiency from output of generator to collector aperture (η_t)	94.0	94.0	95.0
Collection and rectification efficiency (rectenna) (η_r)	64.0	75.0	90.0
Transmission, collection, and rectification efficiency ($\eta_t \eta_r$)	60.2	70.5	85.0
Overall efficiency ($\eta_g \eta_t \eta_r$)	26.5‡	60.0	77.0

* Frequency of 2450 MHz (12.2-cm wavelength)

† This efficiency was demonstrated at 3000 MHz and a power level of 300 kW CW.

‡ This value could be immediately increased to 45 percent if an efficient generator were available at the same power level at which the $\eta_t \eta_r$ efficiency of 60.2 percent was obtained.

II. Estimated capital costs of SSPS power generation ($/kW)

	Confidence Factor		
Cost Element	Low p = 0.25	Medium p = 0.50	High p = 0.75
Solar array	610	1100	1870
Microwave	60	120	190
Rectenna	30	50	70
Transportation	190	450	810
Land	*	*	*
Total	890	1720	2940
Probability estimate	1400	2100	2600

*Negligible