The History of Power Transmission by Radio Waves

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Abstract—**The history of power transmission by radio waves is reviewed from Heinrich Hertz to the present time with emphasis upon the free-space microwave power transmission era beginning in 1958. The history of the technology is developed in terms of its relationship to the intended applications. These include microwave powered aircraft and the Solar Power Satellite concept.**

I. Introduction

THIS PAPER addresses the history of power transmission by radio waves with emphasis upon the more recent development of microwave systems for that purpose. "Free space" is defined as being point-to-point transmission, that is, we will not deal with lenses or reflecting mirrors interposed between the transmitting and receiving locations. We will assume that the power transmission can take place in space completely or that the Earth's atmosphere may also be involved and introduce attenuation and other undesirable effects.

"Power transmission" is defined as a three-step process in which: 1) dc electrical power is converted into RF power, 2) the RF power is then transmitted through space to some distant point, and 3) the power is collected and converted back into dc power at the receiving point. Because the overall efficiency is necessarily the product of the individual efficiencies associated with the three elements of the system, a premium is placed upon efficient conversion technology as well as upon aperture-to-aperture transfer efficiency. In many respects the modern history of free-space power transmission has been the development of components for the transmitting and receiving ends of the system that have sought to achieve the combined objectives of high efficiency, low cost, high reliability, and low mass.

The period of time covered by this history extends from the early experiments by Hertz to the present time. The modern history is identified with the intentional use of microwaves for this purpose that began about 25 years ago. At that time the prospect of being able to develop microwave tubes that would efficiently generate hundreds of kilowatts of power at a wavelength of 10 cm motivated the Raytheon Company (in 1958) to study microwave-powered aircraft that could stay on station at high altitudes for long periods of time and function as communication or surveillance platforms. Although such platforms were not developed, the study and proposal activity devoted to them set into motion a number of activities that were to rapidly become the foundation of the technology of microwave power transmission.

The style of treatment used by the author to present the history varies with the time period. The early history, of which the writer has no direct knowledge, has been researched from books and other publications. The early, fragile, and pioneering period of the modern history with which the author was closely associated is presented in an anecdotal style. The treatment of the later modern history is more terse and summarized.

The author assumes that the readers of this paper will be familiar with microwave techniques. The paper is not intended to be tutorial, but considerable insight into the technology can be derived from the account of problems encountered and how they were solved.

II. The Early History of Power Transmission by Radio Waves

Power transmission by radio waves dates back to the early work of Heinrich Hertz [1]. Not only did he demonstrate electomagnetic wave propagation in free space by using a complete system with a spark gap to generate high-frequency power and to detect it at the receiving end, but he also used parabolic reflectors at both the transmitting and receiving ends of the system. In these respects his experiments resemble present practice more closely than the later better recognized work of Tesla that was based on much longer wavelengths and which did not have any provision for focusing the radio waves. There is an exhibit of Hertz's early experiments in the museum of the University of London that includes these parabolic reflectors.

Nikola Tesla carried out his experiments on power transmission by radio waves at the turn of the century [2], [3]. An acknowledged genius in the area of low-frequency electrical power generation and transmission, he became interested in the broad concept of resonance and sought to apply the principle to the transmission of electrical power from one point to another without wires. By means of the alternating surges of current running up and down a mast, Tesla hoped to set up oscillations of electrical energy over large areas of the surface of the Earth, and to set up standing waves into which he would immerse his receiving antennas at the optimum points.

Tesla carried out his first attempt to transmit power without wires at Colorado Springs, Colorado, in 1899 (Fig. 1). Under a $30 000 grant from Colonel John Jacob Astor,

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Fig. 1. Nikola Tesla in his Colorado Springs Laboratory which was constructed to experiment with radio waves for power transmission.

owner of the Waldorf-Astoria Hotel in New York City, Tesla built a gigantic coil in a large square building over which rose a 200-ft mast with a 3-ft-diameter copper ball positioned at the top. The Tesla coil was resonated at a frequency of 150000 Hz and was fed with 300 kW of low-frequency power obtained from the Colorado Springs Electric Company. When the RF output of the Tesla coil was fed to the mast an RF potential was produced on the sphere that approached 100000000 V, according to Tesla. Such a high potential with respect to the Earth's surface resulted in very long and very visible discharges from the sphere. There is, however, no clear record of how much of this power was radiated into space and whether any significant amount of it was collected at a distant point.

Tesla's work on high-power transmitters did not stop at Colorado Springs. Backed with money granted to him by J. Piermont Morgan, Tesla organized another large installation, this time on 2000 acres of land at Shoreham, in Suffolk County, Long Island, about 60 mi from New York. The building plans called for a wooden tower 154 ft high with a giant copper electrode 100 ft in diameter and shaped like a doughnut at its top. It was nearly completed before Tesla's financial resources were exhausted and work on the project was halted. The installation was torn down during the First World War by the U.S. Government because it was such a conspicuous landmark.

With the advantage of historical perspective, we realize that Tesla's attempts at efficient wireless power transmission were decades ahead of the unfolding technology. Not until the early 1930's was another attempt made to transmit power without wires, and this time experiments were cautiously made within the confines of a laboratory. This experiment, performed in the Westinghouse Laboratory by H. V. Noble, consisted of identical transmitting and receiving 100-MHz dipoles located about 25 ft from each other. No attempts were made to focus the energy, but several hundred watts of power were transferred between the dipoles. This experiment was the basis of a demonstration of power transfer at the Westinghouse exhibit at the Chicago World's Fair of 1933–1934.

The major reason for the lack of serious interest in wireless power transmission during the first fifty years of this century was that knowledgeable people realized that efficient point-to-point transmission of power depended upon concentrating the electromagnetic energy into a narrow beam. The only practical manner in which this could be done would be to use electromagnetic energy of very short wavelengths and to use optical reflectors or lenses of practical dimensions. For the first thirty-five years of this century, devices did not exist to provide even a few milliwatts of energy at these wavelengths. Sufficient power was not even available for experimental work in communication and radar systems.

In the late 1930's, however, two developments capable of generating microwave power that were destined to have a profound influence upon the unfolding of this new technology were made. The first of these was the velocity-modulated beam tube, first described by O. Heil, and with certain modifications now widely known as the klystron tube. The second device, perhaps even more important to the unfolding of this new technology, was the microwave cavity magnetron developed first in Great Britain and then in this country during World War II, under great secrecy [5].

While the development of radar in World War II did much to develop the antenna and the microwave generator technologies so basic to power transmission, there was no immediate serious consideration for employing the newly won technology in this way. Microwave tubes were still small in their power handling capability and the concept of active phased arrays that could make use of many small tubes had not yet been exploited. Nor was there a power device to convert the microwave power into dc power. More than a decade was to elapse after World War II before serious interest in microwave power transmission began.

III. The Modern History of Free-Space Power Transmission

The modern history of free-space power transmission as it relates to microwaves includes not only the development of the technology of microwave power transmission but also several proposed applications. These ranged from the microwave-powered helicopter in which substantial vehicle development was performed, to other high-altitude platforms in the Earth's atmosphere and to the solar-power satellite concept with microwave transmission to Earth. The varied requirements of the proposed applications have had a profound disciplinary impact upon the direction in which the technology has developed.

Another disciplinary consideration are those factors which have confined the frequency used in the development of the technology and thus far in its applications to the 2.4–2.5 GHz band, reserved for industrial, scientific, medical (ISM) application. Although the frequency was originally used because of the use of the ISM band for experimental purposes and the availability of components there, it is also a frequency where the efficiencies of the microwave components are very high. If the Earth's atmosphere is involved, it constitutes an excellent compromise between greater propagation attenuation in heavy rainfall at higher frequencies, and the larger aperture dimensions necessary for efficient transmission at lower frequencies.

The history of free-space microwave power transmission may be divided into the early period that began about 1958 and the period that began in 1977 with the onset of the joint DOE/NASA assessment study of the solar-power satellite concept. The division has been made on the basis of the organizations participating in those periods.

During the early period that began in 1958, the sponsors were: Raytheon Company, the Air Force's Rome Air Development Center, NASA's Marshall Space Flight Center, NASA's Lewis Research Center, and the Jet Propulsion Laboratory under contract to NASA, in that sequence, but with some overlap. Raytheon, in addition to being the first sponsor, continued to directly or indirectly support the activity. During the period, most of the corresponding contractual work effort was carried out by Raytheon, either under the supervision of Owen Maynard, who became involved in 1972, or by myself. The effort included considerable work that was oriented toward the solar-power satellite but which occurred prior to widespread participation by other organizations.

During the later period that began with the DOE/NASA assessment of the solar-power satellite (SPS) concept, there was much larger participation in microwave power transmission studies that included the Boeing Company, Rockwell International, and many others. There was also large participation by the NASA Centers. Many excellent contributions were made by these new participants in the context of the SPS application.

Since the conclusion of the SPS study in 1980, participation in the microwave power transmission area has declined and the major recent activity has been NASA-sponsored studies on microwave-powered high-altitude atmospheric platforms in which I have carried out those portions of the studies that are related to microwave power transmission. Thus I am left as the only individual that has been continuously involved in the technology of free-space microwave power transmission and its applications since its inception. This provides me with an unusually intimate perspective from which to write its history, and I hope the positive aspects of that will outweigh the negative.

A broader perspective, but one that is limited to an excellent treatment of the state of the art of both components and total systems as it existed in 1967 may be obtained from the two volumes of *Microwave Power Engineering* edited by E. C. Okress and published by the Academic Press in 1968 [6].

It may be of particular interest to note that the first IEEE-organized session on microwave power transmission occurred on May 6, 1964 as part of the IEEE Conference on Energy Sources held in Clearwater, Florida. Dr. Ernest Okress was chairman of the session, and papers are summarized in the October 1964 Issue of the *IEEE Spectrum* [7].

On the following day, a special meeting was convened by Dr. Henry Kosmahl on the subject of transferring power to satellites by microwave beam. It is interesting to note that the technology has now matured to the point where it is seriously being proposed as an alternate approach to the use of solar photovoltaic arrays in applications where hundreds of thousands of kilowatts of continuous power may be desired for propulsion or for payload.

A. The Early Beginning

A number of developments converged in the late 1950's to make the efficient transmission of large amounts of power without wires a reasonable concept [8]. An important development was the theoretical and experimental demonstrations by Goubau, Schwering, and others that microwave power could be transmitted with efficiencies approaching 100 percent by a beam waveguide consisting of lenses or reflecting mirrors [9], [10]. This advance helped dispel the widespread but incorrect assumption that power density always fell off as the square of the distance.

Another development was my proposal that the Amplitron, a recently developed re-entrant beam crossed-field amplifier, be further developed into a super power tube producing hundreds of kilowatts of continuous power by taking advantage of a high-dissipation density cooling method that had been introduced by RCA engineers in the late 1930's and which I had witnessed while in the student training course there [11], [12].

Still another development was the growing need to be able to communicate by line of sight over much longer distances, which a platform placed at high altitudes in the Earth's atmosphere would make possible. Later on, of course, the satellite supplied most of these needs, but at the time a microwave-powered vehicle seemed to some like a more logical approach.

The combination of these developments motivated the Raytheon Company to study and propose the Raytheon Airborne Microwave Platform (RAMP) concept in 1959 to the Department of Defense as a solution to communication and surveillance problems.

The proposed platform, to be flown at 50000 ft, was a large helicopter which a number of cooperating helicopter companies studied and concluded would be feasible. While the Department of Defense did not subsequently support the development of RAMP, Raytheon's briefings broadly spread the concept and encouraged the support of technology developments that were felt necessary for its practical realization.

One missing technology was the very high-power microwave tubes considered essential in the transmitter. This lack was one of the reasons that led the Department of Defense, then looking for new technology because of the reaction to Sputnik, to support the development of super power tubes with the crossed-field amplifier approach that I had proposed. A contract was subsequently awarded to Raytheon whose objectives included an Amplitron with an output of 400 kW of CW power at a frequency of 3 GHz and at an efficiency of 80 percent [13]. To carry out this extensive program Raytheon added a large addition to its Spencer Laboratory in 1960 and made me the manager of an activity for both tube developments and the investigation of new applications for them.

Another piece of missing technology was the conversion of the microwaves directy into dc power to drive motors attached to the rotor blades. Because there were no satisfactory microwave rectifiers at that time, the Air Force awarded a number of contracts to study this problem [6]. One of these studies that later became very important was the investigation of the semiconductor diode as an efficient rectifier that was carried out at Purdue University under the leadership of Prof. Sabbaugh and Prof. George [14].

Unaware of the activity at Purdue, I had persuaded Raytheon management to support the development of a close-spaced thermionic diode rectifier which was to be used in demonstrating a microwave power transmisssion system within the laboratory [15]. While I worked on the rectifier, Neil Heenan in my lab worked on the overall design and on the demonstration which would involve a horn-illuminated ellipsoidal reflector that would focus the microwave beam into a trapezoidal horn at a distance of about 20 ft where the microwaves would be converted into dc power by the close-spaced thermionic diode rectifier [16].

The first opportunity to demonstrate this system was in May 1963, when a large group of Air Force and other DOD officials met at Raytheon to review progress on the super-power Amplitron contract and to witness the generation of several hundred kilowatts of CW microwave power from one tube. A successful demonstration of the microwave power transmission system was carried out. Of the 400 W of CW power generated by the magnetron at the transmitter, 100 W of dc power was retrieved at the receiving end and used to drive a dc motor attached to a fan (Fig. 2).

Among those witnessing the demonstration was Dr. John Burgess, Chief Scientist at the Rome Air Development Center, who saw the potential of extending what he had seen to a microwave-powered atmospheric platform for line-of-sight communication over long distances, similar to the RAMP helicopter concept but now made more feasible because of the ability to convert the microwave power directly into dc power.

To encourage Dr. Burgess's interest, as well as to encourage the interest of my young son in craftmanship, he and I in the summer of 1963 constructed in my home workshop and flew thirty or more feet above my lawn a small tethered helicopter. Its 4-ft rotor was driven by a conventional electric drill motor supplied with power from a cable. The helicopter carried aloft as a dead load one of the close-spaced thermionic diode rectifiers, which in principle could have supplied the power to the motor if the helicopter had also carried aloft a lightweight horn or reflector to capture power from a microwave beam. Motion pictures were taken of the helicopter flights, shown to Dr. Burgess and Raytheon management, and were believed to have been a major factor in motivating Dr. Burgess to set aside discretionary funds for the development and demonstration of a small microwave-powered platform in the form of a helicopter. We were to receive the funds in the following year.

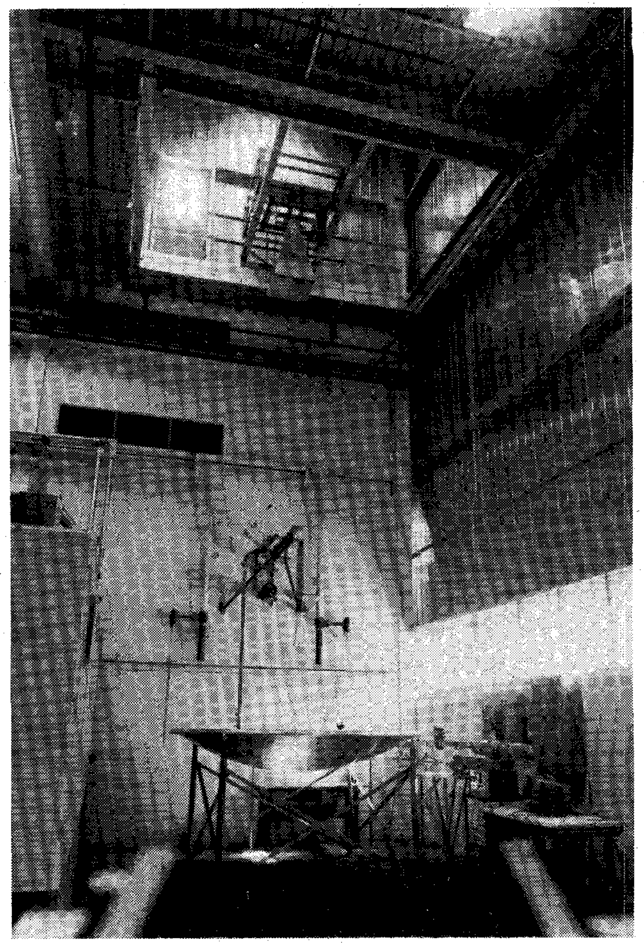

Fig. 2. This complete microwave power transmission system, believed to be the first, delivered 100 W of dc power when it was demonstrated at Raytheon's Spencer Laboratory in May 1963. Overall dc to dc efficiency was about 13 percent.

Meanwhile, we continued to examine the feasibility of the microwave-powered helicopter concept. It had become evident that any receiving arrangement using horns or reflectors had serious flaws for use with a helicopter. They would be much too directive for the expected roll and pitch of the vehicle and their collection efficiency would also be poor. The close-spaced thermionic diode was also proving to be an unreliable and short-lived device. The prospects for a successful helicopter development and flight were deteriorating rapidly.

Fortunately, earlier in the year I had had a chance meeting in the Boston airport with a college friend, Dr. Thomas Jones, and told him of my problem. He had become head of the Electrical Engineering Department at Purdue and was well aware of the work going on there on solid-state diodes as rectifiers, and, of course, he told me about it. I then made a trip to Purdue and met Prof. Sabbaugh and Prof. George.

Roscoe George, who had been carrying out most of the activity, had been using dense arrays of closely spaced diodes within an expanded waveguide and had achieved as much as 40 W of dc power output from microwaves in the 2- to 3-GHz range of frequency with respectable efficiencies. Although he had not made any measurements with free-space radiation, he had shown how the microwave semiconductor diode, previously ignored as a power rectifier because of its very low individual power handling capability, could be combined in large numbers to produce reasonable amounts of dc power [17].

In the absence of any other successfully developed microwave power rectifier, I was drawn to the semiconductor diode approach. However, the use of George's dense arrays within a waveguide attached to a receiving horn would not solve the problems of low collection efficiency and directivity of the receiving horn itself. It was from this dilemma that a device, later to be known as the "rectenna," was conceived. The proposed solution was to take the individual full-wave rectifiers out of the waveguide, attach them to half-wave dipoles, and put a reflecting plane behind them [18].

Once conceived, the development of the rectenna, driven by its need for the proposed microwave-powered helicopter, proceeded rapidly. I employed Prof. George as a consultant to proceed with this approach and make measurements on the characteristics of such a device. With the arrangement of 28 rectenna elements shown in Fig. 3, a power of 4 W of dc power at an estimated collection and rectification efficiency of 50 percent and a power of 7 W at an estimated efficiency of 40 percent were achieved. Of primary importance was the highly nondirective nature of the aperture that had been anticipated because of the termination of each dipole antenna in a rectifier which effectively isolated the elements from each other in a microwave impedance sense except for the secondary effect of the mutual coupling of the dipoles. This feature of the rectenna, which distinguishes it from the phased array antenna, is of the greatest importance [7].

Although this achievement may be considered as the first major milestone in developing a suitable receiving device, the very small power handling capacity of the diodes limited the power output per unit area to values unsuitable for a helicopter experiment. For the helicopter experiment, Prof. George suggested vertical strings of diodes separated by approximately a half-wavelength, but the power density was still much too low [17]. Placed close to each other in a plane to obtain the necessary power density, the impedance of the diode plane was very low and most of the power was reflected. I was able to solve this problem by placing a matching network consisting of a plane array of rods spaced appropriately from each other and at an appropriate distance from the plane of the diode array [19]. The final helicopter rectenna is shown in Fig. 4. It was comprised of 4480 IN82G diodes, and had a maximum power output of 270 W which was more than enough to power the helicopter rotor. The weight of the array was about 3 lb or about 11 lb/kW of dc output.

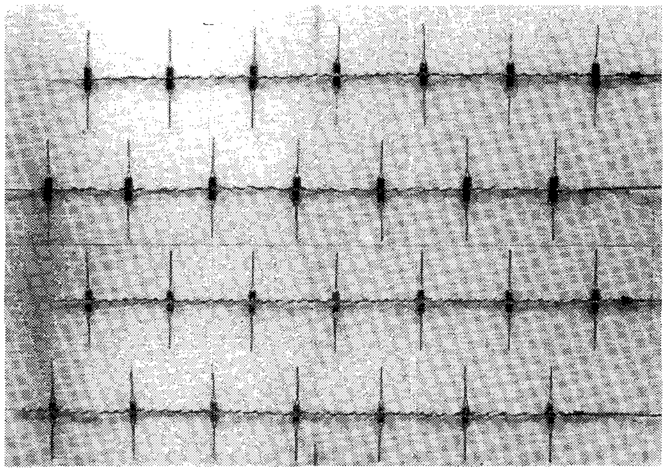

Fig. 3. The first rectenna. Conceived at Raytheon Co. in 1963, it was built and tested by R. H. George at Purdue University. It was composed of 28 half-wave dipoles, each terminated in a bridge rectifier made from four 1N82G point-contact, semiconductor diodes. A power output of 7 W was produced at an estimated 40 percent efficiency.

A microwave-powered helicopter flight with this string-type rectenna was made on July 1, 1964, inside Raytheon's Spencer Laboratory. Although the vertical flight distance was constrained to a few inches, it was the first flight of a heavier-than-air vehicle that was sustained solely from power derived from a microwave beam.

We then became active on the Air Force contract which required that the vehicle fly continuously for 10 h at an altitude of 50 ft [20]. So we moved the helicopter and its microwave power system to an outdoor location where we soon found that the interaction of the wind with the helicopter, constrained as it was on vertical tethers, introduced violent mechanical oscillations into the structure. However, we worked these problems out and were able, jointly with the Air Force, to give a briefing and demonstration to the mass media on October 28, 1964. (See Fig. 5.) This presentation resulted in considerable coverage of the microwave-powered helicopter concept in the press and on TV. The TV exposure included a spot on Walter Cronkite's CBS news program, and it made a welcome diversion from presidential election coverage. In November, the Air Force contract monitor, Dirk Bussey, came down from Rome Air Development Center to witness the 10-h continuous flight required by the contract. We decided to fly the helicopter at night, expecting the atmosphere to be calm. Instead there was a cold rain and the wind blew. At the end of the 10 h all the observers were chilled and dead tired, but the helicopter was still going strong.

In retrospect, I am amazed at how rapidly we moved from the first fragile demonstration of microwave power transmission in May 1963, through the concept of the

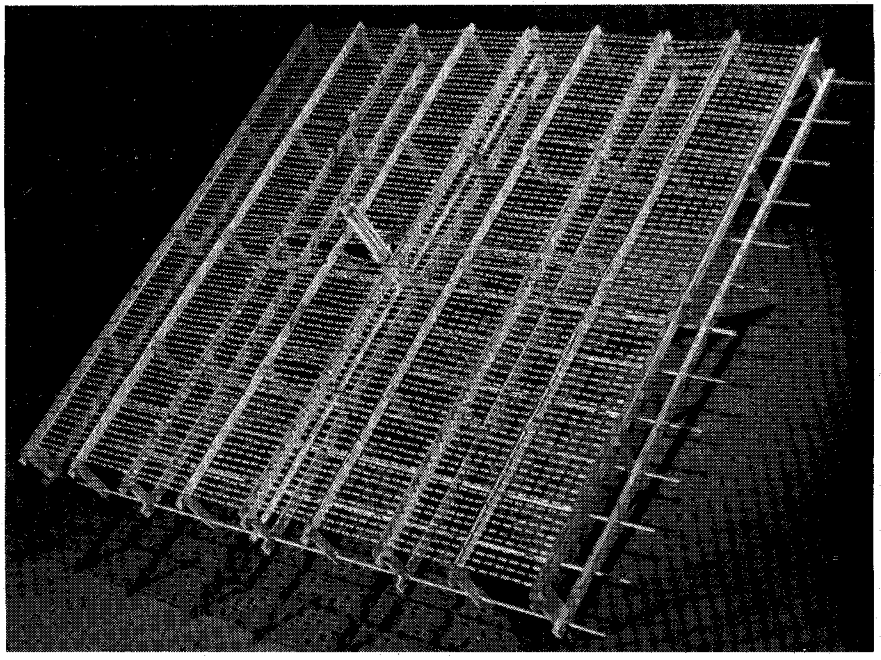

Fig. 4. The special "string" rectenna made for the first microwave-powered helicopter in 1964. The array area of four square feet contained 4480 1N82G point-contact diodes. Maximum dc power was 270 W.

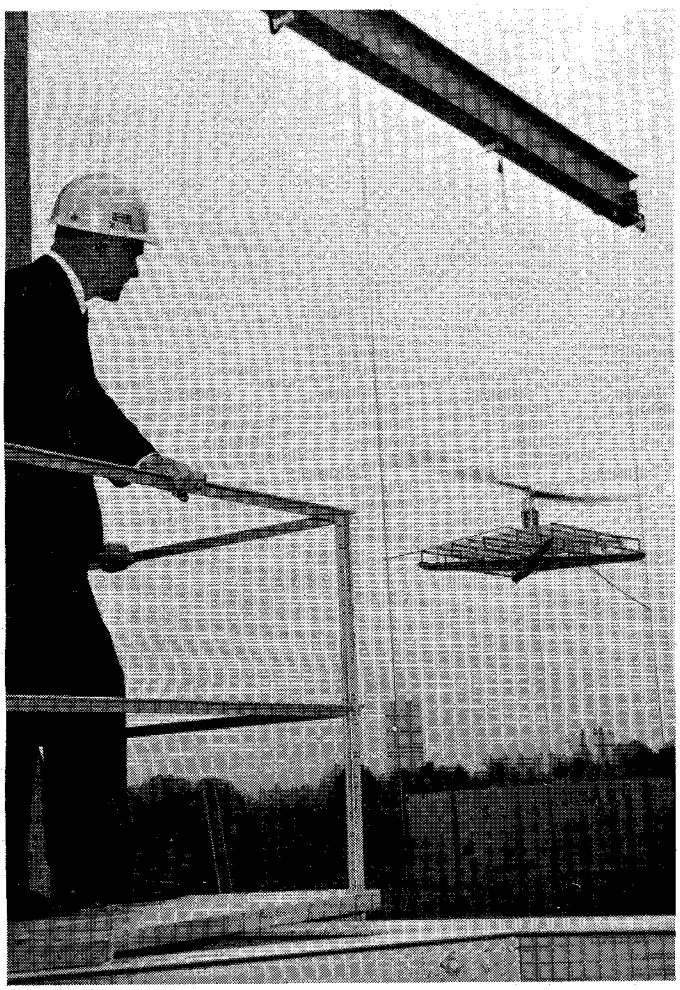

Fig. 5. Microwave-powered helicopter in flight 60 ft above a transmitting antenna. The helicopter was demonstrated to media in October 1964. A 10-h sustained flight was achieved in November of that same year.

microwave-powered helicopter, and through the conceptualizing and development of the rectenna, to a successful press demonstration of a microwave-powered helicopter in 1964. This activity took place amidst other major activities of tube development and microwave industrial processing and could only have happened because of exceptionally talented and devoted staff members and engineers who joined together in a team effort. James (Roy) Mims, Neil Heenan, Robert Bowen, and Robert Peterson were key individuals. Mims was later to take on and successfully complete the task of designing and constructing a fully articulated helicopter.

Another individual who was of great help on this activity, as well as on future activities, was an exceptionally able consultant, Dr. Robert Kyhl of M.I.T.

As a result of the exposure of the concept through the mass media I received a letter from a representative of Hewlett-Packard Associates enclosing some newly developed silicon Schottky-barrier diodes which were indicated to be a substantial improvement over the point contact diodes that had been used. Tests made on the individual diodes (Type 2900) indicated that indeed they were much more efficient and would have more power handling capability. This, combined with their smaller size, made them the subject of a great deal of potential interest and they were to be important in later activities.

The next phase, supported by the Chief Scientist's discretionary funds, was the design, construction, and testing of a 6-ft rotor helicopter that would automatically position itself over the center of the microwave beam and control its roll, pitch, and yaw attitudes with sensors that derived phase, polarization, and amplitude information from the beam itself. In anticipation of such an activity I had dutifully taken a course at Northeastern to learn the princi-

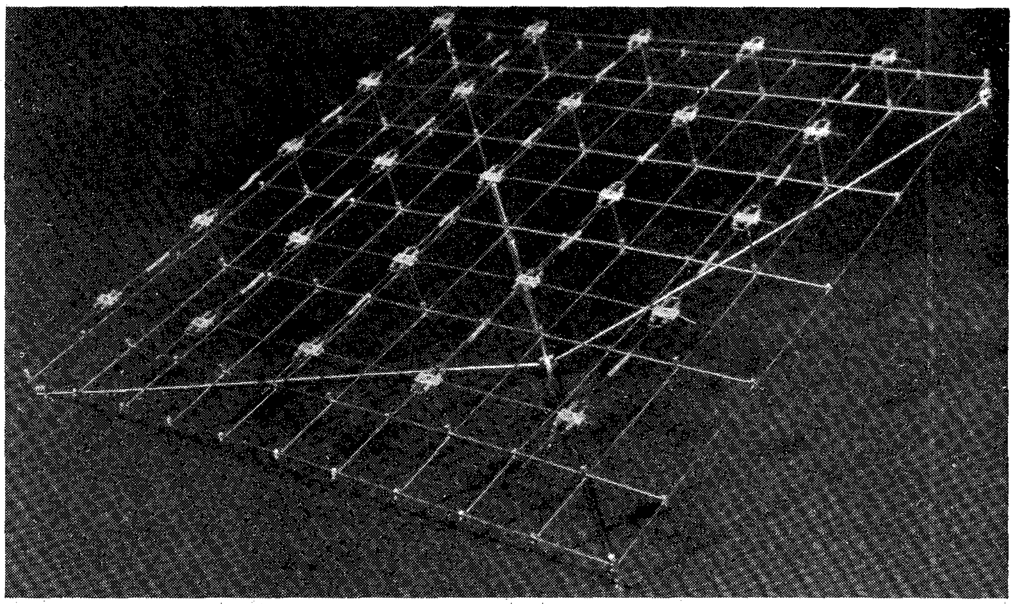

Fig. 6. Greatly improved rectenna made in 1968 from improved diodes (HPA 2900). The 0.3-m^2 structure weighed 20 g and delivered 20 W of dc output for a power to mass ratio improvement of 10 over rectenna shown in Fig. 3.

ples of control theory. When the contract arrived, I engaged Prof. Norman Ham of M.I.T. as a consultant to explain the mechanics of helicopter flight, and I became rapidly involved in designing the sensor and control system for the helicopter while Mims designed the helicopter itself. Within a year from obtaining the contract, we demonstrated the beam-riding helicopter in free flight, except for a power cord to the motor, over the center of the microwave beam with negligible pitching, rolling, yawing, or translational motion [21], [22].

With both microwave-powered and beam-riding helicopters having been demonstrated, the stage was now set for a free-flying microwave-powered helicopter and its incorporation into a full-scale communications or surveillance platform. In effect, we had achieved the original RAMP technical objectives at low altitude, with the basic technology available for a full-scale system.

Unfortunately, the Air Force elected not to go onto the next stage of development and industry elected not to support it either. And in the time period from 1965 to 1970 there was no support of microwave power transmission technology from either government or industry.

Under these circumstances I felt compelled to become a sponsor myself. Using personal funds to buy diodes and other material, I constructed in my home workshop during my vacation period and spare time during the summer and fall of 1968 a rectenna whose objective was to improve the power handling to weight ratio. The rectenna incorporated the improved HPA 2900 Schottky-barrier diodes and reverted back to the format of half-wave dipoles terminated in a full-bridge rectifier. The resulting array shown in Fig. 6 had a mass of only 20 g but produced 20 W of dc power output for an improvement in the power to mass ratio of ten over the string rectenna used for the helicopter demonstration. Moreover, the rectenna was to play an important role in interfacing with NASA's Marshall Space Flight Center and in persuading them to sponsor additional technology development [23].

B. Sponsorship by Marshall Space Flight Center (MSFC)

The interest in microwave power transmission at MSFC grew out of an expected need for some kind of free-space power transmission within a space-based community that would contain a collection of physically separated satellites. A country-wide survey of technical approaches to this problem, made by William Robinson of MSFC in 1967, identified the work that had been done at Raytheon. At his and Associate Director Ernst Stuhlinger's suggestion a demonstration was given to Dr. Werner von Braun and his entire staff. It was the kind of demonstration that would probably not be permissible today. At one end of the long table in the MSFC board room a 3-ft-diameter parabolic reflector was set up as the source of a microwave beam of about 100 W. At the other end of the table I held the rectenna of Fig. 6, now attached to a small motor with a small propellor attached to it. The microwave beam was used to supply power to the motor and I would interpose my body between the source and the rectenna to demonstrate that the power was coming from the microwave beam.

Interest within MSFC resulted in a contract with Raytheon for a system study to be performed in 1970. Initially the system study did not involve any supportive technology development, but it soon became apparent that any significant follow-on sponsorship by MSFC depended upon demonstrating a minimal overall system efficiency. The contract work statement was amended to permit

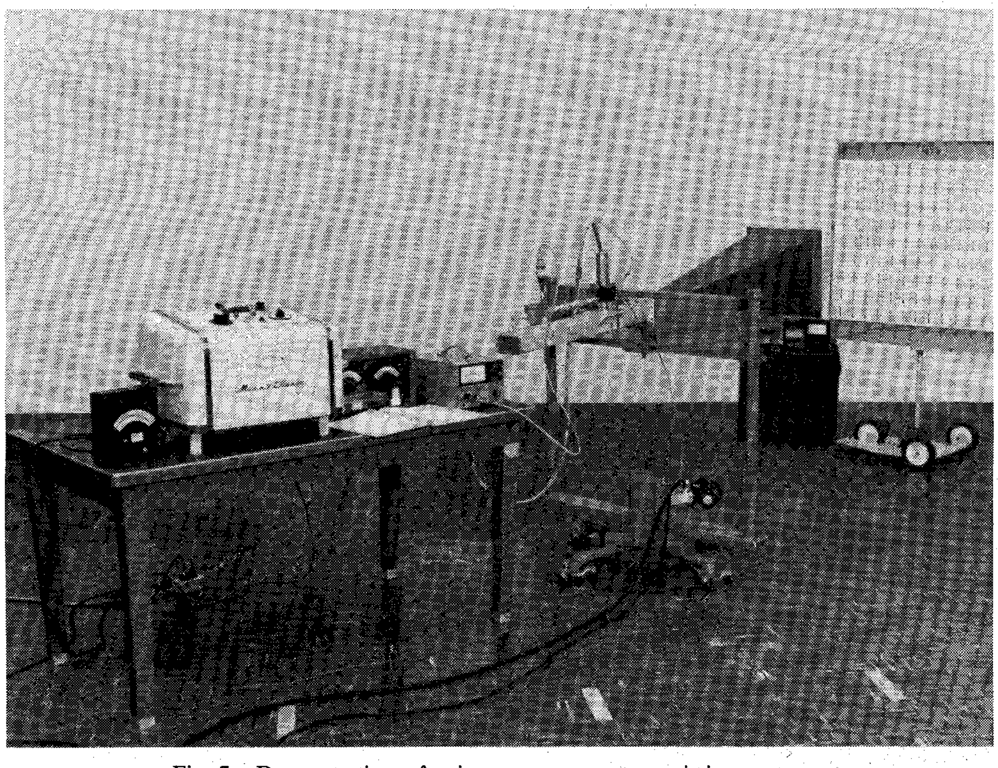

Fig. 7. Demonstration of microwave power transmission system at Marshall Space Flight Center in August in 1970. Overall dc to dc efficiency of 27 percent was achieved. DC output was 39 W.

Raytheon to construct the hardware for an overall efficiency measurement to be made at MSFC.

The system shown in Fig. 7 was hastily put together and demonstrated at MSFC in September 1970. The measured overall dc to dc efficiency was 26 percent, exceeding the specified minimum by 7 percent. From the vantage point of our present knowledge, where much greater overall efficiences have been obtained and broadly accepted, it is easy to forget and painful to remember that initially there was a widespread intuitive feeling among the microwave community that high overall dc to dc efficiencies could never be obtained in a microwave power transmission system. The demonstration at MSFC was a critical one.

Over the next four years there were several amendments to the contract and a succession of improvements involving better rectenna design, a better means of launching the microwave beam, better measurement tools for assessing performance, and better analytic tools for understanding the operation of the rectenna. Following the design procedure developed by P. D. Potter of the Jet Propulsion Laboratory (JPL), a dual-mode horn was designed for launching a Gaussian beam with negligible side lobes. A closed system in which the efficiency of the individual rectenna element could be accurately measured was evolved [24].

A very important input was the suggestion by Wes Mathei of Microstate in 1971 that the gallium arsenide Schottky-barrier diode that had reached an advanced state of development for IMPATT devices might be a very good power rectifier. He provided a number of diodes for testing, and indeed they had greater efficiency and a power handling capability greater by a factor of 10 than that of the HPA diodes that had been the standard. C. K. Kim was subsequently very helpful in developing these diodes specifically for rectenna use.

A decision had to be made about whether to use the new diodes in a four-diode bridge rectifier, a two-diode full-wave rectifier, or a single-diode half-wave rectifier. Although all previous experience had been with a full-wave rectifier, I elected to go with the half-wave rectifier despite an expected lower efficiency because of its much simpler physical configuration and because Eugene Eves in our laboratory was mathematically modeling the operation of the rectenna element in such detail that it appeared most desirable to write the corresponding computer program for the simplest case, that is, the single diode.

As it turned out, the half-wave rectifier option performed very efficiently and had so many advantages in terms of cost and simplicity of construction that there was little temptation to spend effort on the other options. It was also satisfying to observe that the operation predicted by the computer program and that observed experimentally were nearly identical.

The MSFC-sponsored program of effort finally culminated in the design and construction of a laboratory microwave power system that used the improved technology developed over the previous years to maximize the overall dc to dc efficiency of the system [24] (Fig. 8). To optimize the aperture to aperture transfer efficiency, it was necessary to intercept nearly all of the near-Gaussian beam

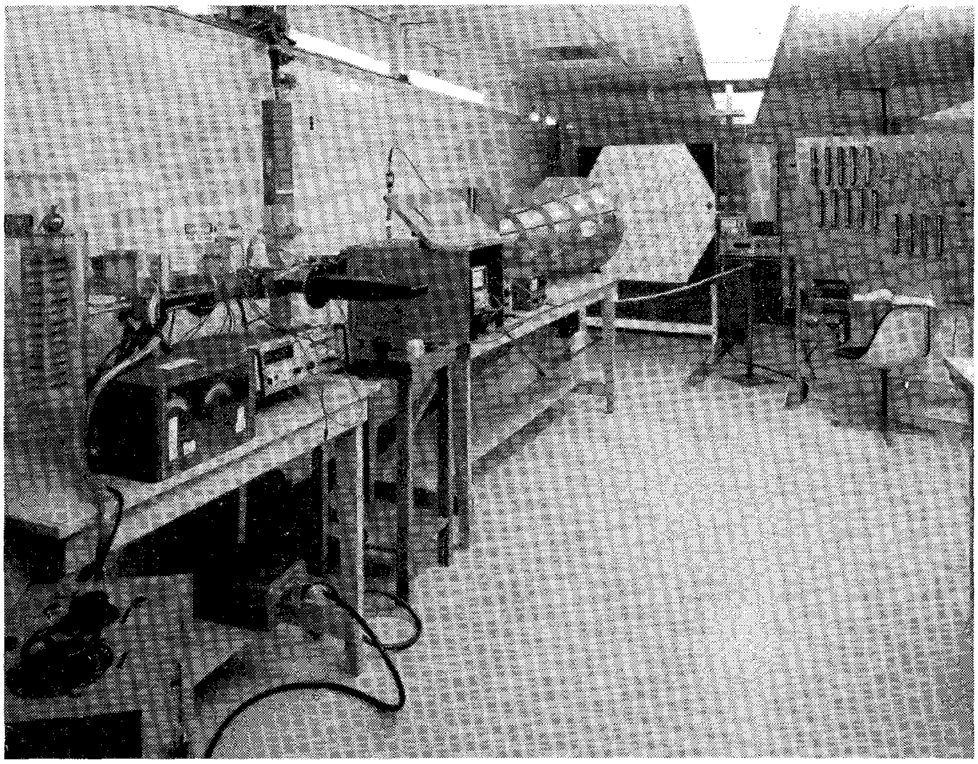

Fig. 8. Test of overall system efficiency in the Raytheon Laboratory in 1975. Ratio of dc power out of the rectenna to the dc power into the Magnetron generator was 0.54 ± 0.009. 54-percent efficiency was certified by JPL Quality Assurance Division. Power Output was 495 Ws.

generated by the dual-mode horn. This implies that the power density at the center of the rectenna may be 50 times that at the edge.

Intercepting nearly all of a Gaussian beam also makes it possible to accurately measure the collection efficiency by standing wave measurements made with a moveable dipole probe in front of the rectenna. By adjusting the dc load resistance at the rectenna output and the spacing of the rectenna element dipoles from the reflecting plane we were able to minimize the reflected power to less than 0.5 percent, thus confirming the theoretical prediction that such an array could absorb 100 percent of the power incident upon it.

The overall efficiency achieved with the setup shown in Fig. 8 was 48 percent ± 2 percent. This same arrangement was later upgraded under JPL sponsorship to 54 ± 1 percent.

C. Progress Associated with Initial Interest in the Solar-Power Satellite (SPS) Concept

A development that was to profoundly affect the future direction of technology development was the solar-power satellite (SPS) concept introduced by Dr. Peter Glaser of the Arthur D. Little Company in 1968. In this concept, the sun's energy is captured in geosynchronous orbit, converted into microwave power, which is then beamed to Earth where it is converted back into ordinary electrical power. The introduction of this concept was to set into motion many activities related to microwave power transmission.

There was an immediate recognition by Dr. Glaser and myself of the mutually supportive relationship between the SPS concept and microwave power transmission technology. Collaborating, we organized the first technical session on the SPS, devoted primarily to its microwave power transmission aspects, at the International Symposium of the International Microwave Power Institute at the Hague in 1970. The microwave requirements of the SPS were a tremendous challenge to the participants, which included G. Goubau, W. J. Robinson, P. Guenard, and V. J. Falcone, Jr., as well as Glaser and myself. The papers were printed in a special issue of the *Journal of Microwave Power* (1970), edited by Dr. John Osepchuk, entitled "A Satellite Solar Power Station and Microwave Transmission to Earth" [25].

This special issue came to the attention of Arthur Herron of Raytheon who was on special assignment to investigate how the company could be involved in solving the growing energy problem. He immediately recognized the importance of the concept and enlisted the support of Owen Maynard, another Raytheon employee with extensive NASA background. At the same time, the Grumman Aerospace Corporation had become interested in the concept. As a result of mutual interest, a four-company team with membership consisting of Arthur D. Little, Raytheon, Grumman Aerospace, and Textron (solar photovoltaics) was assembled to study the technical and economic feasibility of the SPS concept. The results of a six-month study carried out in 1971 and involving four volumes of technical investigation were sufficiently favorable to encourage the management of the four companies to jointly send a letter

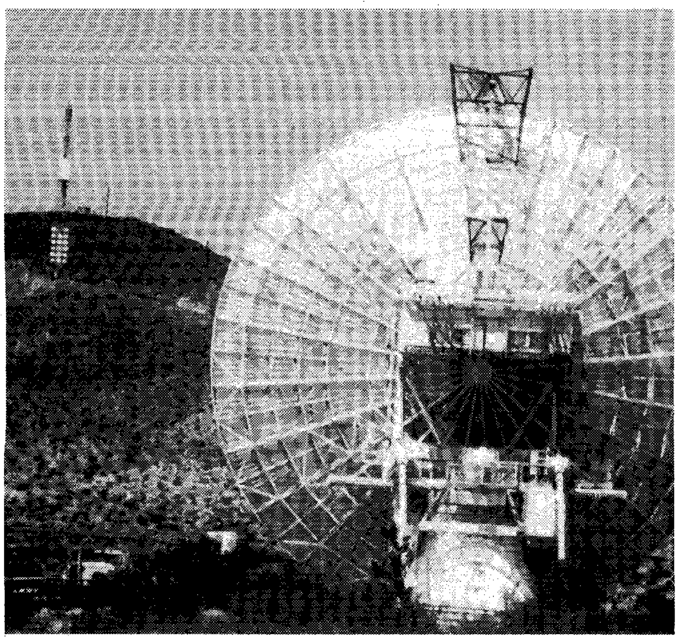

Fig. 9. The microwave power transmission demonstration in 1975 at the Venus Site of the JPL Goldstone Facility. Distance between transmitting and receiving antennae was 1 mi. Over 30 kW of dc power was obtained from the rectenna with a ratio of dc output to incident microwave power of 0.84. Part of dc output was used to energize a bank of lights.

to the Director of NASA recommending NASA's support to study the concept [26], [27]. NASA first responded to this recommendation by sponsoring a modestly funded study in 1973, through the Lewis Research Center [28].

By 1973 the SPS concept had become an important enough consideration to interest NASA's Office of Applications in supporting additional development and demonstration effort related to the microwave power transmission portion of the system. Both the Jet Propulsion Laboratory and Lewis Research Center became involved in supervising the resulting activity. The JPL activity, under the guidance of Richard Dickinson, involved quality assurance monitoring of the demonstration of overall dc to dc efficiency in the Raytheon laboratory and the demonstration of the transfer of large amounts of power over a long distance at its Goldstone facility [29], [30].

In a laboratory setup that was an upgraded version of that shown in Fig. 8, a dc to dc efficiency of 54 ± 1 percent, certified by representatives from JPL's Quality Assurance organization, was achieved.

In the Goldstone demonstration, power was transferred by a microwave beam over a distance of 1 mi with a dc output of 30 kW. This represented a level of distance and power almost two orders of magnitude greater than had been accomplished in the laboratory (Fig. 9). That demonstration, contracted to Raytheon in a turn-key type of arrangement, involved making a 288-ft^2 rectenna and instrumenting the performance of it and the complete system. Maynard was the program manager, I designed the rectenna, and Kenneth Dudley and Robert Bowen supervised its construction [31].

These two demonstrations, carried out in the 1974 to 1975 time period, were undoubtedly an important contribution to the establishment of confidence within the NASA and aerospace communities in the credibility of microwave power transmission technology and its possible use in the SPS.

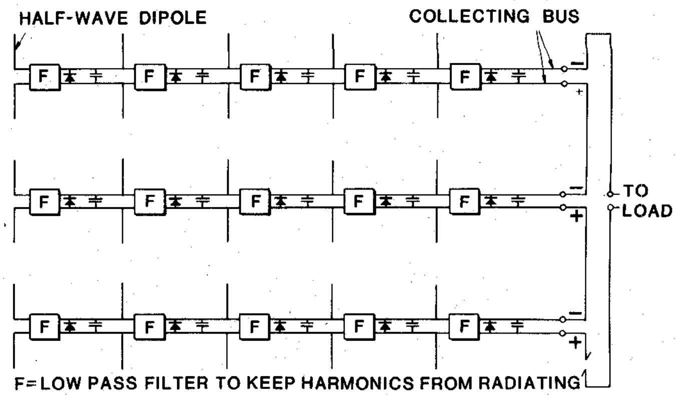

Fig. 10. Schematic of rectenna foreplane circuit showing separate rectenna elements with their dc output connected in parallel. This is proposed arrangement for updated SPS rectenna and also for the thin-film-etched circuit rectenna.

A concurrent study supervised by Lewis Research Center (LeRC) and carried out by the Raytheon Equipment Division represented a very broad and disinterested review of microwave power transmission technology as related to the needs of the solar-power satellite [32]. It was involved with determining critical technology areas and found that the dc to microwave conversion and the phased array antenna in the satellite were such areas. The later responses to filling these critical needs resulted in significant developments and unexpected findings that now form the base for active phased array transmitter technology not only for the solar-power satellite but for more recently pursued applications as well.

Another SPS study that resulted in several important electrical and mechanical improvements to rectenna technology was supported by LeRC in 1976–1977. The most important improvement was changing the mechanical format of the rectenna from a three-plane system to a two-plane system. Heretofore, the standard had been the three-plane system in which the bussing was carried out behind the reflecting plane. This arrangement is inherently more complex, much heavier, and more costly than a two-plane system, in which there is only a reflecting plane and a foreplane in which all of the microwave functions, rectification, and dc bussing are carried out on the foreplane (Fig. 10). This format later led to the thin-film etched circuit format for aerospace applications [33].

We were also able to investigate rectenna elements and diode technology that would permit more efficient rectenna operation at lower power levels, and to perform life tests on the 199-element rectenna shown in Fig. 8 for over 3000 h with no failures or fall-off in efficiency performance. We also refined the validity and accuracy of efficiency measurement techniques by balancing within 1 percent the accurately measured microwave power input against the sum of the dc power output and carefully measured dissipation losses. Good agreement, within 1 percent, was also obtained between measured values of efficiency and those predicted by the mathematical and computer code developed by Eves [33].

D. *Microwave Activity Under the DOE/NASA Concept Development and Evaluation Program for the Solar-Power Satellite (SPS)*

At the time that NASA was developing considerable internal interest in the SPS, the Office of Management and Budget made the decision that, because the electric power derived from the SPS system would be used on the Earth, it should be under the management of ERDA (Energy Research and Development Agency) which had not previously been involved. ERDA responded by appointing a special internal study committee that recommended a program to study the SPS in considerable depth and breadth, including environmental and societal assessments.

The committee's recommendation evolved into a three-year study program begun in 1977 and identified as the DOE/NASA Satellite Power System Concept Development and Evaluation Program. The many detailed studies undertaken during this study were completed in 1980 and resulted in a 670-page document summarizing the studies and findings [35]. They are too numerous to review all of them in this paper. However, I will review two technological developments that I believe are important additions to the development of microwave power transmission technology and that illustrate the positive findings that resulted from the wide range of questions, suggestions, and responses that occurred during the SPS study program.

The first of these developments began with the suggestion by Dickinson of JPL in 1975 that microwave oven magnetrons, combined with a passive directional device to enable them to be used as amplifiers, be investigated for use in an active phased array that would simulate to some degree the transmitting antenna in the SPS. The motivation was to keep the cost of the experimental phased array to a minimum. Because it was desired to test the capability of the retrodirective array principle to cope with physical displacements caused by excitation of mechanical resonances in the transmitter, the proposed demonstration became known as the "shake and bake."

I was frankly skeptical of the microwave oven magnetron because of its reputation for being "noisy." In testing them I found, to my great surprise, that when used with a dc power supply and with the source of cathode heating limited to electron backbombardment alone (that is, with the filament power supply set to zero), the tube was very quiet over a very wide range of operating parameters.

Investigation of the noise from magnetrons, together with other investigations, became the subject of a subcontract to Raytheon from JPL for "beamed power technology improvement." During this investigation we found the microwave oven magnetron was so quiet that it was necessary to develop special test equipment to get better measurements of signal to noise ratios.

These ratios were so high that Raytheon felt it desirable to call the observations to the attention of the SPS in-house study teams at Johnson Space Center and Marshall Space Flight Center. The subsequent briefings alerted them to an option to the klystron, which had been selected for the SPS reference system over a crossed-field device largely on the basis of its reputation for low noise.

Acknowledging the new data, the question was then raised at Johnson Space Center as to the capability of the carburized thoriated tungsten filamentary cathode to meet the long-life tube requirement imposed by the SPS application. To answer this question, I reviewed the extensive literature on the life of such cathodes as a function of operating temperature. I then found magnetrons that had optical windows in them so that I could observe the cathode temperature as a function of imposed operating conditions. I was amazed to discover that an internal control loop in the generation process kept the cathode just hot enough by electron backbombardment to supply the needed emission by primary emission alone [36]. Furthermore, by keeping the required emission current density at a low value, but at one which would still allow satisfactory tube designs for the SPS application, the cathode could be kept at a low enough operating temperature to make the prediction of life measured in scores of years possible [36].

These discoveries were very important and led to a contractual study from MSFC to Raytheon to assess the magnetron for the SPS application [37]. The study also included the conceptual design of a magnetron directional amplifier for the SPS. As part of the study we were able to demonstrate simple control loops that could hold the amplitude of the magnetron directional amplifier to a reference value, and the phase of the output power to that of the driving signal.

Although all of these discoveries and design of control loops were made in the context of the SPS they have broader application, and in fact have become the basis of the design of ground-based transmitters to be used for non-SPS applications.

The DOE/NASA SPS program ended in 1980 with the conclusion that no "show stoppers" of any nature that would preclude a program of research and development to protect this future energy option had been found. But, unfortunately, a program of follow-on research and development, from which support for microwave power transmission technology would have been derived, did not materialize.

In retrospect, the major impact of the SPS program upon microwave power transmission technology was to redirect the design of the transmitter away from the use of a super power tube which, historically, had initiated interest in the development of free-space microwave power transmission, to the active phased array made from a large number of identical and easily fabricated modules using low-power microwave generators derived from the magnetron. For ground-based arrays, the readily available and low-cost microwave oven magnetron that had been used for the magnetron evaluation assessment in the SPS study could be used directly.

E. *Current Orientation of Microwave Power Transmission and its Application*

In the absence of an SPS program it was necessary to look elsewhere for support for microwave power transmis-

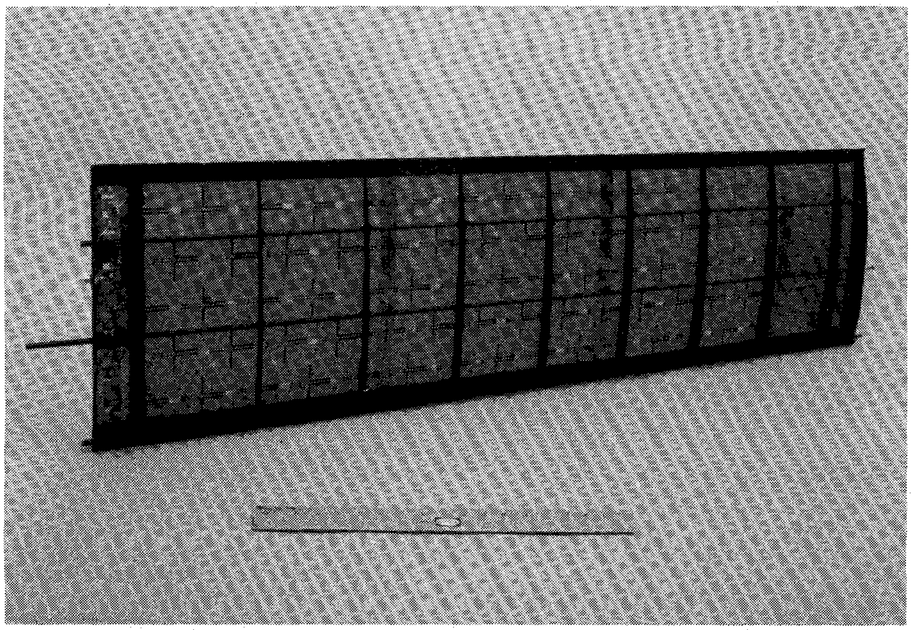

Fig. 11. In 1983, a thin-film etched-circuit rectenna was attached to a 4-ft-long experimental airplane wing. The wing was illuminated with microwave power and the dc output fed without processing to an electric motor that turned the propellor.

sion technology. This support came from a revived interest in microwave-powered high-altitude atmospheric platforms, this time within NASA rather than from the Department of Defense. In 1976, Thomas Rogers, Dr. Peter Goldmark, and Willis Hawkins, all members of the Space Program Advisory Council or its subcommittees advocated a study of microwave powered aircraft as practical communication and surveillance platforms. This advocacy, added to NASA internal interest, resulted in several studies to assess nonmilitary application areas [38].

More directly related to advancing microwave power transmission technology were two study programs from Wallops Flight Facility, devoted to a microwave-powered aerostat or balloon. The first study, devoted to the rectenna carried aboard the balloon, determined the need for a different physical format of the rectenna for aerospace applications and was directly responsible for the start of the thin-film etched-circuit rectenna development [39]. This new format, now supported by discretionary funds from Lewis Research Center, has reached an advanced state of development and is ready for applications. The new rectenna attached to the wing of a small airplane is shown in Fig. 11. The new format has high overall efficiency (85 percent), a high ratio of power handling capability to mass (1 kW/kg), an inherently low cost of manufacture, and is easily stored in a rolled-up form [40]. It is applicable to vehicles in space and to vehicles in the Earth's atmosphere.

The second study from Wallops supported the conceptual design of a ground-based phased array [41]. The design was based upon the use of a large number of low-cost identical modules consisting of a microwave oven magnetron, a ferrite circulator, and control circuitry that locked the output phase of the amplifier to that of the drive signal while still permitting high gain of the order of 30 dB. The beam formed by this large antenna array is kept pointed at the target rectenna on an airplane, balloon, or space vehicle by a control loop that uses a microwave beacon signal located at the center of the rectenna. Using the phase front of the received beacon signal, two interferometers at the transmitter determine the elevation of the target about x and y axes and convert this information to two digitized signals that control the phase of each transmitting module through a row and column matrix, so that the beam is kept pointed at the target. The same matrix can be used to change the focus to a first approximation and to correct for mechanical expansion of the array.

It is interesting to note the convergence of microwave power transmission technology and aircraft technology for high-altitude platforms flying at a level from 50000 to 80000 ft. NASA's Langley and Dryden Research Centers are examining airplane designs for this application [42] and Wallops is examining airships. The type of airplane design that Dr. Paul MacCready used for his solar-powered airplane that flew from Paris to England is a forerunner of such vehicles. Airships are also a distinct possibility.

Currently, there is a considerable amount of thought being given to transmission of power to space by microwaves for such applications as an electric-powered ion engine-propelled interorbital transfer vehicle from low-Earth orbit to geosynchronous orbit, or even to the transfer of power to satellites permanently in low-Earth equatorial-plane orbit [43]. The problems associated with obtaining very large amounts of continuous power measured in hundreds of kilowatts or several megawatts in space by solar photovoltaic arrays or nuclear power are severe and microwave power transmission represents a new option that may be investigated.

IV. Summary

Setting aside the early attempts to transmit power by radio waves, what has been the characterization of the modern or microwave history and what is the present stage of development? The most obvious characteristic of the history has been the many changes in orientation and sponsorship. Although often painful, these changes have brought new perspective and have probably been beneficial. With respect to the development status, the technology has now reached a high level of maturity and represents an available and possibly invaluable resource for immediate or future use.

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