THE HISTORY OF THE DEVELOPMENT OF THE RECTENNA

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ABSTRACT

The history of the development of the rectenna is first reviewed through its early conceptual and developmental phases in which the Air Force and Raytheon Company were primarily involved. The intermediate period of development which involved NASA, Jet Propulsion Laboratory, and Raytheon is then reviewed. Some selective aspects of the current SPS rectenna development are examined.

Introduction

The chairman of this session believes that the perspective given by a history of the development of the rectenna would be of value to those now becoming involved with the application and further development of the rectenna for the SPS. He has asked me to present this history because he is aware that I have been closely and continuously involved with the development of the rectenna since its inception in 1963.

The concept and development of the rectenna arose in response to the need for a device that could be attached to a high altitude atmospheric platform and absorb and rectify microwave power from a microwave beam pointed at the vehicle. After the initial development of the rectenna under Raytheon and Air Force sponsorship for this purpose the rectenna development was carried on further and in a different direction by the author himself. In 1968, NASA became interested in the rectenna and its development in the context of transferring power from one space vehicle to another. This was followed by NASA's interest in the device for the receiving end of a system that would transfer electrical power from geosynchronous orbit to the earth.

Throughout this time period of 17 years, the development of the rectenna has been heavily disciplined by the various applications for which it has been considered. The result has been the accumulation of a large amount of experience which covers many facets of interest, including electrical design and performance, various physical formats, methods for accurate efficiency measurement and validation, life test data, and other items. Its development has also been characterized by contributions from many individuals whose involvement has been in two different areas. The first area is related to technical contributions. The second area is related to sponsorship. The development of the rectenna could not have proceeded very far without the encouragement and support of individuals within and outside the government who have understood the significance of free space power transmission by microwaves and the relevance of the rectenna development to this concept.

In presenting this history the author is treating the early conceptual and developmental phase as an interaction between many technological forces and developments, and people, which is the true nature of history. The history of the intermediate period is identified with the work supported by MSFC, JPL, LeRC and that was largely carried out by Raytheon. It is presented in a more summarized fashion with the presentation focused on technological improvements and refinements. A final section is devoted to what might be considered as technological forecasting which is a projection of the past history combined with the subjective view of the author as to the impact of current and future technological and sociological events.

Early History of the Rectenna

The early development of the rectenna must be examined in the context that its conception and development grew out of the needs for a satisfactory receiving terminal for a microwave power transmission system. In this context we must take into account the factors which gave rise to an interest in the concept of microwave power transmission itself.

The first serious thought about power transmission by microwaves grew out of the development of microwaves for radar in which power was concentrated in relatively narrow beams as contrasted to the "broadcast" mode associated with low frequency radio. However, the element that really gave substance to the concept and distinguished it from the situation that existed when Hertz first demonstrated wireless power transmission with narrow beams using parabolic reflectors and spark gap generators, were newly developed electron tubes that could generate relatively large amounts of power at high efficiencies.

Still, there was no active postwar activity on microwave power transmission until it became recognized that with new approaches microwave generators could be developed to produce levels of CW microwave power about 100 times greater than from generators then available.[1,2,3] Concurrent with this recognition was the inference that one of the potential useful applications of microwave power transmission would be microwave powered high altitude atmospheric platforms for communication and surveillance purposes.

This recognition stimulated Raytheon, under the guidance of Ivan Getting, Vice President for Engineering, to perform an in-depth study of such a platform in a helicopter format and to make a proposal to the Department of Defense in 1959 to develop such a vehicle.[4] The reason why this is important in the development of the rectenna is that for the first time it became widely recognized that there was no efficient means of converting the microwave back into DC or low frequency electrical power at the receiving end of the system. This stimulated the Air Force to award several contracts to study this problem. One of these investigations that was to become a key element in the development of the rectenna was awarded to Purdue University and involved the use of semiconductor diodes as power rectifiers.[5]

While this development at Purdue was proceeding, the development of super power microwave tubes had been started at Raytheon under the sponsorship of the Department of Defense and had achieved CW power outputs of over 400 kW at an efficiency exceeding 70% at a frequency of 3.0 GHz. Recognizing the potential application to free space power transmission the author had persuaded Raytheon Company to support the development of a close-spaced thermionic diode as a rectifier and the demonstration of a complete microwave power transmission system.[6] Such a demonstration using the close-spaced thermionic diode and the physical arrangement of Figure 1 was successfully made in May 1963 with a power output of 100 watts which was used to drive a DC motor.[7] Among those witnessing the demonstration was John Burgess, Chief Scientist at the Rome Air Development Center, who saw the potential of a microwave powered atmospheric platform for line of sight communication over long distances.

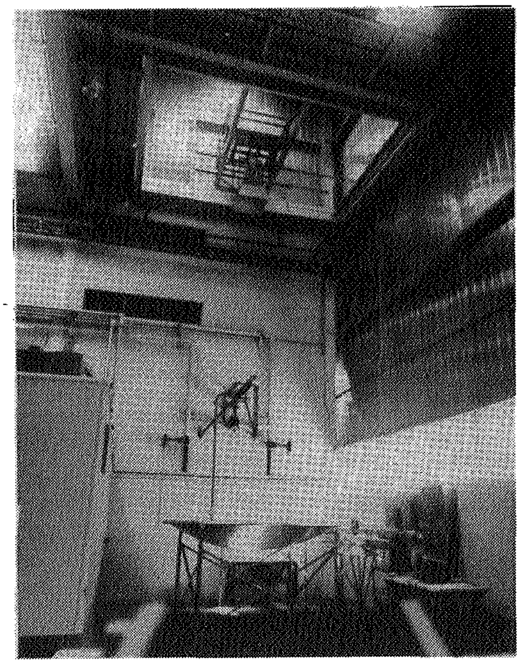

Figure 1. First experiment in the efficient transfer of power by means of microwaves at the Spencer Laboratory of Raytheon Company in May 1963. In this experiment microwave power generated from a magnetron was transferred 5.48 meters and then converted with DC power with an overall efficiency of 16%. A conventional pyramidal horn was used to collect the energy at the receiving end and a close-spaced thermionic diode was used to convert the microwaves into DC power of 100 watts. The collection and rectification arrangement was directive and not very efficient.

To encourage the chief scientist's interest the author privately constructed a small helicopter whose rotor was driven by a conventional electric drill motor supplied with power by a cable and demonstrated that it could carry aloft one of the closely spaced thermionic diodes. This demonstration was a major factor in motivating the chief scientist to set aside discretionary funds for the development and demonstration of a small microwave powered platform. These funds became available in July of 1964, a year later.

Meanwhile it had become evident that the receiving arrangement used in Figure 1 had serious flaws for use in a microwave powered platform. The horn as a collecting element was much too directive for the expected roll and pitch of a vehicle and its collection efficiency was also poor. The close-spaced thermionic diode rectifier also proved to be a very short lived device. It was at this point that the author met by chance a college friend, Thomas Jones, in the Boston airport. Jones had become the head of the Electrical Engineering Department at Purdue University and told the author about the work going on there on the use of semiconductor diodes as microwave power rectifiers. The author immediately made a trip to Purdue and met Roscoe George, who had been carrying out most of the research activity. Professor George has been using dense arrays of closely spaced diodes within an expanded waveguide and had achieved as much as 40 watts of DC power output from microwaves in the 2 to 3 GHz range of frequency with respectable efficiencies.[8] 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. In the absense of any other successfully developed microwave power rectifier the author was obviously 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 low collection efficiency and directivity of the receiving horn itself.

It was from this dilemma that the concept of the rectenna arose. 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. Once conceived[9] the development of the rectenna, driven by its need for the proposed microwave powered helicopter, proceeded rapidly. Professor George was employed as a consultant to proceed with this approach and to make measurements on the characteristics of such a device.

With the arrangement of 28 rectenna elements shown in part in Figure 2 a power of 4 watts of DC power at an estimated collection and rectification efficiency of 50% and a power of 7 watts at an estimated efficiency of 40% were achieved.[10] Of primary importance was the highly non-directive nature of the aperture (Figure 3) 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 that distinguishes it from the phased array antenna is of the greatest practical importance.

Although this achievement may be considered as the first major milestone in rectenna development 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 George suggested vertical strings of diodes separated by approximately a half wavelength, but the power density was still much too low. 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. The author solved this problem by placing a matching network in front of it consisting of a plane array of rods spaced at an appropriate distance from the plane of the diode array. The final helicopter rectenna is shown in Figure 4. It was comprised of 4480 IN82G diodes, and had a maximum power output of 270 watts which was more than enough to power the helicopter rotor. The weight of the array was about three pounds or about 11 pounds per kilowatt of DC output.[11,12]

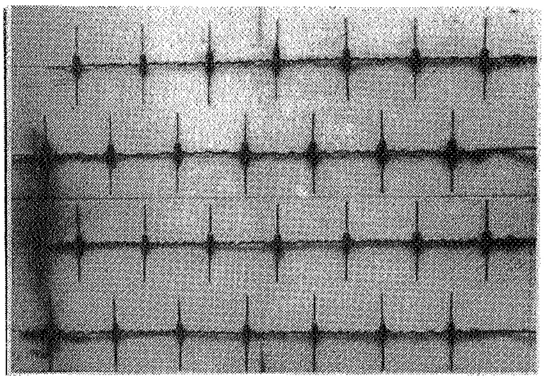

Figure 2. The first rectenna. Conceived at Raytheon Company in 1963, it was built and tested by R. George of Purdue University. Composed of 28 half-wave dipoles spaced one-half wave-length apart, each dipole terminated in a bridge-type rectifier made from four IN82G point-contact semi-conductor diodes. A reflecting surface consisting of a sheet of aluminum was placed one-quarter wavelength behind the array.

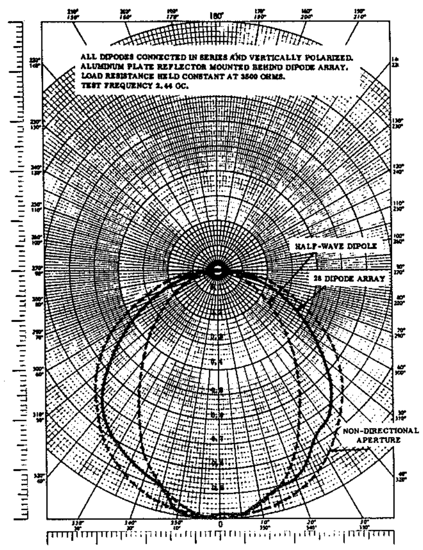

Figure 3. Directivity of the Half-Wave Dipole Array Shown in Figure 2. Directivity was essentially the same about both axes of rotation. Array has slightly less directivity than single half-wave dipole.

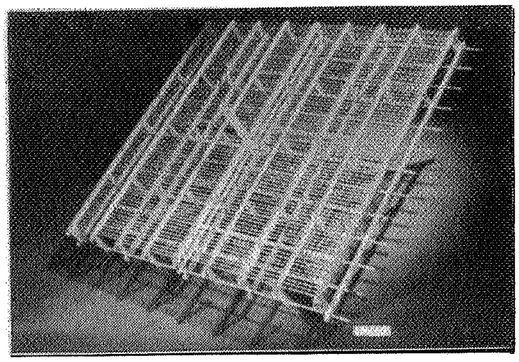

Figure 4. The special rectenna made for the first microwave-powered helicopter. The array is 0.6 meters square and contains 4480 IN82G point-contact rectifier diodes. Maximum DC power output was 270 watts.

A microwave power helicopter flight with this string type rectenna was made on July 1, 1964 prior to the start of work effort on an Air Force contract, to demonstrate continuous flight for ten hours. The Air Force contract was the basis for needed refinements and several notable demonstrations, including the specified ten hour continuous flight of the vehicle.[11,12] Figure 5 shows the helicopter in flight. It was necessary, of course, to use laterally constraining tethers to keep the helicopter on the microwave beam but this limitation was later removed by a study and experimental confirmation that the microwave beam could be used successfully as a position reference in a control system in an automated helicopter which would keep itself positioned over the center of the beam.[12]

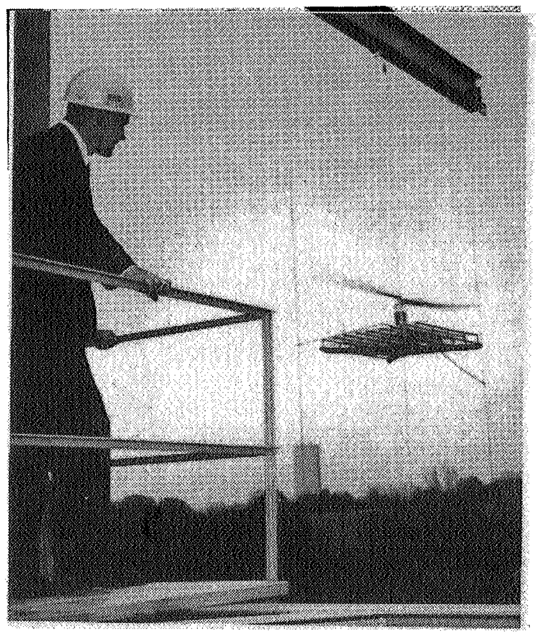

Figure 5. Microwave powered helicopter in flight 18.28 meters above a transmitting antenna. The receiving array for collecting the microwave power and converting it to DC power was made up of several thousand point contact silicon diodes. DC power level was approximately 200 watts. The date of the demonstration was October 1964.

The development of the string type rectenna (Figure 6) is of more than historical significance because it represents an approach in which large numbers of rectifying diodes can be spread over a surface to accommodate a high power density influx of microwave radiation or to operate in the vacuum of space where it may be desired to decrease to a minimum the mass required to transport heat from the diode sources to the heat sinks, in all probability passive radiators. The current status of microwave diodes (1979 technology) is such as to minimize the need for the "string-type" or equivalent arrays. Most applications currently envisaged do not call for incident microwave radiation of a density level beyond what the half wave dipole array with the greatly improved diodes can handle.

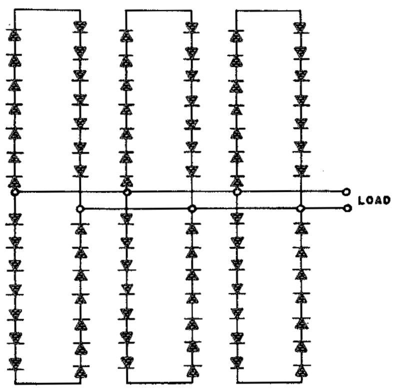

Figure 6. Schematic Drawing Showing Arrangement of Dipoles and Interconnections within a Diode Module used in Helicopter rectenna.

As the first airborne vehicle to stay aloft from power derived from any kind of an electromagnetic beam, it excited considerable interest. A demonstration to the mass media in October 1964 resulted in considerable exposure both in the press and on TV. Probably as a result of this, the author received a letter from a representative of Hewlett Packard Associates enclosing some newly developed 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 of a great deal of potential interest.

Unfortunately, the Air Force elected not to further develop the microwave powered platform. It did, however, support the successful development and demonstration of a helicopter which would automatically position itself over the center of a microwave beam.[12]

In the time period from 1965 until 1970 there was no direct support of rectenna development from either government or industry. However, a substantial amount of development work on the rectenna was carried out by the author using personal funds and time during the 1967 to 1968 time period. This work was primarily aimed at incorporating the improved Schottky-barrier diodes into a very light weight rectenna structure that reverted back to the format of half wave dipoles terminated in a full-bridge rectifier. The resulting array is shown in Figure 7. The array, with a mass of only 20 grams, produced 20 watts of power output for an improvement in the power to mass ratio of a rectenna by a factor of five. However, the rectenna of Figure 7 was also important in that it was used to make a demonstration of microwave power transmission that may have been an important factor in the decision by MSFC to continue with the development of microwave power transmission and the rectenna.

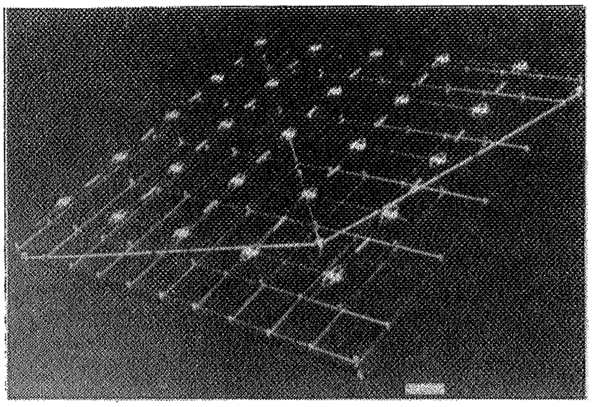

Figure 7. Greatly improved rectenna made in 1968 from improved diodes (HP2900) which became commercially available in 1965. The 0.3 meter square structure weighed 20 grams and delivered 20 watts of DC output power.

Development Under MSFC Sponsorship

The interest in the rectenna at MSFC is believed to have grown out of an interest of Associate Director Ernest Stuhlinger in 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 identified the work that had been done on microwave power transmission at Raytheon. At his and Dr. Stuhlinger's suggestion a demonstration was given to Dr. Werner von Braun and his entire staff. In the kind of demonstration that would probably not be permissible today the author set up a three foot parabolic reflector at one end of the long table as the source of a microwave beam of about 100 watts. At the other end of the table the author held the rectenna of Figure 7 now attached to a small motor with a small propellor on it. The microwave beam was used to supply power to the motor and the author would interpose his body between the source and the rectenna to demonstrate that the power was coming from the microwave beam.

Interest within MSFC resulted in setting up a small in-house facility for laboratory effort under W.J. Robinson and a contract with Raytheon for a system study in 1969. Initially the system study did not involve any supportive technology development. It soon became evident, however, that a barrier to any further interest at MSFC in microwave power transmission lay in demonstrating a minimal overall system efficiency. The contract was hastily amended to permit Raytheon to construct the hardware for an overall efficiency measurement to be made at MSFC.

The system, shown in Figure 8, was hastily put together and demonstrated at MSFC in September 1970. The specified minimal overall efficiency of 19% was achieved with a measured efficiency of 26%.[13] This demonstration focused interest upon further increasing the efficiency of the rectenna and of the overall system. Over the next four years there was a succession of improvements in overall system efficiency, primarily because of improvements in both the collection and rectification efficiency of the rectenna.[15] The focus in this time period was upon the development of the technology rather than upon an application. However, it is believed that the emergence of the solar power satellite concept in the 1968 to 1974 time frame and its need for high efficiency exerted considerable influence upon the drive for better efficiency from all parts of the microwave power transmission system.

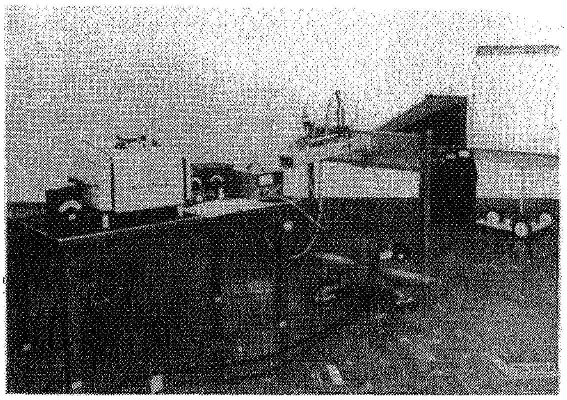

Figure 8. Test set-up of microwave power transmission system at Marshall Space Flight Center in September 1970. The magnetron which converts DC power at 2450 MHz is mounted on the waveguide input to the pyramidal horn transmitting antenna. The rectenna in the background intercepts most of the transmitted power and converts it to DC power. Ratio of DC power out of rectenna to the rf power into the horn was 40.8%. Overall DC-to-DC efficiency was 26.5%.

The MSFC demonstration of September 1970 indicated a number of deficiencies in the system including a rectenna collection efficiency of only 74% versus the theoretical maximum of 100%. This low collection efficiency was associated with improper spacing of the rectenna elements from each other in the rectenna array. The elements were therefore spaced more closely to each other in a hexagonal format, (Figure 9) and, in addition, the DC output of each rectenna element was terminated in a separate resistor to obtain a much greater range of data on the behavior of the rectenna. With the changed geometry the collection efficiency was increased to about 93%.

The decision to terminate each rectenna element in a separate resistor involved a change in the manner in which the DC power was collected and instrumented. The output of each rectenna element was brought back through the reflector plane where it could be directly monitored with DC meters. This arrangement provided such an enhanced capability to study and understand the performance of the rectenna that it was retained in the further development of it. (See Figure 10 for an adaptation to a later MSFC rectenna.) The construction however is not economical and is not recommended for most applications.

It was during this period that an arrangement to separate the measurement of the collection efficiency from the rectification efficiency of the rectenna was developed. The individual rectenna element was placed at the end of a section of waveguide that was expanded into a small horn with an aperture of about 100 square centimeters. A metallic reflecting plane was placed behind the rectenna element and this plane also was used to seal the end of the waveguide so that no microwave power could leave the closed system. This made it possible to accurately measure the DC output power and the microwave power absorbed by the element and thus to accurately measure an efficiency, defined here as the rectification efficiency. Such an efficiency, of course, includes any circuit losses in the rectenna element itself. The test fixture environment in which the rectenna element was placed simulated to a first approximation the environment of the surrounding rectenna into which the rectenna element would eventually be placed. This test arrangement was a key factor in reducing costs for the development of the rectenna.

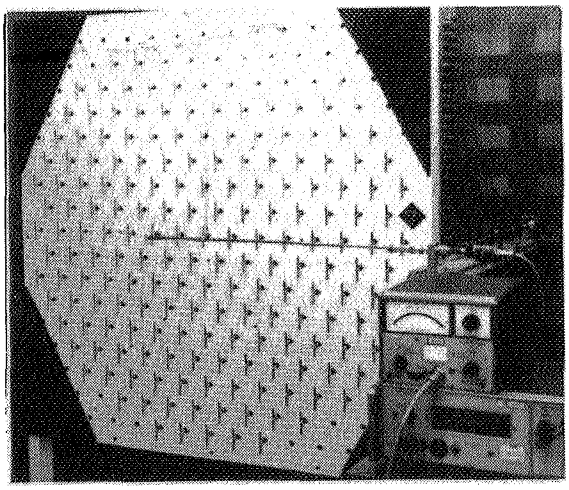

Figure 9. Close up view of rectenna used in measurements of overall system (DC to DC) efficiency. There were 199 elements in a four foot diameter hexagonal array. Rectenna was illuminated with a near gaussian shaped beam with a power density at the center about forty times that at the edges. The probe in front is used to measure the standing wave pattern in space. Probe measurements indicated that after suitable adjustment of DC load resistance and spacing of elements from the reflecting plane a reflection of less than 1% could be obtained, indicating an absorption efficiency approaching 100%. Although overall rectenna efficiency is generally difficult to measure because of edge effects and difficulty of measuring power density in the beam the unique aspects of the test facility made it possible to estimate overall capture and rectification efficiency of 82% for the rectenna within a ±2% error.

The collection efficiency of the rectenna has always been difficult to measure. The termination of a large aperture horn with a large number of rectenna elements, an arrangement which would seem to logically follow the test arrangement for a single element, loses its validity for collection efficiency because many modes are set up within the horn if there is any dissymmetry at all in the rectenna arrangement. Most of the power in these modes gets absorbed in the elements themselves and very little flows back into the throat of the horn and into the waveguide where any measurement of reflected power could be made. The best way to measure collection efficiency is to measure the standing wave pattern directly in front of the center of freely exposed rectenna of sufficient area to minimize diffraction effects from the edge. The measurement is made more valid if the impinging beam has a gaussian distribution, the reflection factor is small and the reflected wave also assumed to be gaussian. These conditions prevail in the arrangement of Figure 11.

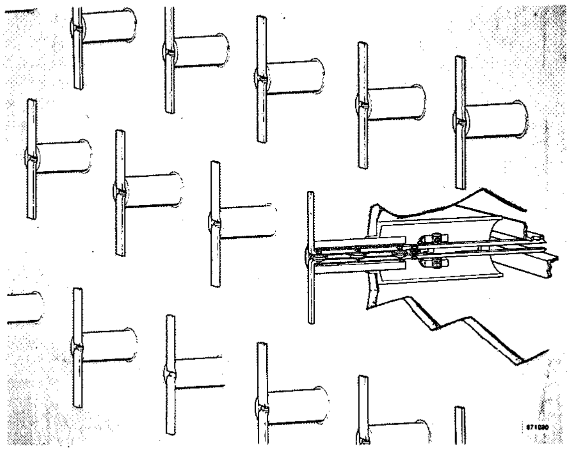

Figure 10. Sketch of the Marshall Space Flight Center rectenna which was constructed in spring of 1974. Cutaway section of rectenna element shows the two section input low pass filter, the diode, and a combination tuning element and by-pass capacitor.

Because the diode rectifier is such an important element in the collection and rectification process, a search for diodes which would improve the efficiency and power handling capability of the rectenna has been a continuing procedure. In 1971, Wes Mathei suggested 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 and provided a number of diodes for testing.[16] These devices were indeed much better. Their revolutionary behavior in terms of higher efficiency and much greater power handling capability rapidly became the basis for the planning of improved rectenna performance.

The knowledge of the superior performance of this device was coincident with the advancement of the concept of the Satellite Solar Power Station by Dr. Glaser of the A.D. Little Co.[17] The earliest investigation of a rectenna design for this concept indicated that the economics of its construction would be crucial and that mechanical and electrical simplicity of the collection and rectification circuitry would be of paramount importance. This factor, combined with the fact that no harmonic filters had existed in previous rectenna element designs but would be necessary in any acceptable microwave power transmission system, motivated a completely new direction of rectenna element development. This new direction was the development of a rectenna element employing a single diode in a half-wave rectifier configuration with wave filters to attenuate the radiation of harmonics and to store energy for the rectification process.

The construction of such a rectenna element and its insertion into a DC bus collection system is shown in Figure 10. This rectenna element was used in the last phase of the MSFC sponsored work at Raytheon to construct a rectenna 1.21 meters in diameter which was illuminated by a gaussian beam horn (Figure 9). The combined collection and rectification efficiency of this rectenna was measured at 82 ± 2%. The overall DC to DC efficiency was measured at 48%.

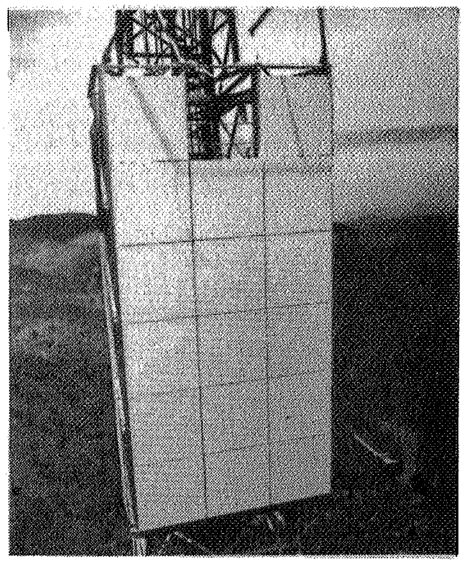

Figure 11. Photo of 24.5 Square Meter Rectenna erected in 1975 at the Venus Site of the Goldstone Facility of the Jet Propulsion Laboratory. Power was transferred by microwave beam over a distance of 1.6 km and converted into over 30 kW of cw power which was dissipated in lamp and resistive load. Of the microwave power impinging upon the rectenna, over 82% was converted into DC power. The rectenna consisted of 17 subarrays, each of which was instrumented separately for efficiency and power output measurements. Each rectenna housed 270 rectenna elements, each consisting of a half-wave dipole, an input filter section, and a Schottky-barrier diode rectifier and rectification circuit. The DC outputs of the rectenna elements were combined in a series-parallel arrangement that produced up to 200 volts across the output load. Each subarray was protected by means of a self-resetting crowbar in the event of excessive incident power or load malfunction. Each diode was self-fused to clear it from short-circuiting the array in the event of a diode failure.

Development Under JPL Sponsorship

By 1973 the solar power satellite concept (then the SSPS) had become an important enough consideration to interest the Office of Applications within NASA to support the development of the microwave power transmission portion of the system. Although it would have been logical to continue the effort at MSFC because of their initial involvement, MSFC indicated that the subject matter was outside of their main interests and that they did not wish to pursue its development further. As a result both JPL and LeRC became involved in efforts that involved the demonstration and further development of the rectenna, and the rectenna became increasingly identified with the SPS.

The JPL activity was involved with the demonstration of the transfer of power over a distance of one mile and at a DC power level of 30 kilowatts, nearly two orders of magnitude greater than had been accomplished in the laboratory. (Figure 11)[18,19] This work effort was carried out in the 1974 to 1975 time period and has undoubtedly been the most important contribution to the establishment of confidence within the NASA and aerospace community in the feasibility of microwave power transmission. Although the emphasis was upon demonstration rather than technology development it did provide some opportunity for additional development, those aspects involving the interface with the useful load on the output side of the array, life test data and improvement and certification of overall efficiency. An unfortunate aspect of the demonstration was that for risk minimizing purposes the uneconomic three level construction of dipoles, reflecting plane, DC power and bussing was retained. However, later work with LeRC featured the development and testing of the economic two level construction.

From the rectenna development point of view the JPL activity included the following accomplishments:

- Demonstrated the parallel-series connection of the DC output power from parallel rows of rectenna elements.
- Developed plated-heat-sink GaAs Schottky-barrier diodes with carefully controlled thickness of epitaxial layer to maximize efficiency.
- Demonstrated "fail-safe" nature of the diodes. If a diode should short out the adjacent parallel connected diodes force enough current through the package of the shorted diode to burn out a one mil diameter wire which acts as a fuse in the package.
- Demonstrated the value of crowbars in protecting diodes from load faults and from excessive incident microwave power but also the desirability of complementing them with capacitors placed across the output terminals of the diode array to absorb short duration spikes of output power from any cause.
- A mechanical design of the rectenna element itself that was much improved over the element developed under MSFC sponsorship.
- The initiating of life test on 199 rectenna elements and diodes arranged in groups that were exposed to different values of incident microwave power.
- Improved the setup in Raytheon's laboratory to demonstrate high overall (DC to DC) system efficiency and then provided certification of the data upon which the calculation of an overall efficiency of 54% was based.[20] The rectenna that was used in this experiment is shown in Figure 9. The overall collection and rectification efficiency of the rectenna was found to be 82 ±2% in this experiment.

Development Under LeRC Sponsorship

Lewis Research Center carried out two activities for the Office of Applications having to do with the rectenna. One, carried out in 1974 and 1975 was a broad study of the entire microwave power transmission system for the SPS. Various approaches to the collection and rectification problem were investigated. Investigation included an examination of all rectifier approaches and all receiving antenna approaches. The rectenna approach was found to be unique in the solution of this problem.[21]

The other LeRC activity dealt exclusively with the improvement of the rectenna[22] and made important contributions as follows:

Improvements in Efficiency

Improvements in rectenna element efficiencies to values slightly in excess of 90% were achieved. These efficiencies were with DC outputs in excess of 4 watts, which is above that currently planned for the SPS. However, notable improvements were made in efficiency at low power densities with improved diodes and higher impedance rectenna elements. The results are shown in Figure 12. Further, directions in which to obtain higher efficiency, particularly at the lower power levels, were discovered.

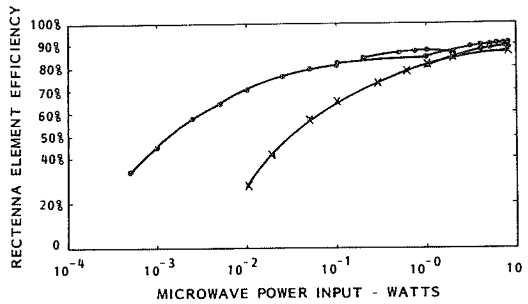

Figure 12. A summary of the efficiencies achieved with new diode in various new rectenna configurations as a function of power level, compared with performance of a standard element used in the JPL Goldstone rectenna and shown as the lower curve.

Improvement in Confidence in Collection and Rectification Efficiency Measurements

A considerable improvement in the confidence of efficiency measurements on the rectenna element was established by equating the microwave power absorbed by the rectenna element to the sum of the DC power output, the losses measured in the diode, and the circuit losses as measured experimentally and by computer simulation. The losses in the diode were measured by a unique substitution method developed at Raytheon and explained in reference 22. The balancing of microwave power input and total power output, as shown in Figure 13, is a good check on the measurement of microwave power input which is traceable to a 100 milliwatt microwave standard at the Bureau of Standards through a secondary standard sent there for calibration, and a calibrated 20 dB directional coupler with which the secondary standard is applied to the test set for the rectenna element.

Mathematical Modeling and Computer Simulation

The mathematical modeling of the rectenna element and simulating its performance on a computer was successfully carried out. Although other computer modeling had been successfully carried out,[22] this was the first time that the computer program modeling was for the same rectenna element on which accurate experimental measurements of circuit and diode losses had been made.

The computer simulation generally gave results that confirmed the experimental results, as may be seen from an examination of Figure 13, but upon occasion indicated differences which have led to investigations to resolve the differences. For example, the diode losses were first computed on the basis of the theoretical design of the diode and found to be less than those measured. It was found that the forward voltage drop as measured by DC voltage measurements was greater than that predicted from theory leading to the conclusion that the ohmic contact is not purely ohmic but retains some Schottky barrier characteristics which contribute to the voltage drop.

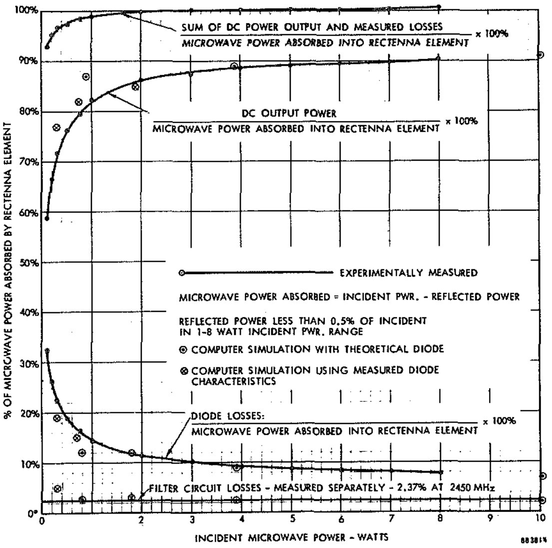

Figure 13. The DC power output, losses in the microwave diode, and losses in the input filter circuit are shown as a percentage of the microwave power absorbed by the rectenna element as a function of incident microwave power level. The sum of all of these is then compared with the absorbed microwave power. Comparison with computer simulation computations is also shown.

A typical set of diode losses as obtained from the computer simulation may be of interest. Total losses were 13.03% of the input power of which 2.08% was skin loss, 2.52% loss in the diode series resistance in the forward conduction period, 1.23% loss in the non-conducting portion of the cycle, and 7.22% loss in the Schottky junction itself. The total losses observed experimentally were 12.8%, an agreement that is probably better than can be justified.

Development of Improved Diodes

The power loss represented by the voltage drop in the Schottky barrier is an important loss in the diode, and it is the major one when the operating power level is low, even when the impedance level of the circuit is raised to minimize these losses. GaAs Schottky barrier diodes commonly use platinum as a barrier metal because it behaves better than other materials for use of the diode as an Impatt device. Tungsten has a lower work function that platinum and would be preferable in a rectenna element. Such diodes were developed and indeed found to have lower loss and to be more suitable for rectenna element application.

Suppression of Harmonic Energy

A means of reducing harmonic energy radiated from the dipole antenna was investigated. A shorted line ¼ wavelength long placed across the terminals of the dipole appears as an open circuit to the fundamental but as a short circuit to the second harmonic. The power in the second harmonic is therefore reflected back into the rectenna element. It was found that this technique will reduce the second harmonic level by as much as 25 dB but the impact of the harmonic reflection upon the overall efficiency needs more evaluation. The technique can be incorporated with no additional cost into the rectenna element in the two-plane format. The third harmonic may be treated in a similar fashion but it is necessary to complicate the physical format of the rectenna element to incorporate it.[22]

Development of a Rectenna Design that is Both Environmentally Sound and is Suited to Low Cost High Speed Production

The development of basic technology for the rectenna for the full scale SPS is well advanced, but the adaptation of this basic technology to a rectenna that is environmentally sound and that can be made at low cost in large volume production was recognized as an area of special study. Effort on this part of the program resulted in the outline of a mechanical design based upon the two-plane rectenna system in which all of the important elements of the rectenna, including the bussing of DC power, are carried out in the foreplane. This foreplane is shown schematically in Figure 14. In effect this design reverts back to some of the earliest rectennas but with greatly improved components and better understanding. A mechanical design of the entire rectenna coupled with the fabrication and electrical testing of a portion of the foreplane was carried out. The overall mechanical design is shown in Figure 15 while the electrically operative foreplane portion is shown in Figure 16.

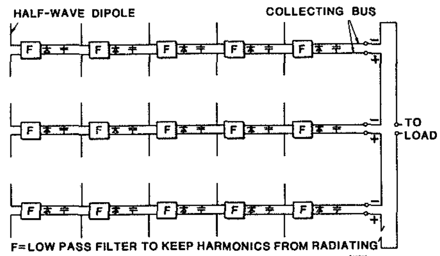

Figure 14. Interconnection arrangement of half-wave dipoles, wave filters, rectifier circuits, and collecting buses in the foreplane of a two-plane rectenna system.

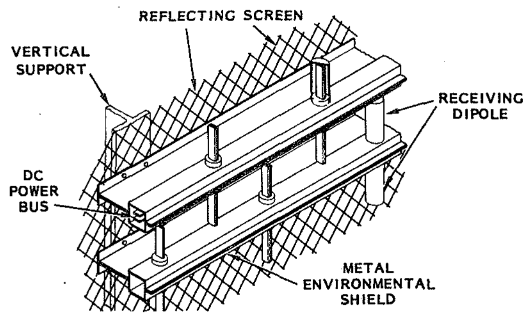

Figure 15. Proposed design of Rectenna motivated by environmental protection and cost considerations. In this design the environmental shield becomes an important load-bearing member of the structural design.

The foreplane shown in Figure 16 was thoroughly evaluated for performance. A special arrangement made it possible to test each of the five foreplane elements in the single rectenna element test fixture while all five remained within the foreplane assembly. The average efficiency of the elements was 88%. To determine its compatibility within a large array of elements the foreplane of Figure 16 was inserted into the 199 element array shown in Figure 17. A careful check was made on any effect it might have had on the performance of the rectenna as a whole, by means of reflection measurements of the kind shown in Figure 9 and by comparison of the power obtained from the five element array with the sum of the power from the five standard rectenna elements it replaced. From the almost imperceptible impact that was noted, it was concluded that the rectenna design depicted in Figures 15 and 16 is electrically satisfactory.

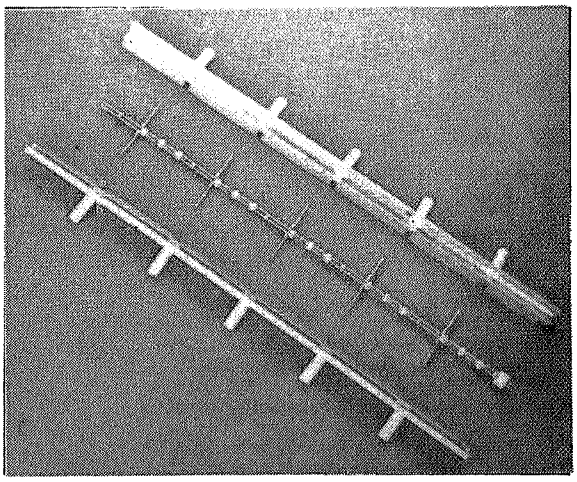

Figure 16. Basic core structure design of the foreplane illustrating the joining of individual rectenna elements to each other to form a linear, easily-fabricated structure performing the functions of DC power bussing and microwave collection and rectification.

Assessment of Life of Rectenna Element

Figure 18 provides a summation of the life test data taken up to a total of slightly over 800,000 diode hours. It is noted that there were no failure of diodes in rectenna elements operated at DC power levels below 6 watts. Even those failing at higher power levels may have been associated with infant or operator-induced failures. There was only one unequivocal self-induced life failure of a diode and that occurred in the group operating at 6 to 8 watts of DC power output.

All of the diodes that were used were the plated-heat-sink GaAs Schottky barrier diodes that were made as part of the effort under the JPL supervised program at Raytheon. The life test was made possible because of the availability of the complete microwave power transmission system and the 199 element rectenna shown in Figure 9. With this arrangement there is a distribution of power density over the rectenna by a factor of about 40.

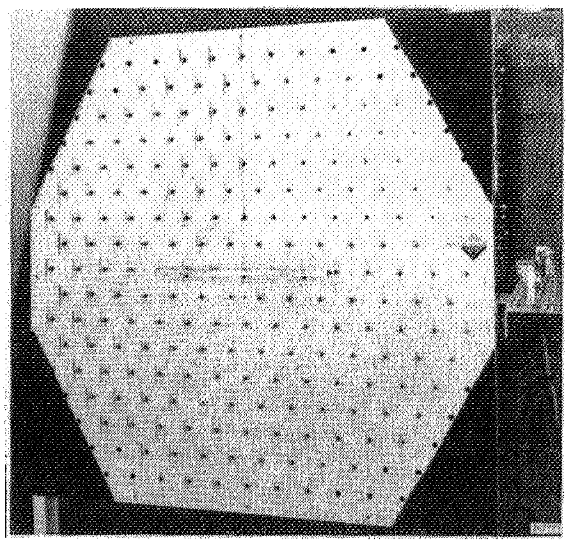

Figure 17. The test set-up for checking the foreplane type of rectenna array. The five element foreplane structure is placed at the center of the larger rectenna array as shown. The DC output is dissipated in a resistive load. The collected power from the foreplane can then be compared with the power that would have been collected from the five elements that it replaced. Reflected power measurements were also made with the probe arrangement shown in Figure 9.

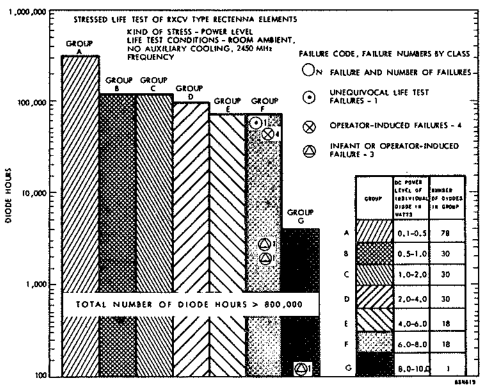

Figure 18. Diode Life Test Results Using Rectenna shown in Figure 9. Rectenna contains 199 rectenna elements which are subjected to a wide range of incident power.

Recent Developments and Future Trends

The SPS rectenna design approach of Figure 15 was structurally analyzed in considerable detail by the author.[23] Material requirements and costs were estimated. To save on material, which is the chief element of cost, airframe design practices should be used, and extensive scaled wind tests should be performed in the early design stages to forestall excessive design safety factors for wind loading.

A set of studies leading to additional understanding of the rectenna have been sponsored by Johnson Space Center, with R.J. Gutmann of RPI being the principal investigator for a number of these.[24]

The most recent trend in rectenna development is the thin-film printed-circuit rectenna for high altitude atmospheric platform and space use. It is not believed to be suitable for the SPS rectenna because of its fragility and higher cost per unit area than the rigid construction of Figure 15. Its application to the high altitude platform, however, may lead to a better general understanding and acceptance of microwave power transmission in the SPS.

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