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FREE-SPACE MICROWAVE POWER TRANSMISSION - STUDY

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MICROWAVE TUBE OPERATION
WALTHAM, MASS. 02154



RAYTHEON COMPANY
Microwave and Power Tube Division
Waltham, Massachusetts

FINAL REPORT*

CONTRACT NO: NAS-8-25374

A MICROWAVE BEAM POWER TRANSFER AND GUIDANCE SYSTEM
FOR USE IN AN ORBITAL ASTRONOMY SUPPORT FACILITY

December 10, 1969 to December 10, 1970

Prepared for
Marshall Space Flight Center
Huntsville, Alabama

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* Final report for contract originally dated December 9, 1969 and amended June 11, 1970.

ABSTRACT

A microwave beam is studied as a means of transferring power between satellites. Emphasis of the study is upon the basic elements of microwave power generation, transmission, and capture and rectification. Experimental work included an accurate measurement of overall dc to dc efficiency of 27% in a laboratory system, and a beam-riding vehicle capable of simultaneously receiving power and automatically positioning itself for maximum power transfer.

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1.0 INTRODUCTION AND STUDY SUMMARY

1.1 Microwave Power Transmission as a Means of Transferring Energy in Space

A space environment poses a number of interesting problems in transferring energy from one point to another. It is difficult to transfer energy in the form of electrical power because of the difficulty or impossibility of running wires. Transferring energy in the form of chemicals is difficult because of the expense involved in transporting energy sources having a low ratio of energy to mass. Energy in the form of a nuclear fuel becomes attractive because of its high energy to mass ratio but it has certain efficiency and radiation problems which limit its usefulness.

Microwave transmission as a means of transferring energy has the unique features of:

1. No mass either in the form of wire conductors or ferrying vehicles is required between the source of energy and the point of consumption.
2. Energy can be transferred at the velocity of light.
3. The direction of energy transfer can be rapidly changed by repointing the transmitting antenna.
4. There is no loss of energy in the transfer of energy through the vacuum of space. Further, over a relative broad frequency range there is little loss of energy in the transfer of energy from space to the Earth's surface.
5. The mass of the transducers between ordinary electrical power and microwave power at the transmitting and receiving points can be small.

In addition to these unique features, microwave power transmission can be a very efficient means of energy transfer over very long distances.

Many of these features can combine to be of great value in a number of energy transfer problems and opportunities in space and it may be of interest to discuss some of them.

The original interest at Marshall Space Flight Center in a microwave power transmission system was in connection with an astronomical observatory in which power was to be transmitted from a central manned station to a co-orbiting daughter satellite.¹ The daughter satellite was to be an observatory requiring independence and physical separation from the manned space station.^{2,3} It was anticipated that the orbiting space station would be in low orbit so that a considerable drag on the daughter satellite would result. To overcome this drag a propulsive force requiring the expenditure of propellant mass would be necessary. The higher specific impulse of electrical propulsion would reduce the weight of the propellant required as well as minimize the amount of propellant which would surround the daughter satellite and possibly interfere with astronomical observations. Electrical propulsion, however, would require large amounts of electrical energy so that a large solar cell array would be required. Such a large solar cell array would further increase the drag and to some degree would be self-defeating. An alternative to the solar cell array, an umbilical cord, also appeared to have some undesirable characteristics. The chief problem with the umbilical cord was considered to be interference with the highly refined position stabilization system in the observatory. Further, in a base station of growing complexity, a large number of umbilical cords coincident with a large number of daughter satellites could provide problems with respect to docking from space shuttles and even docking of the satellites themselves with the mother station.

It became desirable to look for other means of supplying energy to the daughter satellite. One possibility that was considered was wireless power transmission either by means of microwaves or laser beams. In a subsequent investigation by W. Robinson⁴ of NASA-MSFC, it was found that a considerable amount of experimental work in the microwave transmission area had been performed by the Raytheon Company. This experimental work in conjunction with published theoretical work by Goubau^{5, 6} and others indicated that a study of a microwave power transmission system specifically applied to a space station would be desirable.

Another factor of importance in the application of microwave power transmission is the serious consideration that is being given to the use of a nuclear reactor as a centralized source of power in a space base complex. The use of a central nuclear reactor has two implications. First, it is logical that this reactor supply the daughter satellite with power. In addition, it may be desirable to locate the reactor at a distance from the manned space station to eliminate the heavy weight of the shielding that would otherwise be necessary. In both cases microwave power transmission may be considered as the connective power link to the manned station.

There is obviously a considerable difference in the power level requirements of the microwave power transmission system for these two different types of applications. Power transmission to a daughter satellite would probably require no more than a few kilowatts while the power transmission requirement from a nuclear reactor to the manned space station could be 50 to 100 kilowatts.

Another consideration is the complexity of the space station. Originally conceived as an orbiting astronomical laboratory, it may be extended into a base station complex extended to other uses. It is possible that this mounting complexity will result in a growing need for flexibility, convenience, and ease in the transfer of energy between the various elements of the complex. An efficient and reliable microwave power transmission system would be very attractive from the standpoint of flexibility and convenience as the energy is transferred immediately and in any direction the transmitting antenna is pointed.

Still another application for microwave power transmission in space is in connection with the use of solar energy which is captured in space and transmitted to Earth by means of a microwave beam link. This concept, first introduced by Dr. Peter Glaser^{7,8}, was motivated by the rapid depletion of our fossile fuels resources, and the widespread pollution concurrent with their consumption. A large solar cell array at synchronous satellite altitude with attendant microwave transmitting antenna would collect the sun's energy with 99% duty cycle and continuously transmit the captured energy to an area on the Earth's surface where it would be efficiently converted back to dc electrical power. To be useful and economical, this concept would have to handle large amounts of power. The power has to be transmitted over 22,000 miles but the microwave transmission itself can be over 90% efficient including the transmission through the Earth's atmosphere. The use of microwave power transmission in this application is unique - there are no other means by which this nearly inexhaustable and pollutionless source of energy could be transferred to the Earth so efficiently.

This latter application has been discussed to illustrate that the results of a microwave power transmission study initiated by a specific potential application may well have other applications.

Free space microwave power transmission is not a new concept. But it may well be that some of its unique properties will find their first serious applications in meeting some of the challenging problems of transferring energy in space.

1.2 A Summary of the Work Performed Under the Study Contract

The work under this study contract was aimed at a broad investigation of microwave power transmission, primarily aimed at the transfer of power from a manned central satellite to daughter satellites. However, many of the findings of such a study have a broader range of application.

One of the most basic characteristics of any power transfer system is its efficiency. A great deal of the work carried out under this contract concerned itself with this aspect. In particular, a complete system was set up and the overall efficiency accurately measured. These measurements were made both at Raytheon and at a special briefing held at MSFC on September 29, 1970. These experimental measurements are described in Section 2.0.

Another demonstration involved the use of a microwave beam as a position reference. A three-wheeled cart equipped with position sensors and a control system automatically locates itself with respect to the microwave beam for maximum power transfer. The experimental demonstration is described in Section 5.0. A broader based theory of the use of the microwave beam as a position reference is described in Section 4.0

The overall study of the microwave power transmission system is carried out in Section 3.0. A microwave power transmission system can be broken down into three distinct portions:

1. The generation of the microwave power.
2. The formation of the microwave beam and the microwave transmission itself.
3. The collection and rectification of the energy at the receiving point.

It was a major portion of this study to explore these three portions of the system, to select preferred approaches, and to make recommendations for further development. This was done within the limitations imposed by program support, and the results are outlined in the following paragraphs.

A detailed investigation was made into the various classes of microwave power generators and how they fit into the peculiarities of the space power transmission applications. It was recognized that efficiency was of major importance because of the necessity of radiating into space any heat resulting from the inefficiency of microwave power generation. Based upon efficiencies already achieved and the impact of new permanent magnet materials upon a further increase in efficiency, it is reasonable to expect overall efficiencies from crossed-field type devices of 90%. This feature, coupled with other features of a simple mechanical construction, the opportunity to use long-life, non-thermionic, secondary-emitting cathodes, the ability (at lower power levels) to directly radiate dissipated power into space, led to the recommendation of this type of device for microwave power generation. This investigation is the subject of Section 3.2. Detailed recommendations are made in Sections 3.2.4 and 3.5.1.

The formation of the microwave beam and the study of the microwave power transmission itself is the subject of Section 3.3. It was concluded that the preferred approach is a transmitter aperture illumination which has a gaussian distribution. This can be accomplished by either a phased array type transmitting antenna or an ellipsoidal reflector illuminated by a dual-mode feed horn which produces a near gaussian illumination. By either of these means it is expected that 90% of the microwave energy which is generated can be delivered to the area of reception.

The study of the collection and rectification of the energy at the receiving point was a very important part of this study. For many reasons, the preferred approach to this area is the use of a device called the rectenna which both collects the energy and rectifies it back to dc power. The rectenna device, however, is a relatively new device and needs considerable development work performed upon it. This study was used as an opportunity to accomplish some of this need. As a result we were able to demonstrate an efficiency as high as 75% for a single element of the rectenna array. An element of the array consists of a half-wave dipole and the rectifier associated with it. A large scale

rectenna consisting of 126 of these elements was constructed and used in the overall transmission experiments described in Section 2.0. In addition, investigations were made into a flexible rectenna construction, and into new Schottky-barrier diodes which have a power handling capability at least an order of magnitude greater than those currently being used in rectenna structures.

As a result of this study it has been possible to make general recommendations with respect to approaches to be followed. These are outlined in Section 3.5.1.

Finally, it is emphasized that this study should be considered as a preliminary investigation into the technology of microwave power transmission for space applications. Much remains to be accomplished.

1.3 Microwave Power Transmission Efficiencies

There is perhaps no parameter which better describes the status of microwave power transmission or better directs its future development than efficiency. For this reason Table 1-1 is included. This table provides efficiencies for the three portions of the system, and overall efficiency, for three different categories of technical development: 1) Efficiencies presently demonstrated, 2) Efficiencies expected with present technology, and 3) Efficiency expected with additional development. The three overall efficiencies corresponding to these categories are 27%, 51%, and 77%, respectively. The measurements of the presently achieved overall efficiency of 27% are described in Section 2.0. The various efficiencies given in the table are documented by references and other statements.

Table 1-1. Microwave Power Transmission Efficiencies

	Efficiency Presently Demonstrated	Efficiency Expected With Present Technology	Efficiency Expected With Additional Development
Microwave Power Generator	76.7% ^a	85% ^d	90% ^g
Transmission Efficiency from Output of Generator to Collector Aperture	66% ^{b, j}	86% ^e	95% ^h
Collection and Recti- fication Efficiency (Rectenna)	52% ^{c, j}	70% ^f	90% ⁱ
Overall Efficiency dc Output/dc Input	27% ^k	51%	77%

- a. Measured efficiencies on QK1224 Amplitron while producing 300 kW of CW power. Technical Report No. RADC-TR-65-165, November 1965, p. 16.
- b. Experiments in Transportation of Energy by Microwave Beam. 1964 IEEE International Convention Record, Vol. XII, pt. 2, pp 8-17.
- c. Okress, et al.: Microwave Power Engineering. IEEE Spectrum, October 1964, Figure 23.
- d. Data taken on special Amplitron designed for high efficiency. Ruden, T. E.: Large Signal Analysis. Twenty-second Quarterly and Final Report, Contract No. NObsr-77592, Sept 7, 1964, Raytheon Report No. SPO-012, Section 2.3.
- e. Assumes that gaussian illumination of transmitter aperture can be raised to 96 percent and that receiving aperture is capturing 90 percent of beam.
- f. Assumes use of new Schottky barrier diodes operating at 80 percent efficiency and rectenna with 87.5 percent capture efficiency.
- g. Use of very high magnetic field and vane shaping in Amplitrons to optimize efficiency.
- h. Further increase in transmitter aperture illumination efficiency and use of larger receiving aperture.
- i. Additional development work on semiconductor diodes and near 100% rectenna capture efficiency.
- j. b and c together have been experimentally measured at an overall efficiency of 40%.
- k. This measurement consisted of a microwave generator efficiency of 67% and a combined transmission, collection, and rectification efficiency of 40%.

2.0 DEMONSTRATION OF OVERALL EFFICIENCY OF A MICROWAVE POWER TRANSMISSION SYSTEM

The elements of a microwave power transmission system consist of 1) a microwave generator which converts dc power into microwave power, 2) a microwave transmission link consisting of a transmitting antenna and a receiving aperture, and 3) a means of capturing the transmitted microwave energy and converting it back into dc power. Each one of these elements has an efficiency of its own and the overall efficiency should be the product of the three individual efficiencies.

Although there is a substantial amount of data on the efficiencies of the respective three elements of the microwave power transmission system, the overall efficiency of a complete system had never been accurately measured. Furthermore, no efficiency measurements had ever been made on an overall system which incorporated a rectenna. It therefore seemed desirable to make such a measurement and to actually demonstrate the set-up and the efficiency measurements to a number of people. Such a demonstration was held on September 29, 1970, at the Marshall Space Flight Center.

The demonstration made use of the physical test set-up shown in Figure 2-1. A block diagram of the system is shown in Figure 2-2. With the exception of the rectenna, the test set-up made use of components that were either on the shelf or otherwise readily available. Hence, the magnetron used was limited in its efficiency, and the rectangular pyramidal horn was not an ideal transmitting antenna.

The instrumentation used in the experiment is shown in Figure 2-3. All of the meters were carefully calibrated by the Standards Laboratory in the Microwave and Power Tube Division of Raytheon Company. Calibrations were within 1% accuracy. In addition, the dc output instrumentation of the system (items 5 and 6 of Figure 2-3) was checked by secondary standards at the MSFC Standards Laboratory.

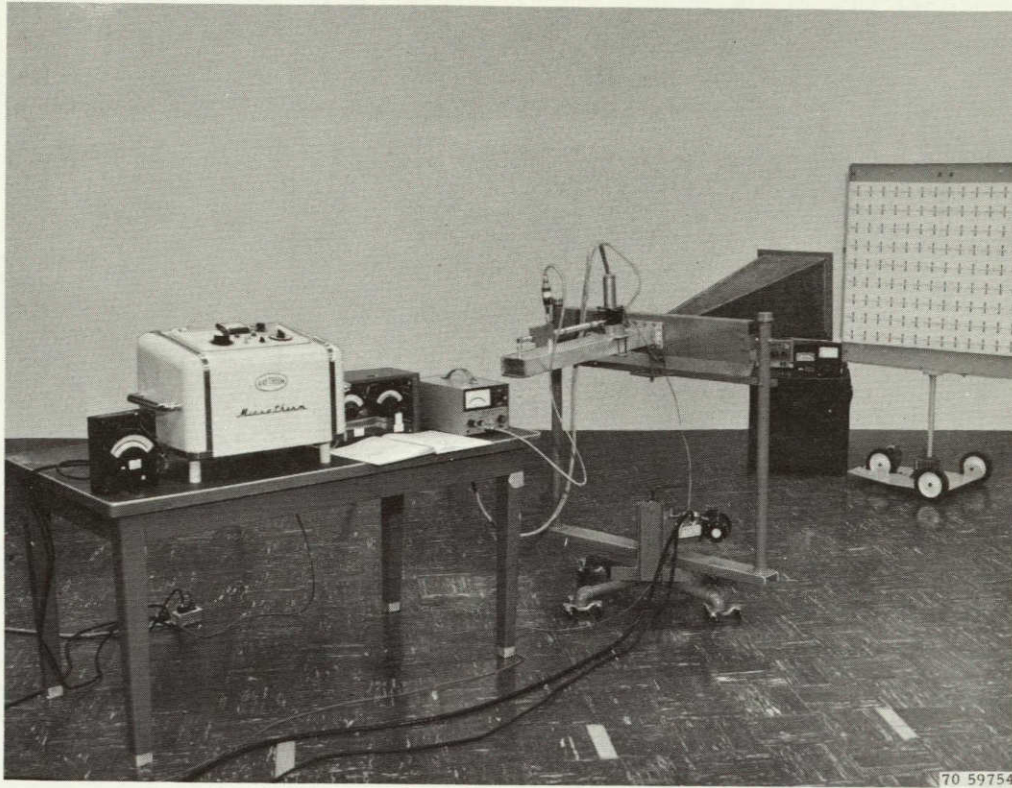


Figure 2-1. Test Set-up of Microwave Power Transmission System

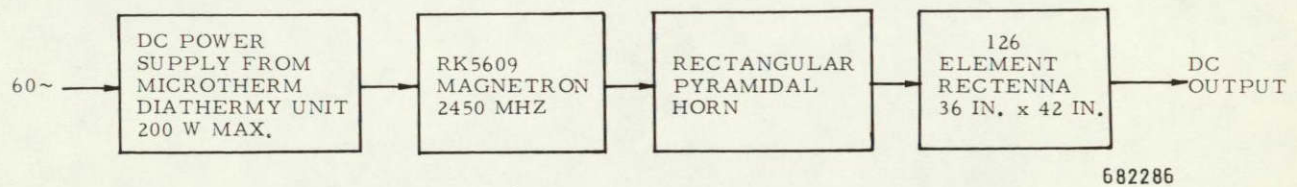
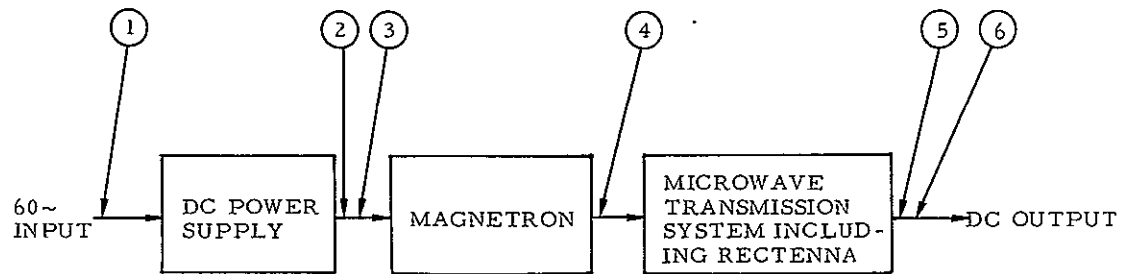


Figure 2-2. Specific Components Used in the Microwave Power Transmission Experiment



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DESCRIPTION OF INSTRUMENTATION

<u>INSTRUMENT</u>	<u>QUANTITY MEASURED</u>
1. WATTMETER	60~ POWER INPUT
2. DC VOLTMETER	DC POWER INTO MAGNETRON AND DC INPUT TO MICROWAVE TRANSMISSION SYSTEM
3. DC MILLIAMMETER	
4. MICROWAVE POWER METER	OUTPUT OF MAGNETRON AND INPUT TO TRANSMITTING ANTENNA
5. DC VOLTMETER	DC OUTPUT OF RECTENNA AND DC OUTPUT OF MICROWAVE POWER TRANSMISSION SYSTEM.
6. DC MILLIAMMETER	

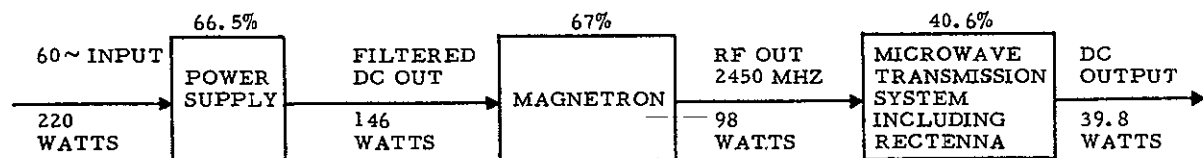
Figure 2-3. Schematic of the Experimental Set-up and Instrumentation for Measuring the Overall Efficiency of a Microwave Power Transmission System.

The measurements of overall system efficiency are shown in Table 2-1. Given in Table 2-1 are efficiency measurements made at MSFC and at Raytheon Company. The efficiencies are approximately the same although the measurements made at Raytheon are at a power level about twice that of the MSFC measurements. Of the various efficiencies listed in the table, the most important one is the dc-to-dc efficiency which includes the conversion efficiencies at either end of the system as well as the microwave transmission efficiency itself. This efficiency is seen to be approximately 27% in both cases.

Figure 2-4 provides the same information as Table 2-1 with respect to the measurements made at Raytheon, but presents them in a more graphic form.

Table 2-1. Measurements on Overall System Efficiencies

	Measurements at MSFC	Measurements at Raytheon
60 input	113 W	220 W
Filtered dc output of dc power supply and input to magnetron	77 W	146 W
Microwave output of magnetron	50 W	98 W
Dc output of rectenna	20.4 W	39.8 W
System rf input to system dc output efficiency	41 %	40.6 %
System dc input to system dc output efficiency	26.6 %	27.3 %
System 60 input to system dc output efficiency	18.0 %	18.1 %



682300

EFFICIENCIES

$$\text{SYSTEM 60~ INPUT TO SYSTEM DC OUTPUT} = \frac{39.8}{220} = 18.1\%$$

$$\text{SYSTEM DC INPUT TO SYSTEM DC OUTPUT} = \frac{39.8}{146} = 27.3\%$$

$$\text{SYSTEM RF INPUT TO SYSTEM DC OUTPUT} = \frac{39.8}{98} = 40.6\%$$

Figure 2-4. Results of Efficiency Measurements Using Experimental Set-up of Figures 2-2 and 2-3. Several system efficiencies of interest are indicated.

The significance of these efficiency measurements can be better appreciated by referring to Figure 1-1 in Section 1.3. Since none of the components were optimized for the maximum efficiency that could be expected from present technology, but were used because they were conveniently available, the results are considered to be good.

3.0 THE MICROWAVE POWER TRANSMISSION SYSTEM

3.1 Study Objectives

The major study objective was to investigate a microwave beam as a means of transferring power in an Orbiting Astronomy Support Facility. The study has been made from the viewpoint of optimizing the microwave system for efficiency, light weight, and electrical reliability. The investigation has been in sufficient depth to recommend specific design approaches in component areas.

The approach to the power transfer aspect of this study has been to consider the complete system as consisting of three elements, namely: 1) microwave power generation, 2) formation of the microwave beam, and 3) the collection and rectification of the microwave power. Each separate element has been considered separately, and the various alternative approaches to the components associated with each element have been considered.

In the study of the component areas, a little broader view than the Orbiting Astronomy Support Facility application has been taken in that large as well as medium operating power levels have been considered. Hence, the conclusions and recommendations may have a broader range of application. The conclusions and recommendations are presented in Section 3.5.

3.2 Microwave Power Generation

3.2.1 Introduction

Microwave power generation may be defined as the conversion of dc power into ac power whose frequency is so high that the corresponding wavelengths are in the range of 50 centimeters to 1 centimeter. The efficient generation of microwave power involves an entirely different technology from that associated with generating 60 cycle or 400 cycle ac power. However, this technology embraces a number of different approaches, some of which are much better suited to the intended application of efficient transfer of power in the space

environment. An outstanding requirement of the space environment is for a conversion process possessing inherently very high efficiency because of the problem of heat sinking in a space environment.

A brief discussion of microwave power generation from an historical point of view may be of some value in appreciating where we now stand. Over a period of time, two general approaches to microwave power generation have evolved. One of these is the electron tube approach, and the other is the solid-state device approach. The electron tube approach evolved much earlier than the solid-state approach. Both of the two types of microwave electron tubes, namely, the velocity-modulated device and the crossed-field device were invented shortly before World War II. The development of the crossed-field device in its magnetron form received great impetus during the War because of its use in microwave radar. It was preferred to the velocity-modulated device because of its simple construction and high efficiency.

The magnetron, however, was an oscillator rather than an amplifier and therefore had important limitations on its use. Because the velocity-modulated device is basically an amplifier, it received much attention after World War II for the communication and the more sophisticated radar applications in spite of its much lower efficiency. Subsequently, the crossed-field device was converted into an amplifying device in the Amplitron (sometimes called "reentrant beam crossed-field amplifier) form which retained the high efficiency of the magnetron device while providing broadband amplification.⁹ The Amplitron device has now been used in many sophisticated applications.

It may be of interest to observe the average power achieved from a single microwave tube as a function of time. This is done with the aid of Figure 3-1. The period from 1960 until the present time is of especial interest since it was the sudden increase in average power levels from fifteen to four hundred kilowatts that motivated individuals to seriously consider the use

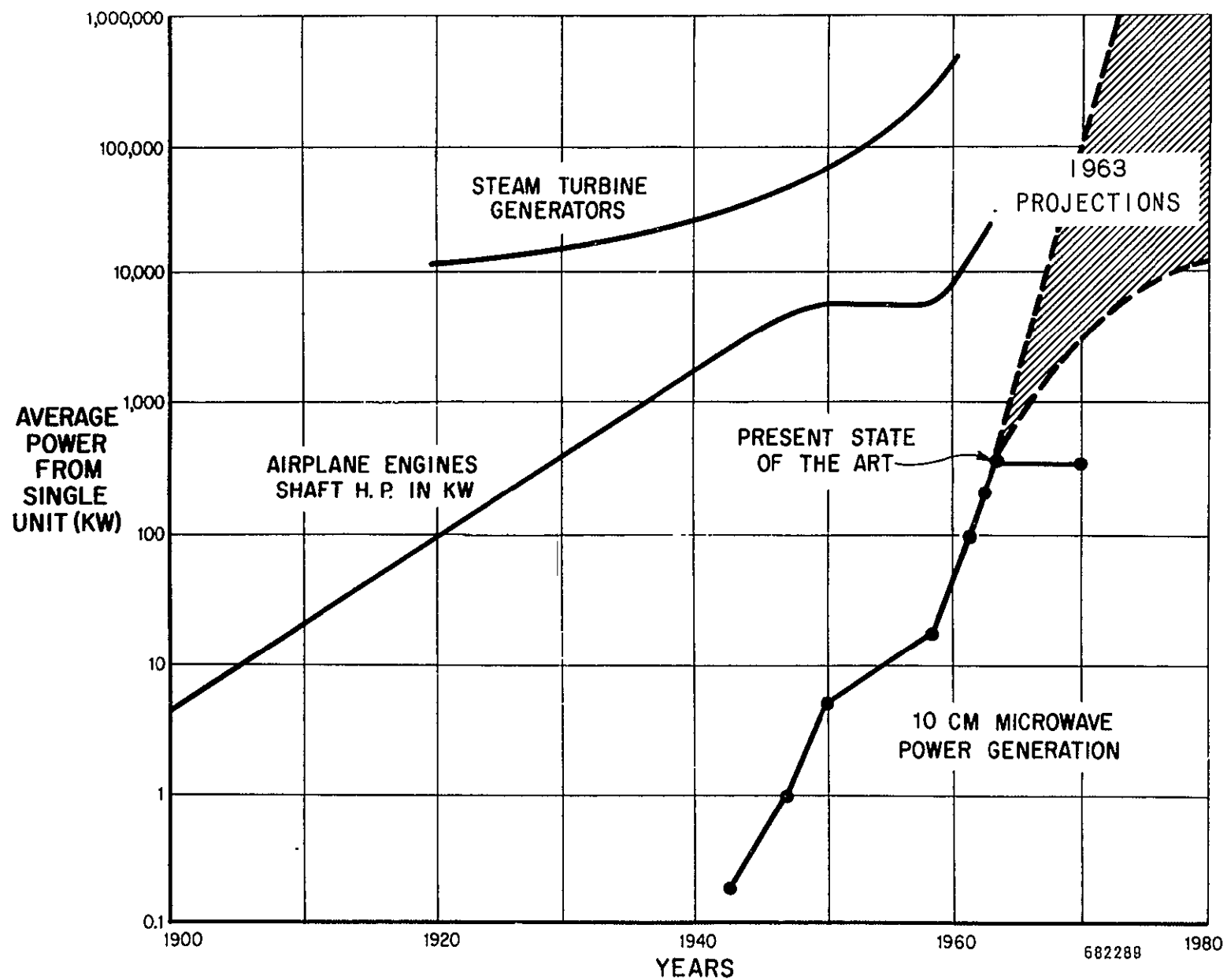


Figure 3-1. Growth of Microwave Power Generation

of microwaves for power transmission. The large power increase was made possible by a substantially funded tube development program by the Department of Defense.^{10, 11} The flat area of the curve in Figure 3-1, between the years 1964 and 1971, is caused not by a lack of approaches to achieving higher power levels, but rather due to a lack of follow-on support for the super power tube development programs.

The development of solid-state microwave devices did not get under way until much later. The early solid-state devices developed soon after World War II all operated at low frequencies. The first microwave transistors were introduced in the time period of 1964. While microwave transistors are under active development and the rate of progress in terms of higher power at higher frequencies is very significant, it is probably safe to assume that they will never achieve the power ratings that have already been achieved by electron tubes. However, if they were to be used in a phased array, and each transistor coupled to an element of the array, a power rating greater than a few watts may not be necessary. A much greater handicap may be the limited efficiency of these devices at the 10 centimeter wavelength range, a wavelength which is desirable for the intended application, and where electron tube devices have already demonstrated high efficiencies and much higher power handling capabilities.

We see, then, that there are three classes of devices that can be considered as microwave generators; 1) the crossed-field electron tube device, 2) the velocity-modulated electron tube device, and 3) the solid-state device. In the material that follows, we will examine the first two devices in some detail, observing their operating principles and principal performance characteristics. The solid-state device will not be similarly dealt with, primarily because of a combination of its relatively low efficiency and low power handling capability at the lowest frequency of interest, which is about 3000 MHz. Some breakthrough in the performance of this device is needed before it can become competitive with the other approaches at high power level. However, it may be useful as a low power rf driver where efficiency is relatively unimportant.

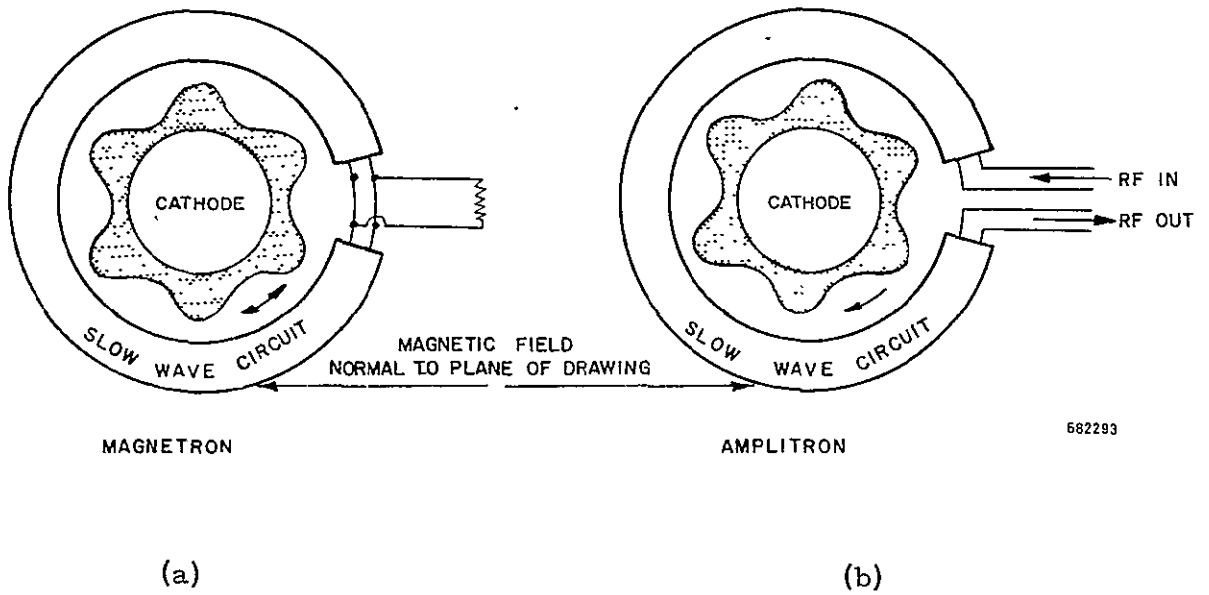
3.2.2 A Comparison of Approaches to Microwave Power Generators

The principal devices used to generate microwave power are the magnetron oscillator,^{13,14,15} the Amplitron,^{9,15,16} and the injected beam crossed-field amplifier,^{14,15} which are all crossed-field devices, and the klystron¹⁵ and traveling-wave tube¹⁵ which are colinear beam (velocity-modulated) devices. These devices are shown in schematic form in Figures 3-2a, 3-2b, 3-3, 3-4a, and 3-4b, respectively.

3.2.2.1 Differences in Energy Conversion Principles

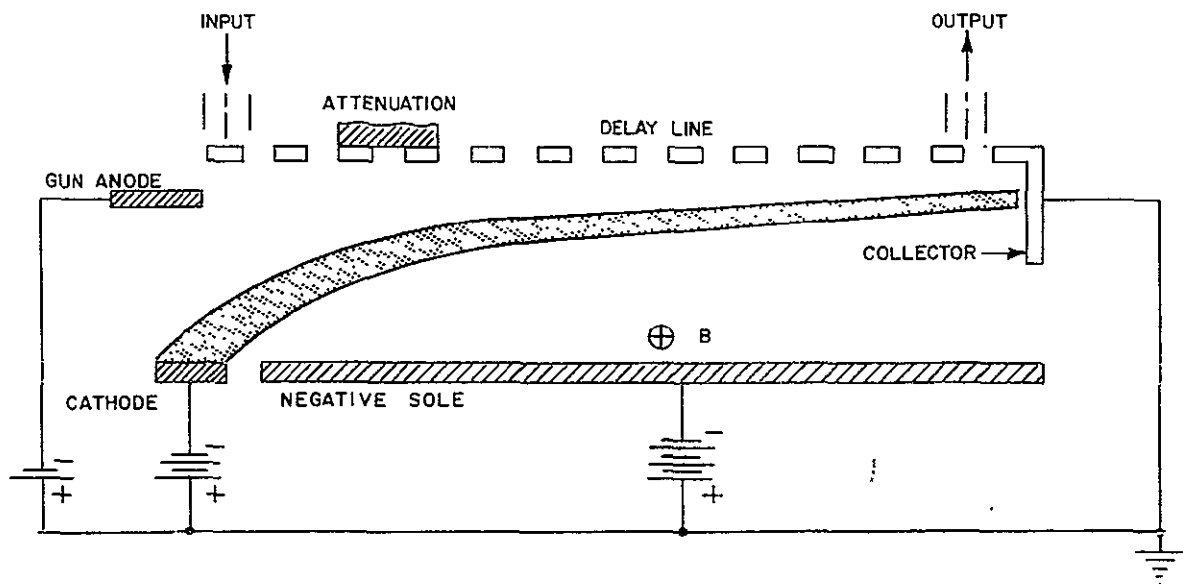
The basic difference between colinear beam and crossed-field devices is in the energy conversion system by which the input dc energy is converted into rf energy. In colinear beam devices the potential energy is first converted to kinetic energy by imparting motion to a beam of electrons. Then a substantial amount of this kinetic energy is converted into rf energy by the slowing down of the electron beam. In the crossed-field device, aside from a small amount which is used to give an initial velocity to the electrons, the potential energy is converted directly into rf energy. Many of the differences in the construction and performance characteristics of the two devices are directly identified with this basic difference of energy conversion. An energy conversion flow diagram shown in Figures 3-5a and 3-5b illustrates the sequence of energy transformation in the crossed-field and the colinear beam devices as represented by the Amplitron and klystron, respectively.

In a well-designed crossed-field device, but one which has not been maximized for efficiency by using high magnetic fields, about 20% of the input energy is converted into kinetic energy and about 80% is converted directly into rf energy. Of the amount that is converted into kinetic energy, about 50% can be retrieved in the form of rf energy. Of the total 85% converted into rf energy, about 2% eventually returns to the cathode in the form of electron bombardment and about 3% is represented by rf circuit losses to give an overall efficiency of 80%.



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Figure 3-2. Continuous Cathode Crossed-Field Devices



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Figure 3-3. Injected Beam - Crossed-Field Amplifier

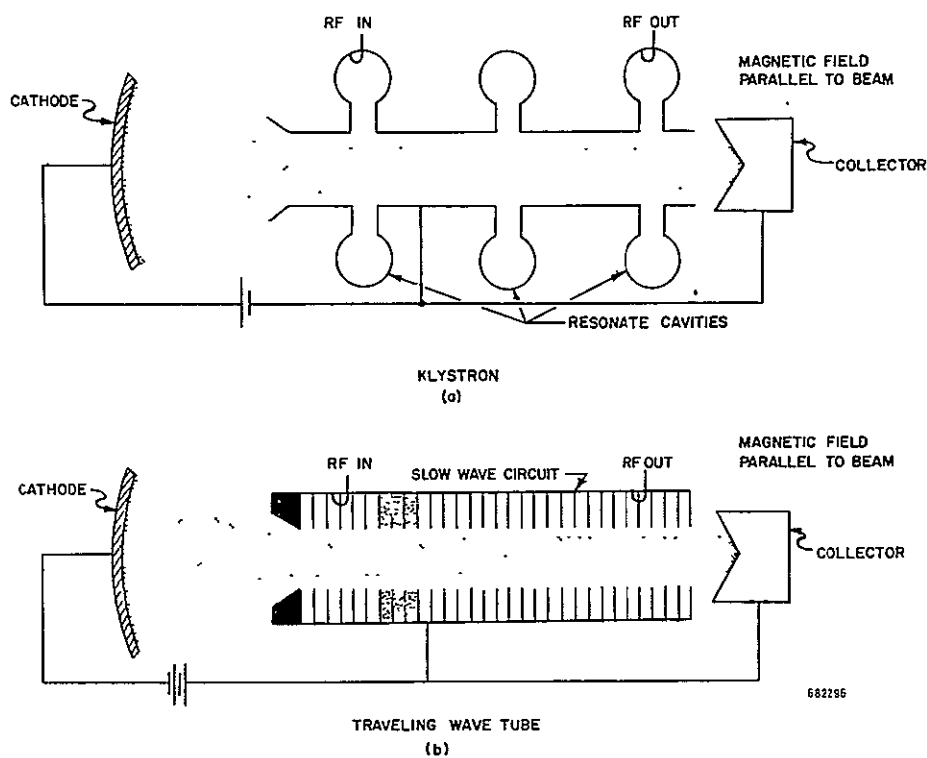


Figure 3-4. Colinear Beam Devices

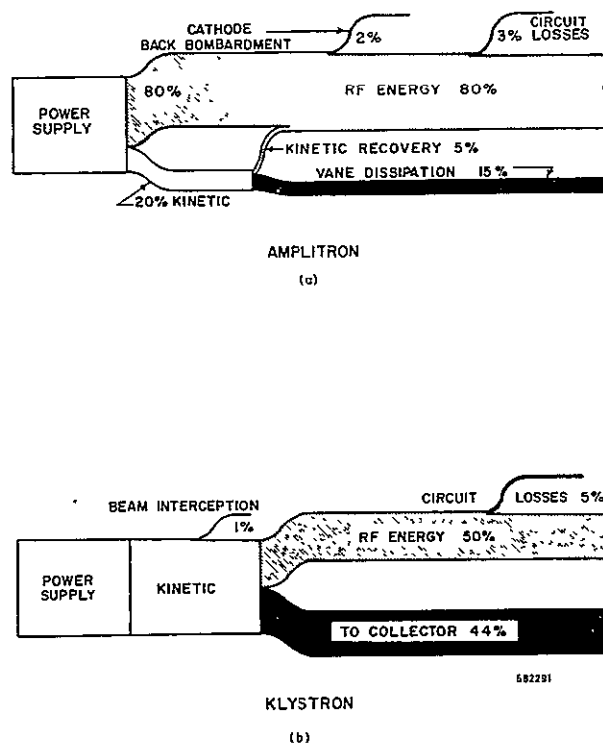


Figure 3-5. Energy Conversion Diagram

In the colinear beam tube, of all the kinetic energy into which all of the potential energy is first converted a small percent strikes the structure leaving most of the beam to interact with the rf circuits. From 50 to 55% of the beam is converted into rf energy and the remainder is dissipated at the collector. After allowing for circuit losses, overall efficiencies of from 45 to 55% can be expected in a colinear beam device in the 10 cm region.

Aside from the large difference it makes in the operating efficiency, the difference in energy conversion systems is also responsible for the much lower X-radiation of the crossed-field device, and for the lower phase pushing figures.

The much lower X-ray generation of the crossed-field device is brought about because the average kinetic energy of an electron when it strikes the anode is only 10 to 15% of the input energy, whereas in the colinear beam case the average energy at the collector is about 50% of the input energy, and any energy collected on the circuit is at full input energy. The X-rays which result then are much more penetrating, and in addition, a larger percentage of the dissipated power is converted into X-rays.

Phase pushing is defined as the amount of incremental phase shift between the input and output terminals resulting from changes in applied anode current or voltage. In the colinear beam tubes the phase change is highly dependent on the beam velocity and therefore the beam voltage. Particularly in the klystron case any information is carried forward at beam velocity and the incremental phase shift is then equal to $\frac{\Delta V}{2V_0} \theta$ where ΔV is the change in the potential of the beam, V_0 and θ are the unperturbed beam voltage and input-to-output phase shift, respectively. If θ is of the order of 2000° , which it may readily be, a 1% change in voltage will effect a 10° incremental change of phase. Traveling-wave tubes have similar figures. The Amplitron, on the other hand, has pushing figures which are typically 0.5° for a 1% change in current.

3.2.2.2 Injected Beam and Continuous-Cathode Devices

A second classification of devices of almost equal importance can be made on the basis of whether the beam is injected from outside the rf interaction area or whether it is obtained from a large and continuous cathode in the rf interaction area. All colinear beam tubes use an injected beam while crossed-field devices are sub-divided into those that do use an injected beam and those that make use of a continuous-cathode in the interaction area. With injected beam tubes of the colinear beam tube type, the functions of beam interaction and beam collection are separated. This arrangement has an advantage from the dissipation point of view as long as the beam transmission is good. The injected beam crossed-field amplifier does not share in this advantage so completely since a large share of its spent beam is collected on the anode circuit. The continuous-cathode crossed-field device has the disadvantage from a dissipation point of view of having to utilize the same structure for rf interaction as for collection of the spent beam, but if the tube has high efficiency, such a dual function of the rf structure makes for great simplicity in overall mechanical design.

There is a great difference in the beam forming problems in the two types of devices. There is essentially no problem in the continuous-cathode crossed-field device in which the space charge spoke is automatically formed by the rf wave on the network. The fact that most of the emission is obtained as secondary emission from back-bombarding electrons, a process for which there is no known emission current density limitation, makes the problem of obtaining emission in the continuous-cathode crossed-field device a relatively easy one. This is particularly advantageous at higher frequency levels where emission density problems occur in the injected beam class of tube. Provisions must be made, of course, for removal of the heat incurred by the back bombardment. The fact that it is possible to start a rapid buildup of emission from a completely cold cathode in an Amplitron by injection of normal rf energy from the driver at the input terminals, makes it possible to eliminate the need for any heater excitation. In the case of a magnetron oscillator, a cold cathode can also be used but in this case an auxiliary starter cathode concealed in one of the pole pieces is used to start the tube.

Turning now to the injected beam as employed in the klystron and traveling-wave tube type of device we note that there are three problems, 1) obtaining the emission, 2) forming the beam, and 3) maintaining the beam. These problems have been solved in a generally satisfactory manner. The primary emission current density is kept to a satisfactorily low level by means of converging lenses which concentrate the emission obtained from a relatively large emitting surface into a sufficiently small diameter beam for efficient interaction with the rf circuit. An axial magnetic field, parallel to the beam motion, is employed to confine and maintain the integrity of the beam as it moves through the interaction area, thus giving rise to the nomenclature "colinear". One limitation on this process is an upper limit to the amount of current that can be sent down the beam for a given beam accelerating voltage. The ratio $I_0/V_0^{3/2}$ where I_0 is the beam current and V_0 is the beam voltage is usually referred to as the beam perveance. This ratio is seldom over 2×10^{-6} for tubes in the microwave frequency range. Higher perveance can be obtained with the use of a hollow beam or multiple beams but both these solutions have attendant problems. Although the term "perveance" is seldom used to describe the current-voltage characteristics of a continuous-cathode crossed-field device, ratios of $I_0/V_0^{3/2}$ are typically three to six. Corresponding to these different values of perveance for the injected beam colinear device and the continuous-cathode crossed-field device are different operating voltages for a given rf output level. The Amplitron runs at typically 60% of the operating voltage of the klystron. The lower operating voltage is another factor in addition to the difference in energy transformation system which makes for much reduced X-ray generation in the continuous-cathode crossed-field device.

3.2.2.3 The Dissipation Problem

The dissipation problem in microwave power generation takes on special significance in space, since ultimately, whether the device itself is radiation or liquid cooled, the heat rejection must be made into space itself. It is therefore essential that the generator device be made efficient.

The importance of efficiency in reducing the amount of power to be dissipated is shown in Figure 3-6, in which the ratio of the rf power output to the power dissipated is plotted as a function of the tube efficiency. Thus, at 50% efficiency there are equal amounts of generated rf power and dissipated power, while at 90% efficiency the ratio of generated power to dissipated power is 9 to 1. At 95% efficiency, the ratio is 19 to 1. Hence, because of the problem of radiating dissipated power into space, there is good reason to have the generator efficiency just as high as possible. This is why it is desirable to strive for 95% efficiency over 90% even though the 5% increase in efficiency may not be important as far as increasing the size of the prime power source is concerned. It is a very adequate reason for preferring to use a device that is 90% efficient to using one that is 60% efficient, since the dissipated power in the second case will be six times as great for the same rf output level.

If the efficiency is high enough then it makes it much easier to get rid of the small amount of dissipated power by direct radiation into space. Both the linear beam device and the crossed-field device can radiate substantial amounts of power into space directly. In the case of the linear beam device, the collector can be made of a material such as tungsten and allowed to operate at a high temperature and thereby radiate a great deal of power. In the case of the crossed-field device, the dissipated power is carried readily through the highly conducting vanes to an outside cylinder which can radiate directly into space. It cannot operate at such a high temperature but the much higher efficiency of the crossed-field device will permit a lower operating temperature.

The direct radiation of dissipated power from the tubes into space makes it highly desirable to have the internal structure of the tube directly exposed to the vacuum of space. Both classes of tubes will be operating with an appreciable temperature of the internal parts which would outgas over a period of time and cause sputtering and other life problems. Operating directly into the vacuum of space may cause some initial processing problems in the case of the linear beam tubes since they employ a thermionic emitting cathode. Such a cathode, if it is made up in the Earth's environment, must be protected in some manner until it is used in the space environment. The pure metal secondary emitting cathode of the crossed-field device needs no such protection. The starter cathode, if an oscillator is used, may consist of a piece of pure tungsten wire which will readily emit electrons at a temperature consistent with reliability.

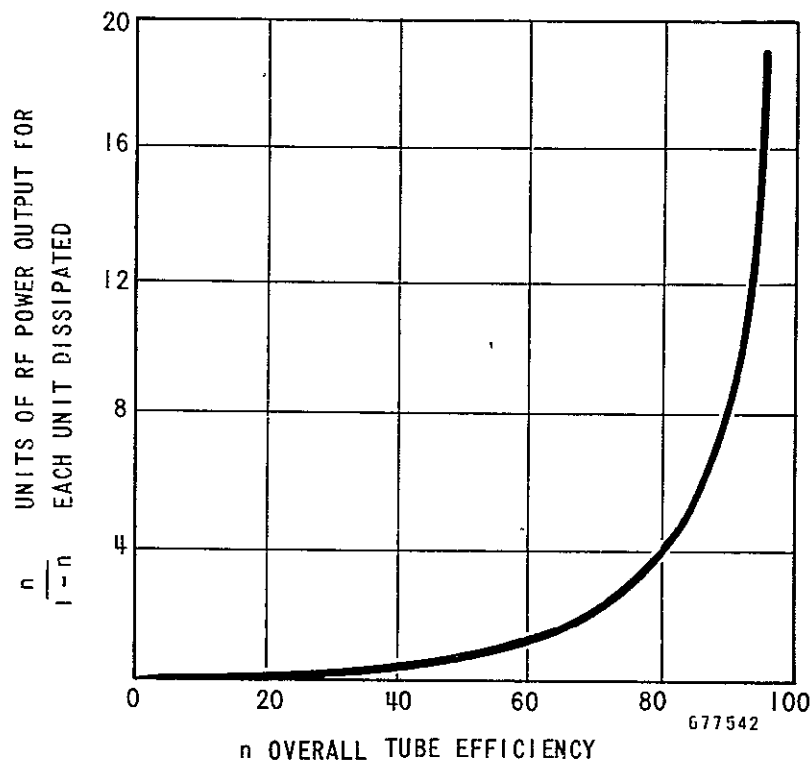


Figure 3-6. Relationship Showing Ratio of rf Power Output to Dissipated Power as a Function of Tube Overall Efficiency, n

If the tubes cannot reject their heat directly into space, then some other form of cooling will have to be considered. Heat pipes may be one approach. With the use of heat pipes, it may be possible to transfer large amounts of dissipation from internal parts of the tube out into a region of space removed from the tubes. Getting rid of the backbombardment power on the crossed-field device cathode may be one area of application of the heat pipe.

There has been a great deal of study and much experimental evaluation of high density liquid cooling systems. A detailed study on how to apply this technology to the problem at hand must await a more specific specification for the power level of the tube.

3. 2. 2. 4 RF Circuit Properties and Configurations

Still another way to classify microwave tube approaches to the generation of super power is by their rf circuit properties and configurations. That these differences are important is forcefully illustrated by the great change that was made in the performance of the magnetron by cutting the reentrant slow-wave circuit structure and matching the two severed ends to two sets of terminals. In place of a resonant device that behaved only as an oscillator, a device capable of broadband amplification was created. The difference between the naturally broadband properties of the traveling-wave tube and the naturally narrow band properties of the klystron lies in the fact that the former has a continuous circuit from input to output whereas the klystron consists of a series of resonant cavities with only electronic coupling between them.

The magnetron, Amplitron, klystron, traveling-wave tube, and injected beam crossed-field amplifier use circuits which may be described as follows:

1. Magnetron - The magnetron employs a slow-wave type structure, usually used at the lower cutoff frequency of the pass band. The circuit is reentrant, imposing integral multiples of phase shift around the circuit, which are recognized as resonant circuit modes.
2. Amplitron - The Amplitron employs a slow-wave type structure, used at frequencies well within the pass band. The circuit is non-reentrant and matched at either end to external circuits. The circuit coupling between input and output is very tight.
3. Traveling-wave Tube - The traveling-wave tube employs a slow-wave structure, used at frequencies well within the pass band. The coupling between input and output is limited by attenuation which is inserted to eliminate unwanted oscillations.

4. Injected Beam Crossed-Field Amplifier - This tube employs a slow-wave structure, used at frequencies well within the pass band. Coupling between input and output is limited by attenuation which is inserted to eliminate unwanted oscillations.
5. Klystron - The klystron employs a series of resonant cavities connected only by an electron beam. Broad-band qualities can be introduced by staggered tuning of the cavities. There is no circuit coupling between input and output.

The type of circuit, along with certain properties of the beam determines the relative amount of stable gain that can be obtained. The Amplitron, in its present form, with its close circuit coupling between input and output, and its reentrant beam, is limited in gain to a maximum of about 16 dB and gains of the order of 10 dB are more representative. The klystron, on the other hand, can be made with very high gains, as high as 50 dB or greater in some cases, due in no small part to the high degree of circuit isolation between input and output. The gains achievable in high power traveling-wave tubes and injected beam crossed-field amplifiers lie somewhere in between, typically 25 to 35 dB. It is interesting to note that if Amplitrons had distributed attenuation inserted near their input they would closely resemble the circuit of the traveling-wave tube, but their stable gain would still be somewhat lower because of the modulated reentrant beam.

Of all the devices being considered only the Amplitron has the circuit capability of low loss transmission in the reverse direction. The other devices employing slow-wave circuits connected to input and output have this basic capability but have inserted attenuation which prevents a consideration of duplexing on the input side.

In a very narrow beam application, as in power transmission, there may be appreciable amounts of reflected power from the receiving array which will reach the transmitting antenna. Where this is the case it may be better to absorb the power in the transmitter than to reflect it. This would be particularly true in a phased array where the re-reflected power from the many different elements may have different phase relationships and would result in a distortion of the shape and direction of the beam. In this case the klystron and magnetron which reflect the power are at a disadvantage to the other types which absorb the power in their circuits. This is illustrated in Figure 3-7.

The nature of the circuits is related to auxiliary circuit components. The Amplitron requires some form of directional attenuator at its input. However, if the assumption is made that transmitting tubes will radiate into space, then there will be little reflected power and each tube can be matched to space for minimum reflected power. If such is the case, then reverse directed power should be held to 2% of the output power. Such a reflection is equivalent to an output mismatch of about 1:3 VSWR. Hence, there is not a serious strain on ferrite directional devices at the input.

3.2.2.5 Summary

The various microwave tube approaches to the generation of super power have been reviewed from the point of view of how their construction and mode of operation affect operating characteristics which may be important in the generation and application of microwave power. It has been found that many important differences in performance of the various devices are the result of the difference in energy conversion systems, the difference between injected beam and continuous-cathode arrangements, and a difference in circuit properties and configuration. The differences in the performance capabilities of the various devices is summarized in Table 3-1.

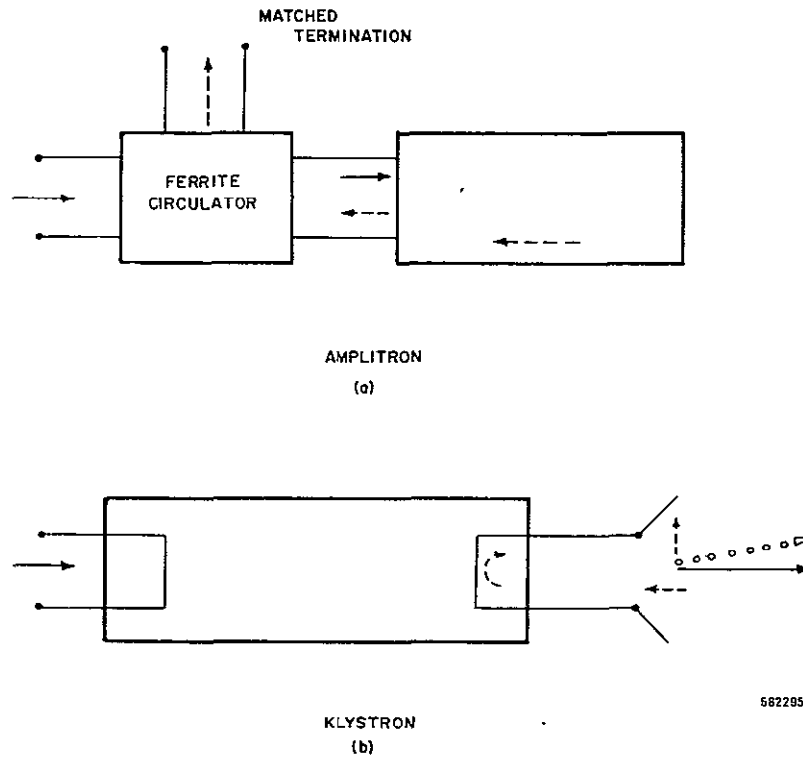


Figure 3-7. Difference in Effect of Reflected Power in Amplitron and Klystron Devices

Table 3-1. Differences in Performance Capabilities of Various Devices

<u>Characteristic</u>	<u>Klystrons</u>	<u>TWT's</u>	<u>Amplitrons</u>	<u>Magnetrons</u>
Efficiency at 3 GHz (%)	35 - 55	25 - 40	65 - 85	65 - 80
Bandwidth (%)	8 - 12	10 - 20	5 - 12	- - -
Gain (dB)	30 - 60	30 - 40	8 - 14	- - -
Perveance	1 - 2	1 - 2	3 - 6	3 - 6
Relative operating potential	1	1	0.6	0.6
Phase linearity rating	2	1	1	- - -
Phase pushing rating	3	2	1	- - -
Phase pushing	9 - 20°	5 - 12°	0.1 - 0.3°	- - -
Low level duplexing	No	No	Yes	No
AM linear amplification	Yes	Yes	No	No
FM linear amplification	Yes	Yes	Yes	No
X-ray generation	High	High	Very low	Very low

Because of the overwhelming importance of efficiency in a space application, it appears that the crossed-field device in its oscillator form, the magnetron, and in its amplifier form, the Amplitron, are the preferred devices.

3.2.3 More Detailed Discussion of the Crossed-Field Device for Space Power Transmission Applications

3.2.3.1 Examples of Highly Efficient Crossed-Field Devices

The performance characteristics for four different crossed-field tube designs possessing high efficiency are given in Table 3-2. One of these devices is a magnetron while the other three are Amplitrons. The measured electronic efficiencies of these devices range from 76.7 to 90%. Such microwave generator efficiencies are much higher than those available from any other kind of device, either electron tube or solid-state.

It is probably desirable to discuss in somewhat more detail the background and significance of the various tubes described in Table 3-2. In the case of the first item, the magnetron oscillator, Twisleton¹⁸ made a substantial effort to construct a very efficient device. This was done largely through the use of a high value of magnetic field relative to the frequency of oscillation, but attention was also paid to some of the finer design details. The tube described by Twisleton has a basic electronic or dc-to-rf energy conversion efficiency close to 94%. Losses, chiefly those in the rf circuit, reduce the overall efficiency to 86%.

The next device, the QK1224 Amplitron, combines a high efficiency with a very high average power output at 3000 MHz. This tube was developed under a contract with the U.S. Department of Defense, and its development is well-documented in government reports.^{10,11,19} It represents a very substantial step in the state-of-the-art of microwave power generators. One very interesting aspect of this device is that it is equipped with a cold cathode surfaced with platinum which operates completely on secondary emission and therefore avoids the life, construction and processing, and poisoning problems associated with a thermionically heated cathode. A space environment would be ideal for this type of device.

Table 3-2. Data on Efficient Crossed-Field DC-to-RF Converters

Device Designation	Type of Device	Overall Efficiency	Amplifier or Oscillator	Frequency	Pulsed or CW	Average or CW Power Level	Remarks
8684*	Magnetron	86%	Oscillator	915 MHz	CW	30 kW	Shelf item
QK1224	Amplitron	76.7%	Amplifier	3000 MHz	CW	300 kW	Available as special item only.
QK622	Amplitron	80%	Amplifier	3000 MHz	Pulsed	15 kW	Shelf item
QK1220	Amplitron	90%	Amplifier	485 MHz	Pulsed	--	Research model

* This is the RCA type designation for this tube which is made by several companies.

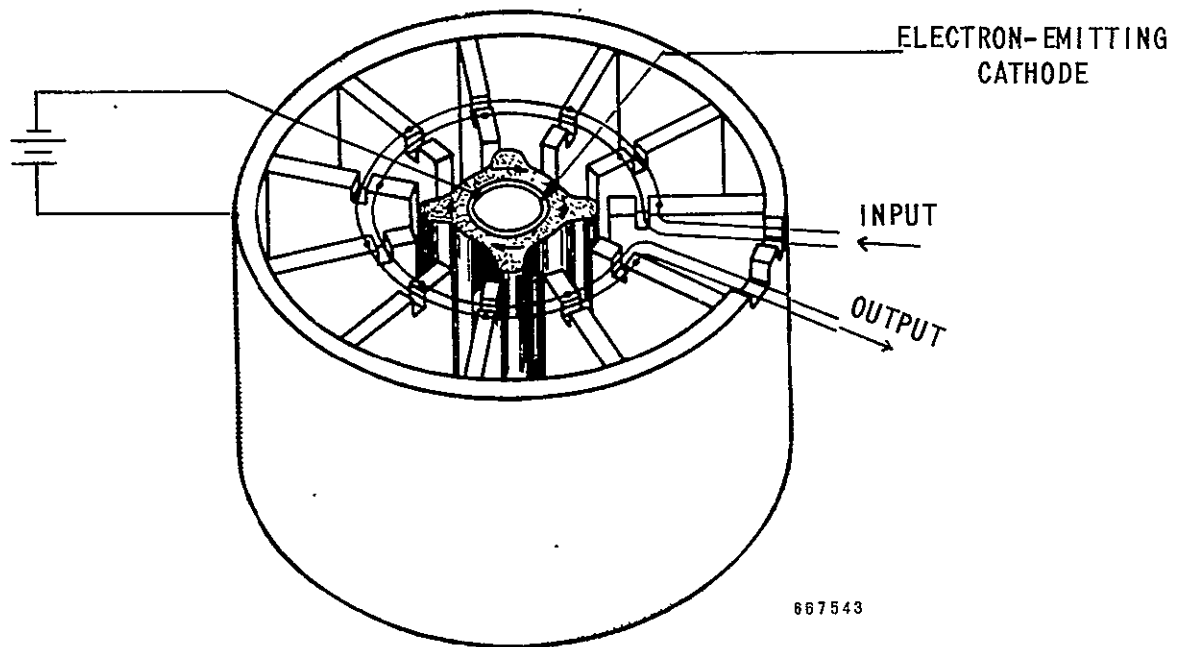
The QK622²⁰ was the first high average and high peak power Amplitron developed in the S-band region. This tube has a very high efficiency and was the first hardware confirmation that very high efficiencies could be obtained from the Amplitron device.

The final Amplitron listed, the QK1220,²¹ was strictly a research-type device where an effort was made to obtain as high an overall efficiency as possible. The average power level was low and the frequency was also made low, chiefly in order to investigate the affect upon efficiency of high magnetic fields relative to frequency. Because of the relatively low average power level, it was more difficult to get a highly accurate efficiency reading, so the confidence level in the 90% efficiency is lower than in the more accurately measured efficiencies of the three other devices listed. The probability of the efficiency being greater than 85%, however, is close to unity.

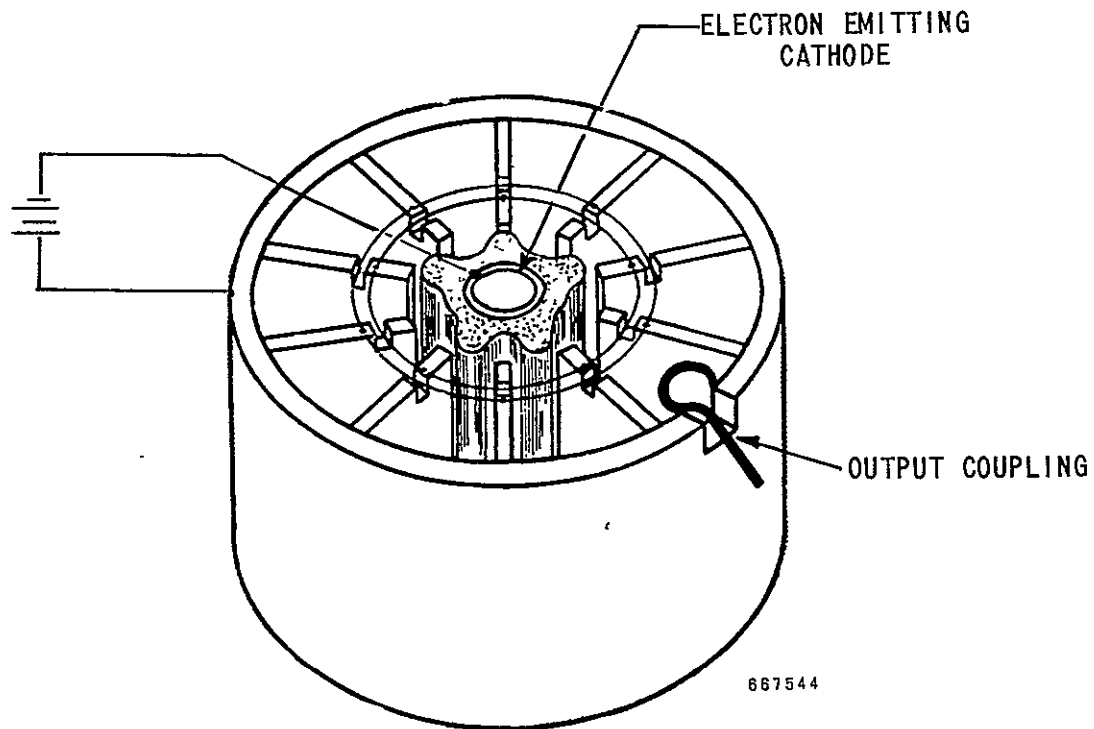
Because of the potential capability of the magnetron and Amplitron to meet the very high efficiency desired in the dc-to-rf converter, it may be desirable to discuss the factors affecting efficiency in these devices. In order to do this, however, it will be necessary to describe the principles of operation of the magnetron and Amplitron devices.

3.2.3.2 More Detailed Description of Operation of the Magnetron and Amplitron

The magnetron oscillator and the Amplitron^{9, 22, 13} are very closely related in that they utilize the same means of converting dc into microwave energy. The chief difference in these devices is in their microwave circuit arrangements which make the magnetron a self-excited oscillator and the Amplitron a broadband amplifier. The two different devices are shown schematically in Figures 3-8a and 3-8b. The magnetron has a reentrant microwave circuit and has but a single output. The Amplitron, on the other hand, has two rf connections, one of which is an input and the other an output, located at the two opposite ends of a non-reentrant circuit. This makes the device an excellent amplifier over a relatively broad band of frequencies. Whereas the electron efficiency of the two devices should be very similar, the Amplitron possesses an inherently higher circuit efficiency, particularly at the higher frequencies.



a



b

Figure 3-8. The pictorial diagrams a and b showing the operating principles of the Amplitron and Magnetron, respectively, provide a basis for understanding the operating principles of both of these devices and the differences between them. The magnetron has a reentrant circuit and is therefore a resonant type of device limited to an oscillatory mode of operation. The Amplitron has non-reentrant circuit matched to an input and output circuit and is capable of broad band gain. Both devices utilize the same dc to rf energy conversion principles.

Both the magnetron and Amplitron make use of a geometry in which a cathode which emits electrons is surrounded by a concentric rf circuit (Figures 3-8a and 3-8b). To place the device into operation, a dc potential is applied between the cathode and the anode, the negative terminal of the power supply being connected to the cathode. Now assume that in some manner the cathode emits electrons and that an increasing potential is applied between the cathode and the anode. Under the influence of the electric field which this potential creates between cathode and anode, electrons leave the cathode and are caused to move around the cathode in concentric paths by the presence of the static magnetic field. As the dc potential between cathode and anode is further increased, the electrons move in circular orbits of ever larger diameter and with increasing speed until their speed becomes synchronous with the rf wave in the anode circuit. When synchronism is reached, the electrons then begin to interact with the rf field and deliver energy to the rf field, losing potential energy as they do so and drifting closer to the anode where they are collected after delivering most of their original potential energy directly to the rf field. The electrons then surrender the balance of their original energy as heat when they strike and are collected by the anode. The rf energy which is generated by the interaction process flows out of the output connection.

3.2.3.3 The Long-life Pure Metal Secondary Emitting Cathode

Not all of the electrons which leave the cathode reach the anode. Some are returned to the cathode with a considerable amount of energy. In a high power tube, this energy is sufficient to cause the emission of more secondary electrons than the number of electrons returning to the cathode. Hence, once started, the tube need not rely upon primary emission or a thermionic cathode.

Since the life of a thermionic cathode is limited, it usually determines the life of the tube in which it is used. Hence, in a crossed-field tube, we have the opportunity of using a secondary emitting cathode material which does not have a life limitation. Such a secondary emitting material is platinum. This material, which has a relatively high secondary emission ratio,

has been the basis for the high power performance capability of the 1224 Amplitron. Since its introduction into the 1224, the platinum cathode has been used in many Amplitron designs and is a proven component.

Although the magnetron oscillator and the Amplitron employ the same energy conversion process, there is a distinction between how the initial supply of electrons is obtained from the cathodes of the two devices during transient startup. In the case of the magnetron, some electrons must be supplied initially by heating up the cathode to thermionic emission temperature. In some cases, an alternative scheme has been employed in which electrons are injected into the interaction area from a "starter" cathode placed at one end of the interaction area. In the case of the Amplitron device, the injection of rf into the input of the device causes an immediate buildup of electron flow from the cold cathode. It is of interest that the buildup of electrons caused by injected rf is so fast that within 20 to 30 rf cycles the buildup of power can be complete. In order for the Amplitron to start in this fashion, the dc potential between cathode and anode must be of the order of 12 kilovolts or more. Hence, Amplitrons in the low power category such as the one used in the lunar excursion module on the Apollo Project must employ a thermionic cathode, just as the magnetron does.

3. 2. 3. 4 The High Efficiency Potential of the Crossed-Field Device

The energy conversion process of these two devices may be looked at from the point of view of conversion of the potential energy of the electron into rf energy in the circuit as the electron drifts from the cathode to the anode. When the electron is at the cathode, its potential energy is equal to that of the voltage at the terminals of the power supply. Some of this potential energy is converted into kinetic energy as the electron leaves the cathode and is accelerated to synchronous velocity with the traveling rf wave on the anode. From that time on, however, as the electron drifts toward the anode, any loss of potential energy is converted into rf energy. When the electron arrives at the anode, it has zero potential energy but still has some kinetic energy due to its angular rotation. The difference between the potential energy of the electron at the cathode and its kinetic energy when it strikes the anode represents useful rf energy that has been generated.

From this consideration, an expression for electronic or dc-to-rf conversion efficiency can be derived. This expression is related to the value of magnetic field, B , placed across the tube and a parameter B_0 which depends upon the geometry of the interaction area and upon the frequency of operation.

$$\eta_e = \frac{2 \frac{B}{B_0} - 2}{1 \frac{B}{B_0} - 1} \quad (1)$$

where η_e = electronic efficiency
 B = the magnetic field applied

$$B_0 = 2 \frac{m}{e} \frac{2\pi f}{k} \frac{1}{1 - \left(\frac{r_c}{r_a}\right)^2} \quad (2)$$

and e/m = ratio of electron charge to mass
 f = frequency
 k = mode number
 r_c/r_a = ratio of cathode-anode radius.

It will be noted in Eq. (2) that B_0 is dependent upon the frequency of operation of the device so that, in general, a higher frequency of operation implies that a higher value of the magnetic field, B , must be used.

The relationship shown in Eq. (1) and plotted in Figure 3-9 implies that with high ratios of B/B_0 very good efficiency can be obtained. This is in fact the case providing care has been exercised in other design aspects of the tube. For example, in the case of the 8684 magnetron cited in Table 3-2, the value of B/B_0 used was 10. Eq. (1) indicates an efficiency of 95%. The actual operating efficiency of 86% also contains circuit losses and cathode backbombardment losses; and if these losses are assumed to be 6 - 9% of the dc input power, the electronic or dc-to-rf conversion efficiency of the 8684 magnetron is very close to the theoretical 95%. The measured performances of the other tubes listed in Table 3-2 are also shown in Figure 3-9.

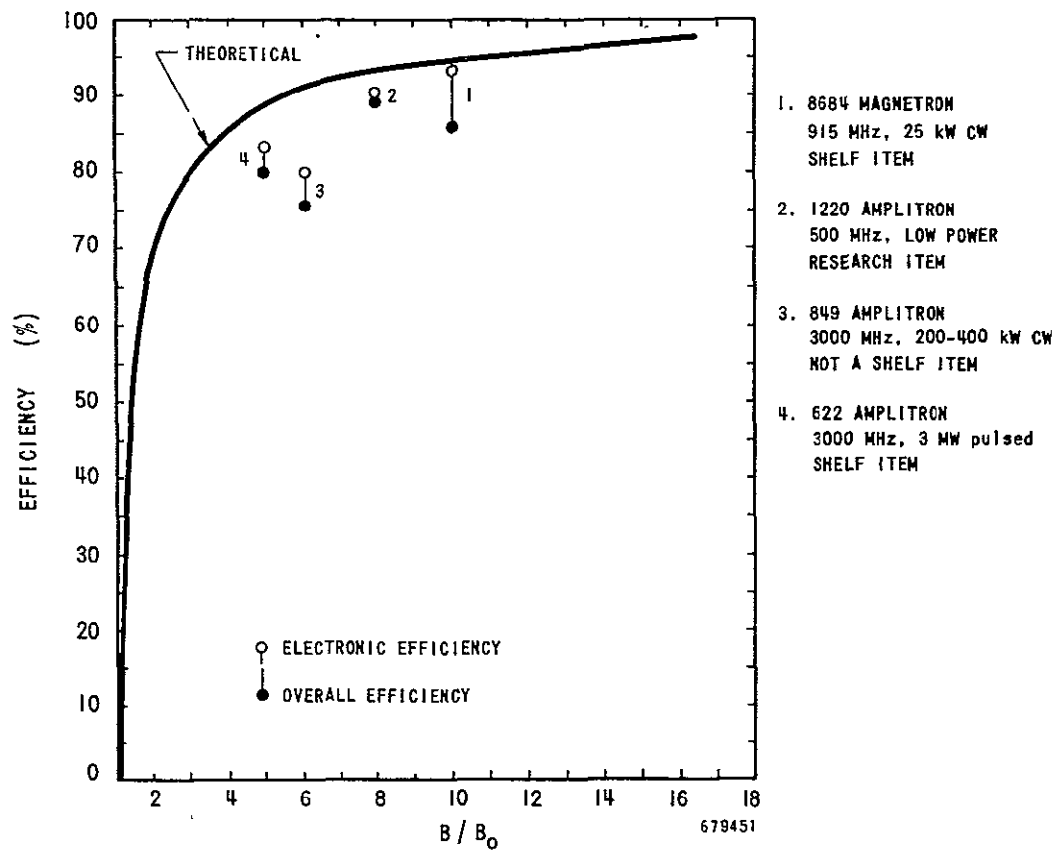


Figure 3-9. Magnetron and Amplitron Efficiency as a Function of B/B_0 Ratio

3. 2. 3. 5 The Importance of High Circuit Efficiency

The preceding material has indicated that with proper design procedures and the use of high B/B_0 ratios that an electronic efficiency of at least 90% is realizable and that 95% is a realistic objective to strive for. With these high electronic efficiencies care must be taken with the design or it will be found that the circuit efficiency will become the dominant element in the overall efficiency. This can be readily seen from an examination of item 1 in Figure 3-9, where the circuit efficiency is shown to be no greater than the electronic efficiency.

It is of interest to note that at 3000 MHz the efficiency of the crossed-field amplifier of the Amplitron form is better than 90% and approaches a figure of about 95%. It may be stated that if both amplifiers and oscillators make use of the same rf network configuration, the amplifiers will be more efficient since there are no standing waves involved to increase the circuit losses as is necessarily the case in the oscillator. One way to increase the circuit efficiency of an oscillator is to make use of the coaxial magnetron cavity to be described later.

Because of the circuit-loss dependence upon the skin depth which varies as the half-power of the wavelength, circuit efficiency is higher at the lower frequencies.

3. 2. 3. 6 The Impact of New Permanent Magnet Material Upon High Electronic Efficiency

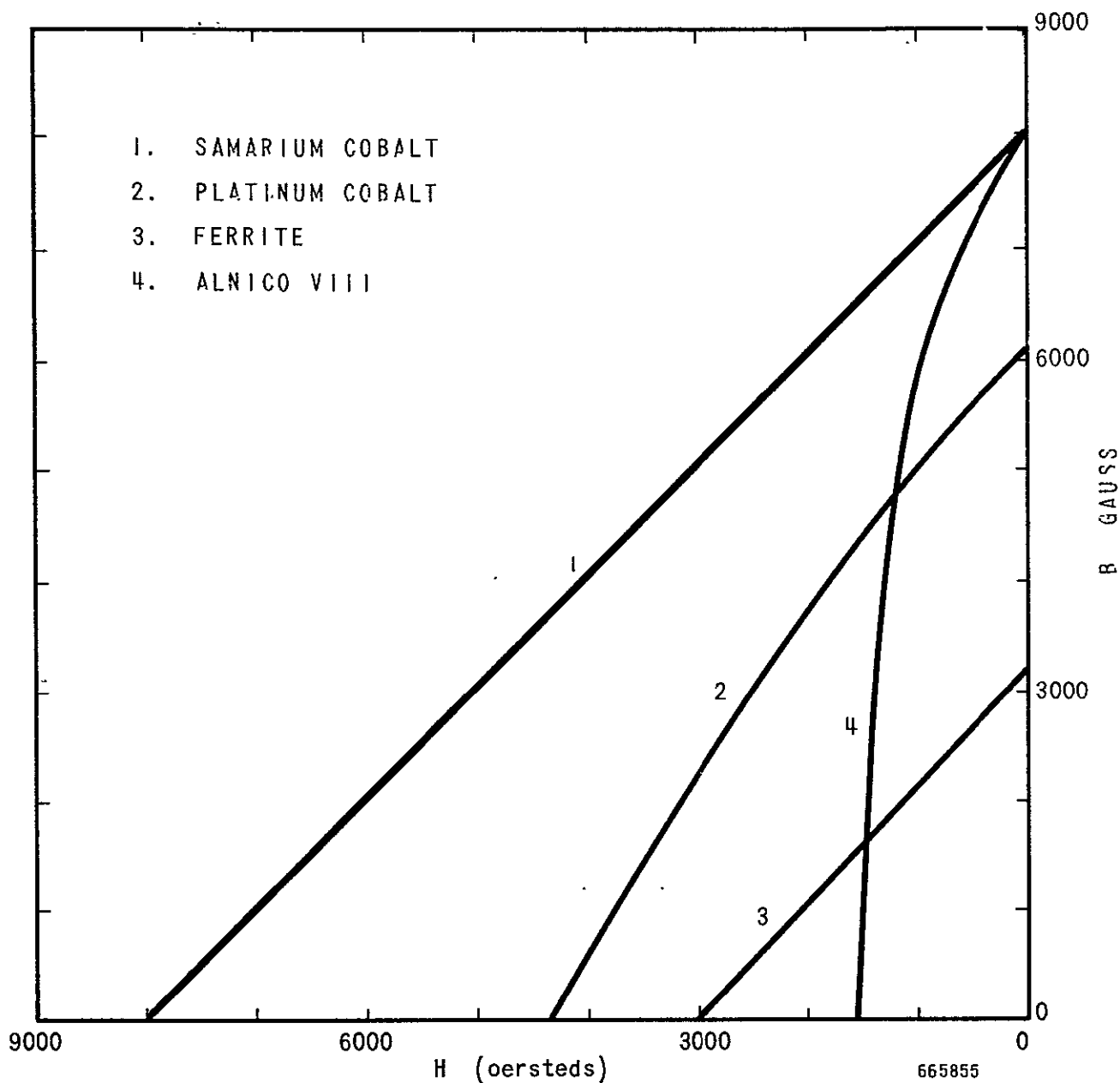
The principal factor which has prevented the design of crossed-field tubes possessing exceptionally high efficiency has been the difficulty of obtaining the high B/B_0 ratios needed for this purpose. This difficulty has been caused by the limitations of available permanent magnet materials whose application to obtain large B/B_0 ratios has invariably resulted in excessively large and heavy magnets. This situation would be doubly objectionable in the construction of the space power station because of the heavy weight of material that would have to be transported into space.

It is therefore very fortunate that a breakthrough in permanent magnet materials has recently occurred.^{23, 24} These materials are the so-called rare-earth cobalt materials. One of these materials, samarium cobalt, has now been developed to the point where substantial amounts are being made for a variety of uses, and its quality is under good control.

The impact which this material has upon obtaining the high magnetic fields required for efficient crossed-field interaction may be seen from an examination of Figure 3-10. Although the energy product of this new material is three times that of the conventionally used Alnico V, its weight saving potential is greater than that. Because of the high coercive force of the material, about ten times that of Alnico V, only a short length of the material is necessary to achieve the required flux density in the gap. This short length greatly reduces the amount of leakage flux present and therefore cuts down on the cross-sectional area of the magnet required. The saving in magnet weight in the types of tubes that are being discussed is probably more of the order of five to ten. The absolute weight of the magnet material for tubes that might be used for the microwave power generators in space may be only a few ounces for each kilowatt of power rating.

3.2.3.7 The Power Handling Capability of the Amplitron

It may be of interest to look at the power handling capability of the Amplitron, both in terms of what has been achieved, and what may be possible. Although the power handling capability is a function of a number of parameters, as the following analysis will show, it is highly dependent upon the wavelength or frequency of the radiated power. This is not only so because the scaling laws dictate that the active interaction areas of the tube scales as the square of the wavelength, but also because the skin losses are inversely proportional to the square root of the wavelength. As the wavelength is reduced, the first factor makes for a much larger tube, while the second factor makes for a more efficient one.



DEMAGNETIZATION CHARACTERISTICS OF MAGNET MATERIALS

The value along the Y axis (B) expresses magnetic flux. The value along the X axis (H) is the coercive force, or the ability of the material to resist demagnetization.

The product of $B \times H$, called "energy product", is a measure of the quality of the magnetic material, and is higher as the curves move to the left.

Figure 3-10. The coercive forces and flux density properties of several commonly used permanent magnet materials are shown, together with

The relationship between anode area, dissipation density, and dc-to-rf energy conversion efficiency n are summarized in Eq. (3).

$$\text{RF Power Generated} = (\text{Anode Area}) (\text{Dissipation Density}) \left(\frac{n}{1-n} \right) \quad (3)$$

A plot of this equation for an anode area of 1 cm is shown in Figure 3-11.

It is easily seen from Eq. (3) and Figure 3-11 that the rf power generated is highly dependent upon the efficiency and the dissipation density. We have already discussed efficiency, but have not discussed dissipation density.

One of the important recent discoveries is that it is possible to design cooling systems¹⁰ which will dissipate very large amounts of heat incident upon the external surface of the cooling system. Such cooling systems have been demonstrated in the laboratory to dissipate as much as 20 kilowatts per square centimeter of surface area. It is amazing then to see the impact of this high dissipation density combined with high efficiency upon the amount of power which can be generated for each square centimeter of anode area.

From Eq. (3) and Figure 3-11 it is seen that if we have an overall efficiency of 90% and a dissipation density of 10 kW per square centimeter, we can obtain 90 kilowatts of rf power output for each square centimeter of dissipation area. Is this a realistic possibility? To answer this question, we first note that conversion efficiency and dissipation density are independent of each other and that it should be possible in the laboratory to achieve such high figures. In practice, however, a highly efficient tube such as the 8684, which has an electronic efficiency of 93% and whose overall efficiency could probably be increased to 90%, has never been combined with such high dissipation density. Nevertheless, very creditable performance has been obtained from 76% efficient Amplitrons operating with an average dissipation

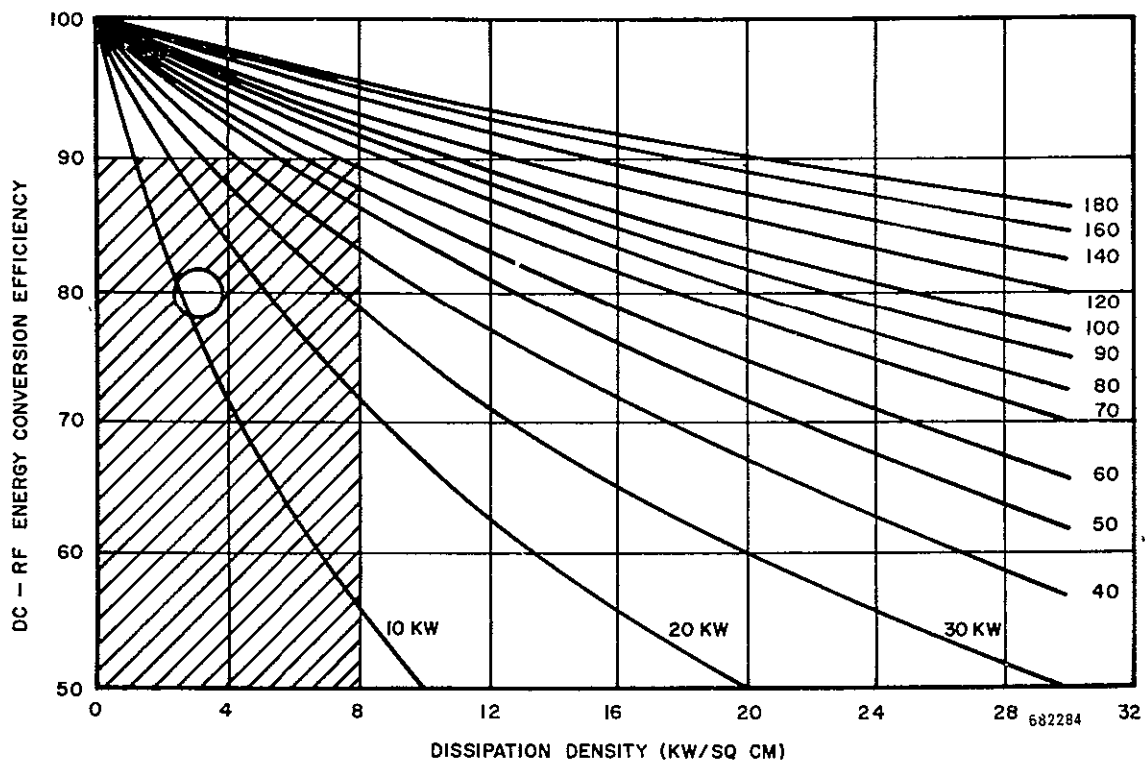


Figure 3-11. The relationship described in Equation (3) between rf power generated, overall efficiency, and anode dissipation density is plotted above. The rf output powers that can be generated for each square centimeter of anode area for various combinations of overall efficiency and dissipation density are shown as contour lines in the graph. Cross-hatched area indicates values that could be achieved based upon expected values of overall efficiency and values of dissipation density already achieved.

density of 3.3 kilowatts per square centimeter. Such an Amplitron, the 1224, is shown in Figure 3-12. This two section Amplitron, operating at 3000 MHz or a wavelength of 10 cm, delivered as much as 425 kilowatts of rf power while operating at 76% efficiency with a total anode area of 36 square centimeters.

Because of the potential importance of a cooling system capable of such high dissipation density, it may be desirable to describe it in more detail. Basically, as indicated in Figure 3-13, the cooling system consists of high velocity water flowing through cooling channels of small diameter. The inside of these cooling channels is faced with monel or other oxidation resistant material. The high velocity flow washes out any steam bubbles which tend to form and the surface condition of the channels remains in good shape because of the materials used.

In space, it may or may not be possible to use such a cooling system. Only further study could determine this. It seems likely that a dissipation system based upon the use of the heat pipe¹⁷ which has been introduced in recent years would be a likely candidate and should also be examined. The geometries of both the anode and cathode of the Amplitron lend themselves nicely to the use of the cylindrical heat pipe. The permissible operating dissipation densities will be less and the high operating temperature of the heat pipes will increase the rf skin losses somewhat.

3.2.4 Specific Recommendations for Microwave Generator Device Development

No one specific microwave generator device is the best for all of the potential applications for microwave power transmission in space. Generally, the device to be recommended will depend upon the transmitted power level. It is the purpose of this section to recommend different approaches for different power levels. However, it should be realized that in a specific application there may be other requirements that may bar the recommended approach. For example, the recommended device for a lower power application is the coaxial magnetron. However, this device is an oscillator and if for some reason an amplifier were essential, this approach could not be utilized.

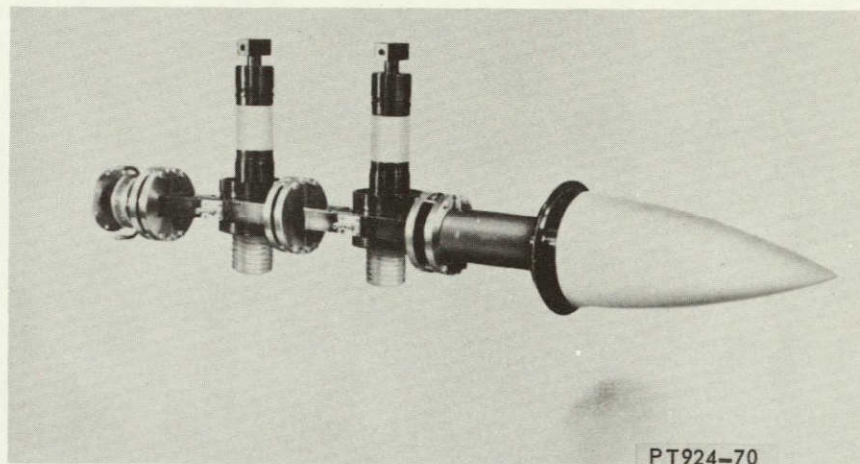


Figure 3-12. The QK849, shown above without permanent magnets, has been operated at 425 kilowatts of continuous power at a frequency of 3000 MHz (10 cm wavelength) at an efficiency of 76%. Overall dc to rf efficiency was computed after subtracting the rf drive power of 50 kilowatts from the rf output, making the net rf power contributed by the tube 375 kW. The tube was tested for several hundred hours at power levels in excess of 300 kW without any degradation of the high dissipation density cooling system.

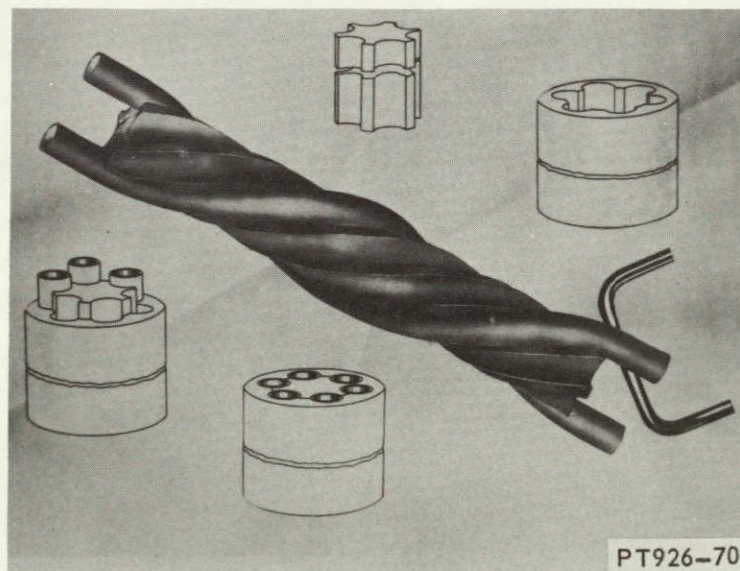


Figure 3-13. Pictorial description of the high dissipation density cooling system.

3.2.4.1 Coaxial Magnetron Recommended for Applications in the Transmitted Power Range of Zero to Ten Kilowatts

We have seen in Section 3.2.3.4 and Figure 3-9, that the crossed-field device can have very high electronic or conversion efficiencies associated with it, providing the B/B_0 ratios are sufficiently high. While this high B/B_0 ratio has been difficult to achieve for tubes in the 10 cm wavelength range because of practical limitations on the size and weight of the permanent magnets, this limitation has recently been eliminated by the development of remarkable new magnetic materials as described in Section 3.2.3.6.

Now that we have the practical means for achieving the high conversion efficiencies, we must proceed to a consideration of the circuit efficiency of the device. It will be noticed that the overall efficiencies of the tubes shown in Figure 3-9 are considerably lower than their electronic efficiencies. This difference is occasioned by circuit losses within the tube itself which absorbs a portion of the microwave power before it emerges from the tube. In general, these losses are greater in the oscillators shown on the graph than in the amplifiers. However, the use of an amplifier entails the need for an rf driver which adds to the overall complexity of the generator. Moreover, even the amplifiers are limited in their circuit efficiency because the rf power generated in the tube has to flow through the rf structure and this is a type of rf structure which has some loss associated with it.

For the sake of system simplicity, we would prefer to have an oscillator, but as we have seen from Figure 3-9, conventional magnetron oscillators have relatively poor circuit efficiency. However, a coaxial magnetron can have very high circuit efficiency. A coaxial magnetron^{14,15} is closely related to the conventional magnetron. The design of the interaction area and the mode of interaction of the electrons with the rf circuit is identical.

But the coaxial magnetron has a large high Q cavity surrounding the structure into which the power flows directly from each interacting set of vanes. In this large outer cavity, energy is propagated to the tube output with only a very small fraction of the loss that occurs in the conventional magnetron. The principle of the coaxial magnetron is shown in Figure 3-14.

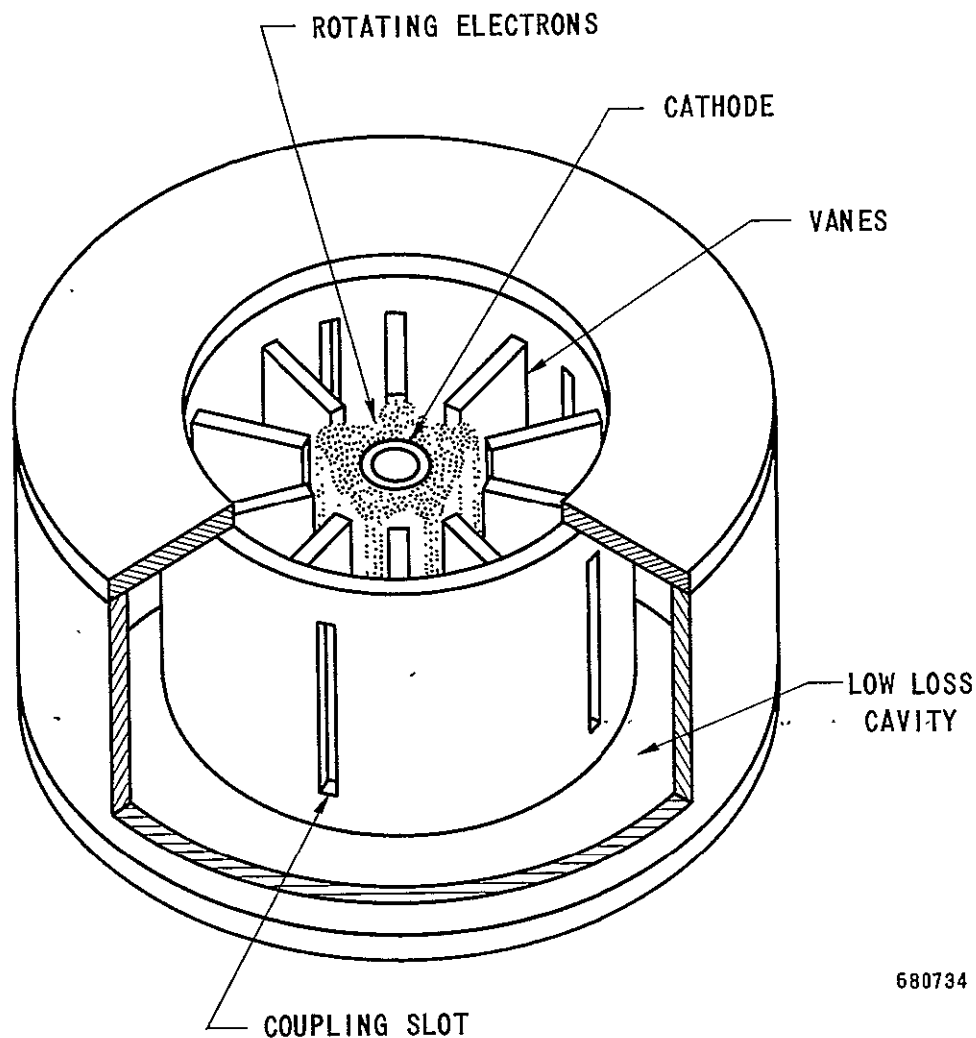


Figure 3-14. Schematic diagram of the coaxial magnetron. Large coaxial cavity, tunable in this example, surrounds a conventional interaction area. Microwave energy generated by interaction of electrons with the vane tips is fed out radially through the slots of the large outside cavity.

The principle of the coaxial magnetron is not new. It has been used most effectively in improving the overall performance of magnetrons in the high frequency ranges, corresponding to wavelengths of 5 cm and shorter. In fact, coaxial magnetrons have now replaced conventional magnetrons in most commercial and military requirements for power oscillators at the higher microwave frequencies. In all of these coaxial magnetrons the circuit efficiency is much better than it is in conventional magnetrons, and this has made better overall efficiency possible. However, because of the difficulty of obtaining the high B/B_0 ratios at high frequencies, the electronic efficiencies of the coaxial magnetron have not approached those of 90% or even 80%. With the lower frequency under discussion for this application, and with the samarium cobalt magnetic material now available, there is a unique opportunity to employ the coaxial magnetron approach to design a highly efficient 10 cm oscillator for the first time. It is expected that with this approach a generator with a circuit efficiency of 95% and an electronic efficiency of 95% to produce an overall efficiency of 90% could be developed.

With an overall efficiency of 90%, the total power to be dissipated would represent only 10% of the power input. In a tube design with a power output of 2 - 10 kW, this dissipation would represent 200 - 1000 W. It is reasonable to assume that in the first instance the tube would be sufficiently large to be capable of radiating the dissipated power directly into space, while in the second instance the use of supplementary heat pipe cooling might be necessary.

Before reaching a conclusion that the coaxial magnetron, which is a crossed-field device, is the preferred device for the application in mind, linear-beam devices such as the klystron and traveling-wave tube should be considered. However, the writer knows of no serious proposal to build such devices with overall efficiencies greater than 70% at the frequencies and power levels under consideration. Even at this much lower proposed efficiency a collector operating at a depressed voltage which greatly complicates the overall power supply is required. The coaxial

magnetron, with the potential of 90% overall efficiency, requiring no rf driver, operating at a nominal plate voltage of less than 20 kV, and making use of a long-life cathode, appears to have many attractive features.

3.2.4.2 Multiplicity of Hybrid Amplifiers in a Space-fed Active Array Recommended for very High Power Applications

If the power levels to be transmitted are very high, of the order of 500 kilowatts and more, then a space-fed active array in which each element of the array is a power amplifier should be considered. The major reason for this is that the total power level is broken down to lower levels in which each amplifier can probably directly radiate its dissipated power into space. Another advantage is that it eliminates the necessity for developing a super power tube which does not now exist in the 1000 kilowatt regime. Further, it is an approach which would allow the incorporation of solid-state devices. Although these devices would at first be used for low level gain only in the hybrid amplifier, the avenue is established for solid-state devices to play a more important role as a power amplifier if further development should make them of importance in this area.

The space-fed active phased array principle is schematically illustrated in Figure 3-15. As indicated, the active phased array is space-fed from a point source. Each hybrid amplifier has an input antenna which picks up the rf excitation. As shown schematically in Figure 3-15, each hybrid amplifier has within it a pickup antenna, a low-level gain section in those applications needing it, a phase shifter for setting the phase of the output, a low-level ferrite circulator or isolator, an Amplitron amplifier, and a means of initially adjusting the output amplitude of the hybrid amplifier. The Amplitron is of sufficient efficiency and constructed in such a manner that it can radiate its dissipated power directly into space.

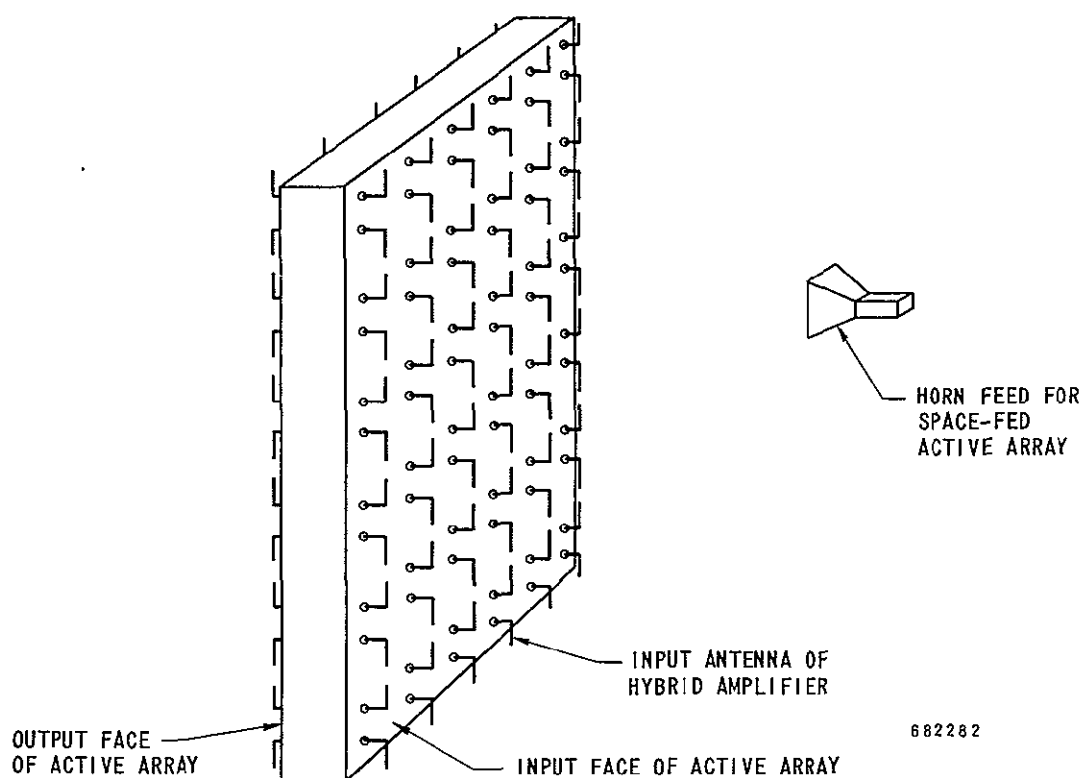
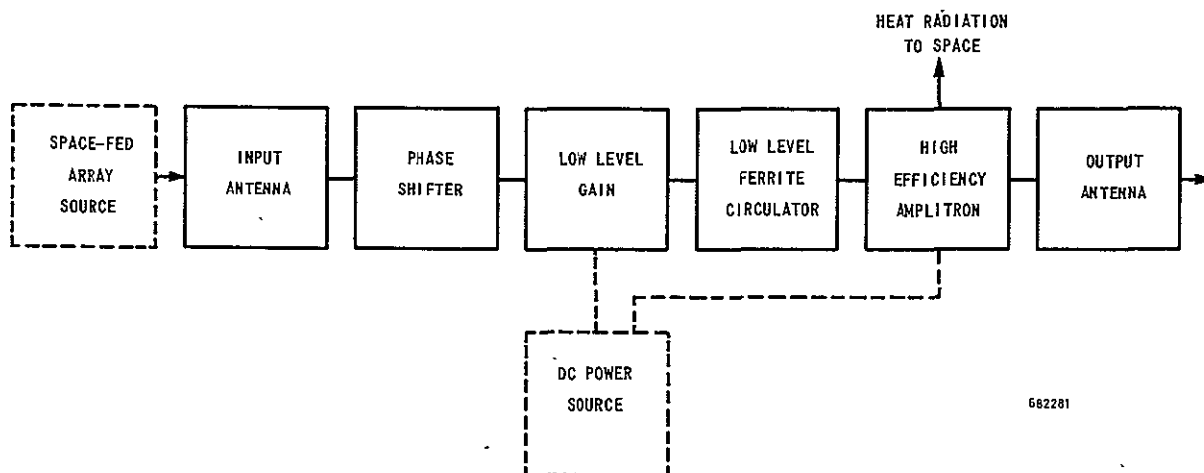


Figure 3-15. Schematic Showing Space-Fed Active Phased Array Principle

The hybrid amplifier as outlined in Figure 3-16 consists of a number of parts. However, with the exception of the Amplitron output stage, all elements are working at very low power and a strip line type of construction would be an ideal arrangement. The ferrite circulator need function only at low power level, since the reverse directed power to the circulator can be adjusted to an arbitrarily low value by a reflection trimmer in the output of the Amplitron. The fact that this system has a fixed frequency requirement makes this adjustment simple and practical.

The Amplitron output power gain would be of the order of 16 to 20 dB. This greater gain is again made possible by the relatively narrow bandwidth requirements of the system.



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Figure 3-16. Block Diagram of Active Hybrid Element of Active Phased Array

If the assumption is made that the Amplitron will be operating at the 250 watt output level or below, it is probable that it can be constructed so that it can radiate its dissipated power directly into space. To examine this further, let us assume an output of 250 watts, an operating efficiency of 85%, and a radiating temperature of 250°C . At this temperature, a black body will radiate 0.43 watts per square centimeter. A total radiating area then of 103 square centimeters will be required. If a single radiator fin is used, it can radiate heat from both sides, and so the total radiating area of 103 square centimeters would correspond to a square fin of 7 centimeters on the side. This area is less than the area which would be allocated to each radiating element in a phased array at a wavelength of 10 centimeters.

There is, of course, some additional build up of temperature within the tube in order to provide the temperature gradient to move the heat from where it is generated within the tube to the radiating fin. However, the copper vanes in the normal Amplitron construction are arranged in such a way as to efficiently conduct this heat to an external radiator. The temperature drop across the vanes is of the order of 30°C . Since the vapor pressure of copper is very low at temperatures of 300° to 400°C , the device can be run successfully at this temperature.

It may be of some interest to observe the microwave power density that can be radiated from a phased array which is radiation-cooled. If the example of a 10 cm hybrid amplifier is used above, it may be assumed that about 16 of these per square foot would be needed. This corresponds to a radiated power density of 4 kilowatts per square foot. The total power, P , radiated from an antenna having a gaussian illumination is $p_{\rho_0}\pi\rho_r^2$, where ρ_r is the radius within which 63% of the power is contained and p_{ρ_0} is the power density at the center of the array. If ρ_r is considered to be 4 ft, then the total power radiated would be 200 kilowatts. The outside radius of the radiator could be truncated to $2\rho_r$ without materially affecting the pattern or the total power radiated because the gaussian illumination drops very rapidly at radial distances greater than ρ_r .

In summary, the best approach to the microwave power generation for a power transmission system in space which must handle large amounts of power is a space-fed active phased array in which the active elements in the phased array are hybrid amplifiers consisting of solid-state amplification at low level and efficient Amplitrons for high level gain. The dissipated power is rejected into space by direct radiation from the Amplitron envelope.

3.2.4.3 Recommendation of Power Generator for Intermediate Power Levels

In the power range over ten kilowatts and up to the power range in which the active phased array becomes clearly the best choice, we make no specific recommendation other than to add the option of the use of a high-powered Amplitron which of necessity must be liquid or vapor-cooled and which must have some form of an rf driver. Coaxial magnetrons could undoubtedly be designed for operation at higher power levels than ten kilowatts but would have to be liquid-cooled. Active phased arrays could also be made at lower power levels, and if transistor amplifiers become efficient enough at frequencies of 3 GHz, they could be considered for a low-power active phased array type of transmitter. Clearly, in the intermediate power levels, all of the possible tradeoffs must be considered and a decision made as to the best approach among those possible.

3.3 Formation of the Microwave Beam and Transmission of Microwave Power

3.3.1 Introduction

Perhaps one of the most difficult aspects of microwave power transmission to accept is that the microwave power - excluding the conversion process at either end - can be transferred over long distances at near 100% efficiency. This acceptance difficulty is caused in large measure by the identification of free space power transmission with the communications applications of microwaves where only a minute fraction of the radiated energy is picked up in the receiver.

However, a relatively small group of people have made a thorough theoretical and experimental study of the matter and reported it in the literature.^{5,25,26,27,28} The material has not been mixed into the mainstream of contemporary microwave engineering for there has been no real use for the material in the communications area and the concept of power transfer by microwaves is

a concept that is also not in the mainstream of microwave engineering thought. Efficient transmission is, however, a reality and has been demonstrated in several different ways.

The early work in this area was done by Goubau and Schwering.²⁵ Later, the work was found of great value in the laser area²⁷ and the theory was further refined as well as given ample experimental proof. Work carried out at the University of Illinois in 1963 with millimeter radiation gave further experimental confirmation.²⁶ Work done at 3 cm under this contract provided further experimental verification.

3.3.2 The Gaussian Beam - Generation and Capture

This theoretical and experimental work in efficient free space microwave transmission is primarily based upon a solution of the wave equation which is identified with a beam of electromagnetic energy with a spherical phase front and a cross-section possessing a gaussian distribution of power. It is certainly possible to get efficient power transmission by utilizing beams that do not have a gaussian distribution. One of the common approaches is to assume a uniformly illuminated aperture and then assume the receiving aperture is illuminated by the far-field or Fraunhofer pattern corresponding to such illumination. The gaussian beam, however, is a better starting point because of the simpler mathematics involved, and it turns out that it has some practical advantages as well when the problem of illuminating the transmitting aperture is considered.

A gaussian beam can be formed in different ways. It is automatically formed between two spherical mirrors²⁷ having radii with certain restricted dimensions if the outside energy is introduced at a proper frequency. In this case, we have multiple reflections involved which lead to a resonance phenomena and critical frequencies corresponding to these resonances. The beam can also be formed by illuminating the transmitting aperture with a gaussian distribution of energy. The energy will then continue to flow through space with a gaussian distribution of energy and can be absorbed at the receiving point by means of a properly designed collector. In this case no multiple reflections are involved and there are therefore no corresponding resonances and resonant frequencies.

Efficient power transmission depends upon the size of the transmitting and receiving apertures, and also the shape of the phase front at these apertures. If we assume the optimum formation of the microwave beam and that all of the energy that is intercepted by the receiving aperture is absorbed by the receiving aperture, we find the relationship between the efficiency, aperture areas, distance of transmission, and wavelength of the radiation given in Figure 3-17.²⁸ The horizontal parameter in Figure 3-17 is

$$\sqrt{A_t A_r} / \lambda D$$

where A_t = Transmitting aperture area
 A_r = Receiving aperture area
 λ = Wavelength of radiation
 D = Separation of the apertures

In many applications the aperture areas will turn out to be appreciable and it will be desirable to consider a tradeoff between efficiency and aperture size.

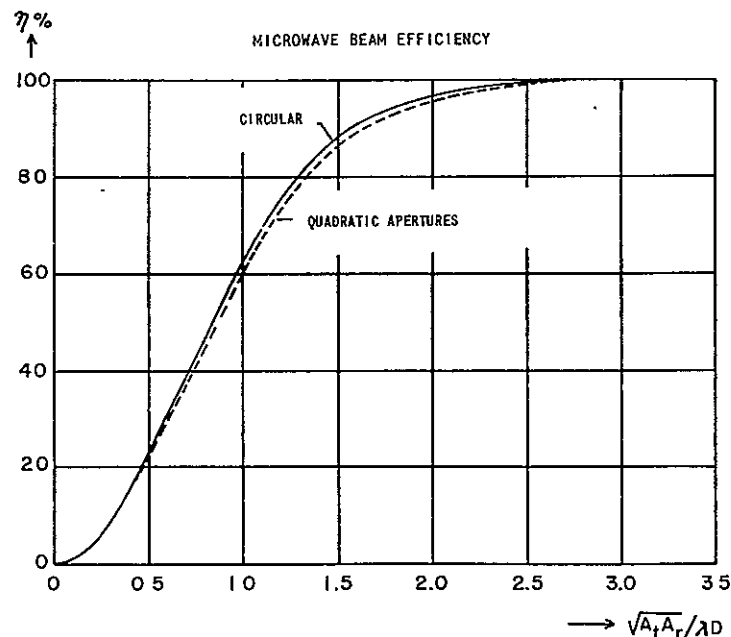


Figure 3-17. Microwave Power Transfer Efficiency Between Transmitting and Receiving Apertures

It has been assumed in the above discussion of efficiency that the transmitter aperture is properly illuminated. This can be accomplished but requires some care in doing so. There are several ways of illuminating the aperture. One is to construct a phased array in the plane of the aperture. Another is to illuminate a reflecting aperture by means of some kind of feed horn placed in front or to the side of the aperture. A third is to use a spherical mirror resonator with one of the mirrors being partially transparent, thus leaking the gaussian beam into space. In the space application, there are advantages and disadvantages to all of these arrangements. The feed horn technique is by far the simplest, but one of the difficulties with this has been obtaining a gaussian distribution of illumination. This difficulty has been overcome by the development of improved feed devices such as the dual mode feed horn.²⁹

The phased array approach is far more complex but has the very great advantage in very high power cases in that active elements in the array may efficiently generate the microwave power while getting rid of their dissipation by thermal radiation to space. This can be of utmost importance in several different applications. This type of array has been discussed in Section 3.2.4.2 where microwave power generation was considered.

The third approach is described in reference 32 and was experimentally investigated in considerable detail during this study. Although it initially appeared to be a sound approach, a microwave beam generated in this manner has a limited excitation efficiency. This is caused by the need for a relatively large excitation aperture on the input side of the cavity. The large input opening causes significant scattering losses which places a practical upper limit of about 85% on the beam excitation efficiency. A further disadvantage is the high Q of the device which necessitates isolation of the generator from the cavity by means of a ferrite circulator.

It was further assumed in Figure 3-17 that any power intercepted by the receiving aperture would be 100% absorbed by that aperture. This would be true in a reflector-horn type of arrangement only if the reflector illumination matched that produced by the horn. If there is a sharp discontinuity of illumination at the edge of the reflector as would often be the case where the receiving aperture is limited in size, a horn cannot be designed to provide the corresponding illumination, and some of the intercepted power would inevitably be reflected.

There are, however, other approaches to the capture problem. One is to make the receiving aperture in the form of a phased array so trimmed as to match the illuminating pattern of the incoming energy. Still another one, believed to be superior to this technique, is to break up the receiving array into a large number of apertures as in the phased array case, but to terminate each aperture with a microwave rectifier. This type of device, discussed in Section 3.4, has been termed the "rectenna".

3.4 The Microwave Receiving Antenna and Rectifier

3.4.1 Introduction

In some applications of microwave power transmission systems it is desirable to separate the device which intercepts the microwave energy at the receiving end from the rectifier device. When this approach is utilized, the transmitted microwave energy is collected in some type of antenna such as a parabolic reflector and the energy is then transmitted by waveguide to some form of rectifier device. The approach to a practical near-term system of this kind, however, is severely restricted by the limited availability of suitable rectifiers. At the present time the only microwave rectifier satisfactory from an efficiency and reliability point of view is the semiconductor diode. However, these devices are severely restricted with respect to the power which each one can handle, so that many diodes must be connected together in parallel or series to produce significant amounts of power output. If these devices are placed together in large numbers - for example, in a waveguide - radiation cooling is not sufficient and some auxiliary cooling means must be supplied.

In an aerospace application the collection of the energy by means of a parabolic reflector, large mouth horn, phased array, or other device has an additional disadvantage in that such an aperture is highly directive and must be pointed very accurately toward the transmitter in order to effectively collect the energy.

An excellent solution to the rf collection and rectification problem for many aerospace applications is the "rectenna". The rectenna is a device which combines the efficient semiconductor diode with the receiving antenna aperture in such a manner as to offer a large number of advantages. One example of this approach is a large receiving antenna composed of a large array of half wave dipoles each of which is terminated with a semiconductor bridge rectifier. The output of the individual rectifiers is collected by busses and fed into a common dc load. In this manner a number of desirable features are achieved: 1) the directivity of the large aperture is the same as that of a half wave dipole which, of course, has a high degree of nondirectivity, 2) the small semiconductor diodes are dispersed in such a manner that they can easily transmit their dissipation to adjacent metal elements which can conduct and radiate the heat and thereby eliminate the need for an auxiliary cooling system, 3) the construction accuracy requirements are much less than those required in the construction of large apertures in which the microwave energy is eventually collected into a single waveguide, and 4) a high degree of flexibility in mechanical design is afforded, including the distinct possibility of a rectenna which can be rolled up for storage purposes, 5) a very lightweight device weighing no more than ten pounds per kilowatt and as low as one-half pound per kilowatt depending upon the environment in which the rectenna is used and upon the incident power density, and 6) the high efficiency of the semiconductor diode can be taken advantage of while its relative low power handling capability is no disadvantage.

From this brief introduction it may be readily concluded that there is substantial reason to concentrate upon the rectenna concept for the receiving and rectification portion of the space microwave power transmission system. However, for those who may be interested in investigating other kinds of microwave devices which might be considered as rectifiers, a summary of their performance and literature references is given in Table 3-3. Even a cursory examination of other approaches will reveal the great efficiency advantage of the Schottky-barrier diode, and its relative advanced hardware status. Coupled with the many additional advantages which the solid-state device provides when it is combined with the rectenna concept, it seems almost

mandatory to concentrate upon the further refinement of the rectenna device. Hence, a large proportion of the work done under this study contract was concerned with the further refinement of the rectenna device, largely from an experimental approach.

For further background on the rectenna, the reader is referred to Appendix A which describes the rectenna concept, its development history, its basic properties, and some of the more recent developments made prior to the initiation of this study contract.³⁰

Table 3-3

<u>Type of Rectifier</u>	<u>Reference</u>	<u>Experimentally tried</u>	<u>Experimental Efficiency (%)</u>	<u>Results Avg. Power (W)</u>	<u>Pk. Power (W)</u>	<u>Remarks (in context of rectifier for space application)</u>
Magnetron analog	34, 35, 6	Yes	30	--	30,000	Operation requires that electrons leave cathode which is positive with respect to anode. This causes many complications and results in low efficiency.
Close-spaced thermionic diode	6, 36	Yes	50	300	--	Close spacing of cathode to anode causes problems. Efficiency is low. Cooling problems.
Analog of injected beam crossed-field device	6, 37	Yes	40	160	--	Efficiency is low. Cooling problem. Complex construction.
Analog of klystron device	6	No	--	--	--	Doubtful for efficiency and cooling reasons.
Cyclotron-wave rectifier	38	Yes	34	10	--	Doubtful for efficiency and cooling reasons.
Analog of TWT device		No			--	Doubtful for efficiency and cooling.
Schottky-barrier solid-state device	6, 39	Yes	80-90	0.1-5	--	Excellent for application. Low power is compensated for by using it in rectenna construction.

References are listed in Bibliography

3.4.2 Contributions to the Development of the Rectenna Device
Made under this Contract*

The contributions to the development of the rectenna which were made under this study contract are outlined below. The discussion of several of these areas will be carried out in more detail in subsequent sections.

1. Progress on the development of a design and test procedure in which the performance of the rectenna at the various levels of assembly can be evaluated. These levels are: the diode level, the rectenna element level (usually the dipole and rectifier combination), and the complete rectenna. Only by working out efficiency tests at the first two levels and relating these tests to the design of the overall rectenna can an orderly design procedure be evolved. An in-depth understanding of the rectenna and its components is essential for optimizing the overall efficiency of the device. Substantial progress was made in this area as described in Section 3.4.2.1. However, more remains to be done.
2. Assembly and test of a 134 element rectenna. The first rectenna to be assembled from known high efficiency elements was constructed under this contract. It was not an ideal rectenna because the collection efficiency was poor (about 25% of the incident microwave energy was reflected). It was, however, the first rectenna to be used in an overall microwave power transmission system in which the overall efficiency was carefully measured. (See Section 2.0.) While only an initial exploration of the reasons for the low capture efficiency was made, the 134 element rectenna remains as an important and essential means for the further investigation of rectenna capture efficiency.

* The efforts applied to items 4 and 5 were not charged to the contract but are reported because they directly relate to the development of the rectenna.

3. Preliminary investigation of the design of a flexible rectenna made by means of printed circuits to which are bonded Schottky-barrier diodes made by integrated circuit techniques. Some initial work was performed in this area and certain basic findings indicate the direction in which further work in this area should proceed.
4. First tests on Gallium Arsenide "flip chip" Schottky-barrier diodes. These devices are revolutionary in their potential impact on rectenna devices. Power handling capability of these devices is more than an order of magnitude greater than previous devices tested and their efficiency appears equally good. They also can operate at a higher temperature which makes it easier to radiate their dissipation. The first known tests on these devices as power rectifiers were made during the contractual period.
5. Development of balanced line impedance measuring equipment. The development of the rectenna elements was handicapped because of a lack of impedance measuring equipment for balanced microwave components such as each half wave dipole and the bridge circuit rectifier. The test gear was constructed and initially tested toward the end of the contract. It did not have much impact upon the work done under the present contract but will favorably affect any future work. These items will now be discussed in greater detail.

3. 4. 2. 1 Development of a Design and Test Procedure for the Various Levels of Rectenna Design

From the viewpoint of an engineering procedure for designing the rectenna, it is highly desirable to be able to break up the design considerations of the rectenna into the categories of 1) the diode rectifier itself,

2), the rectenna element, consisting, for example, of the half wave dipole and the bridge-circuit rectifier, and 3) the final assembled rectenna. Each of these categories needs to be understood very well from the theoretical point of view, and in addition, it is necessary to relate each category to the next higher category in the assembly. Efforts on rectenna design in the past have been limited to theoretical analyses and experimental measurements on the rectifier configuration itself, and to experimental work in the fabrication of the rectenna elements and the overall rectenna. At no time had there been an accurate efficiency measurement on the rectenna element itself, a step essential to the engineering design procedure.

One of the significant contributions of the work carried out under this study contract has been the design of a rectenna element whose efficiency has been measured within a closed system, and whose efficiency is in the 70 to 75% efficiency range. An attempt was also made to design the closed system test so that it would be related to the overall rectenna design. In this respect the results were not so successful. Within the closed system the reflection from the elements and even groups of elements was very low while from the finished rectenna the reflection was from 15 to 30%.

The closed system for checking the rectenna element is shown in Figure 3-18. It consists of the insertion of the dipole and rectifier combination into an expanded section of waveguide. In this arrangement the dipole is positioned about $1/4$ wavelength in front of the end of the waveguide which is normally short circuited by a metal sheet. This short represents the reflecting plane in the rectenna. The dipole also reflects itself in the walls of the waveguide.

A block diagram of the test set up is shown in Figure 3-19. Some discussion of the accuracy of the measurements with this set up is in order. As will be seen from Figure 3-19, there are a number of instruments involved in making the efficiency measurement. Fundamentally, there are two types of

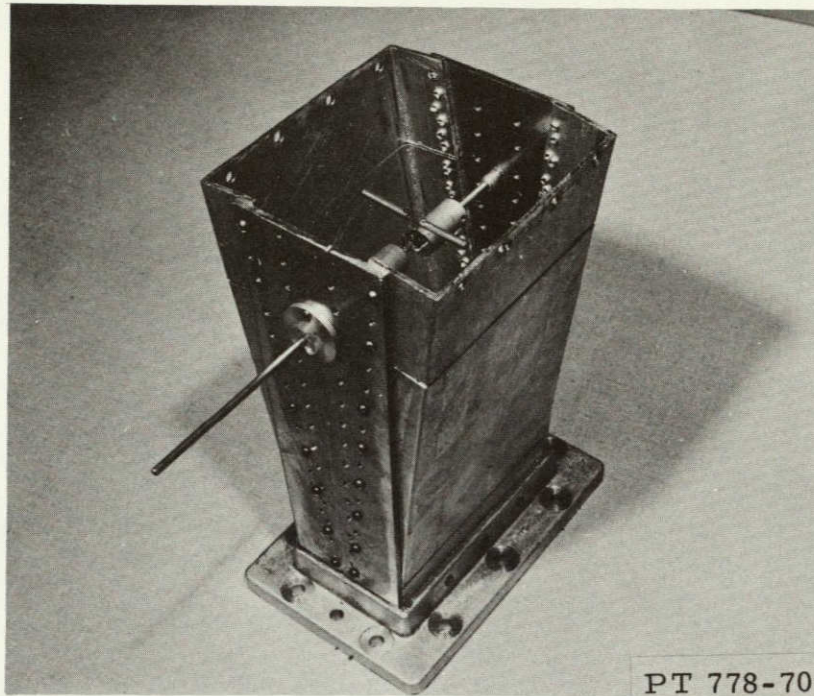


Figure 3-18. Test fixture for measuring collection and rectification efficiency of sub-element of rectenna array; it shows overall view of test fixture which fits on the end of a section of 2-1/4 in. x 4-1/2 in. waveguide.

measurement, the dc output measurements and the rf power measurement. With respect to the first, both the dc voltmeter and dc milliammeter used to measure the dc output power were checked against laboratory standards. The milliammeter was within 0.2% of the standard in the range in which it was tested. The voltmeter was within 1% of the standard in the range in which it was used.

The rf power input was measured by means of a 30 dB directional coupler and a power meter. Directional couplers normally retain their calibration and the one used had a manufacturer's calibration of 30.0 dB at 2450 MHz. However, Raytheon has a standards laboratory capable of checking directional couplers to 0.02 dB. The laboratory rechecked the directional

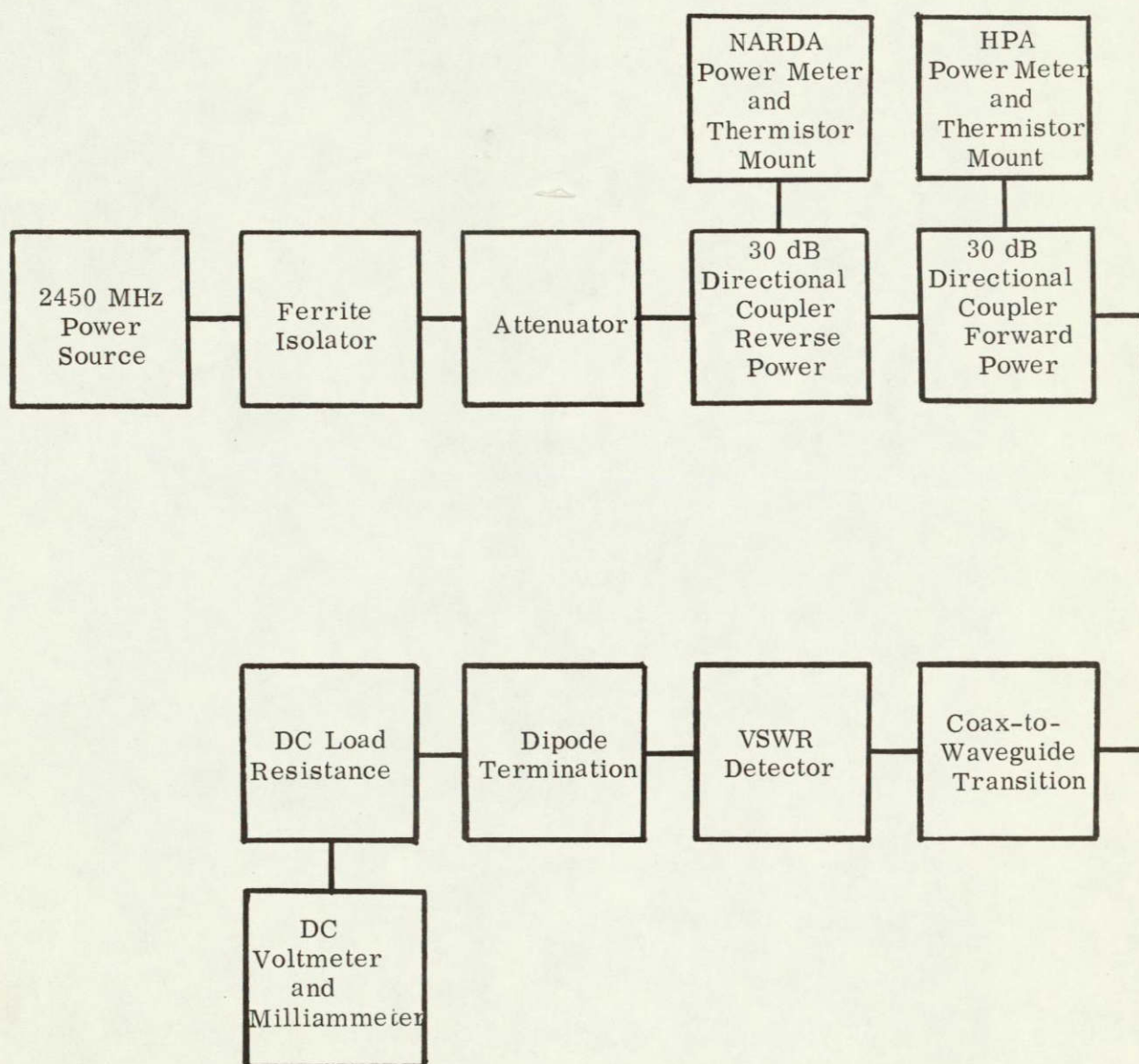


Figure 3-19. Block diagram of test equipment for measuring efficiency and input impedance of the "dipode" sub-element of a rectenna array.

coupler and found the ratio to be 30.0 dB at 2450 MHz. The input power measurement was made with a combination Hewlett-Packard 432A Power Meter and a 478 Thermistor Mount. These two elements are calibrated in combination and normally retain their calibration to within 2% over a long period of time. Just before the 74.5% measurement recorded in Table 3-4, the combined thermistor and power meter was checked and found to be within this 2% error over its entire range - and then the unit was trimmed to be directly on calibration at the 0.5 milliwatt point.

The conclusion is therefore drawn that the accuracy of the measurement is good - certainly to within a probable error of $\pm 2\%$.

Some of the experiments may be helpful in indicating the complexity of designing the dipole-bridge rectifier combination and designing a suitable test arrangement. Table 3-4 when used in combination with Figure 3-20 indicates some of the results achieved from various dipole-rectifier geometries.

It will be noted that two types of efficiencies have been used in Table 3-4. Overall efficiency is defined as the ratio of dc output power to incident power. Dipole* efficiency is the ratio of dc output power to power absorbed in the combination dipole and rectifier. The power absorbed by the dipole is defined as the incident minus the reflected power. Reflected power is computed from VSWR measurements or is measured by means of a directional coupler and power meter. Hence, we have two types of efficiencies. One is the efficiency of the dipole-rectifier combination by itself, while the other also involves the matching efficiency of the dipole-rectifier into the waveguide. From the standpoint of rectenna design we are interested in the overall efficiency.

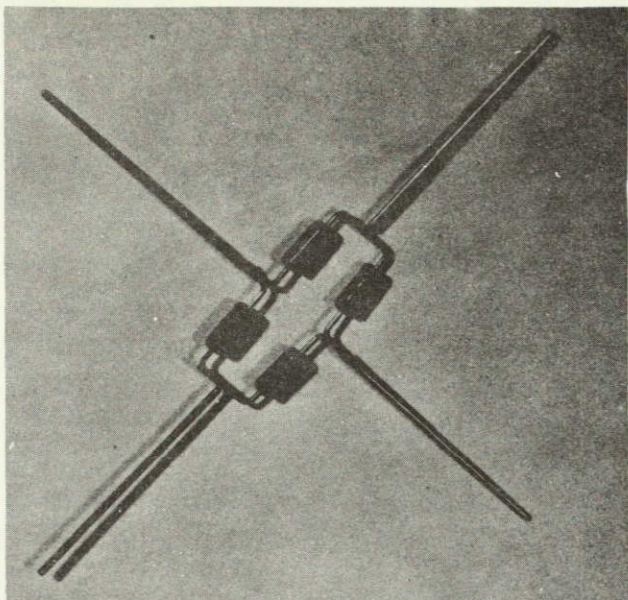
* The word "dipode" is derived from the words "dipole" and "diode" and denotes the dipole-rectifier combination.

Meas. No.	Dipole-Rectifier Config.	Wave-guide Test Config.	Construction Features of Dipole-Rectifier Combination					Incident Power MW	Reflected Power MW	DC Power MW	DC Load Resistance OHMS	Dipode Eff.	Overall Eff.
			Plane Config.	Bent Config.	Second Harmonic Chokes in DC Leads	1/8" Dia. Legs on Antenna	Additional Length Between Rectifier Bridge and Dipole						
1	Fig. 3-20a	1*	X					600	320	81	500	29%	13.5%
		1*						600	220	97	200	25%	16.0%
2	Fig. 3-20b	1*						500	140	234	155	65%	47%
		1*		X				500	130	210	75	57%	42%
3	Fig. 3-20c	1*		X	X			500	110	255	255	65%	51%
4	Fig. 3-20d	1*						500	110	285	280	73%	57%
		1*						500	72	308	365	72%	61.5%
		2*						500	113	292	290	76%	58.4%
		2*						500	71	292	197	68%	58.4%
		3*						500	70	265	230	62%	53%
		3*		X	X	X		500	50	290	270	64.5%	58%
5	Fig. 3-20e	3*		X	X	X	X	500	2	372	382	74.5%	74.5%

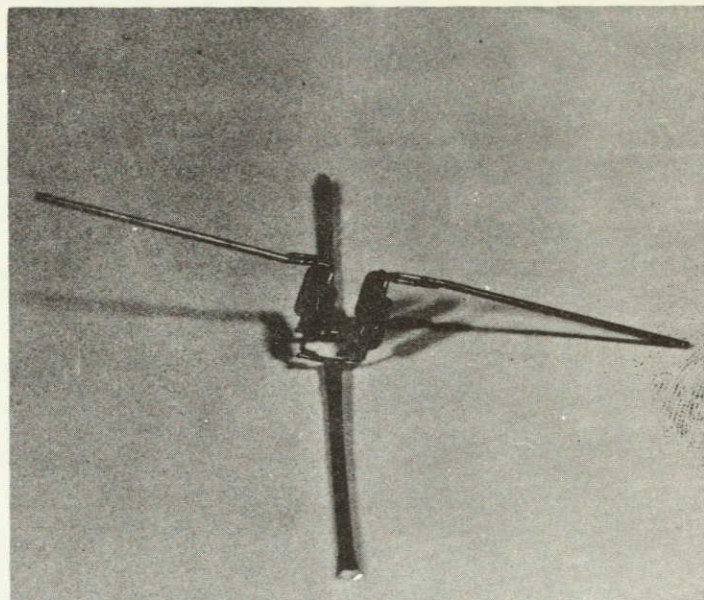
*Waveguide Configuration for Test:

1. Unexpanded 2-1/4 x 4-1/2 guide.
2. 2-1/4" dimension of guide expanded to 2-3/4".
3. 2-1/4" dimension of guide expanded to 4-3/8".

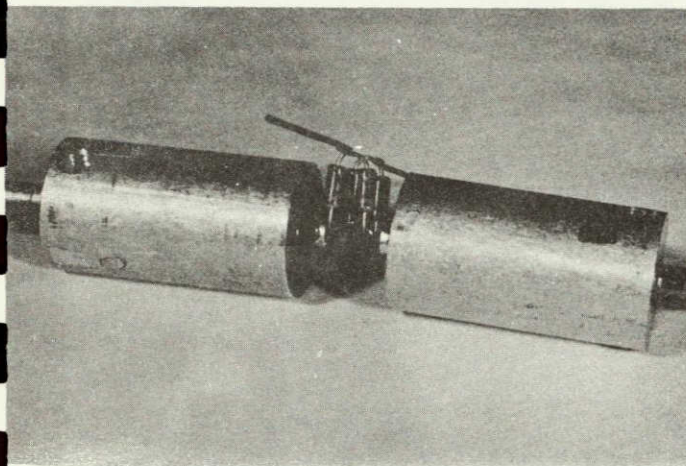
Table 3-4. Efficiency as function of configuration of dipole and bridge rectifier combination which terminates a waveguide.



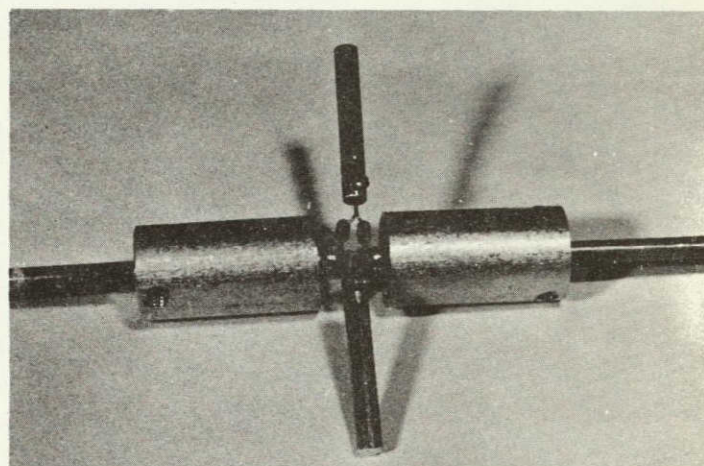
A



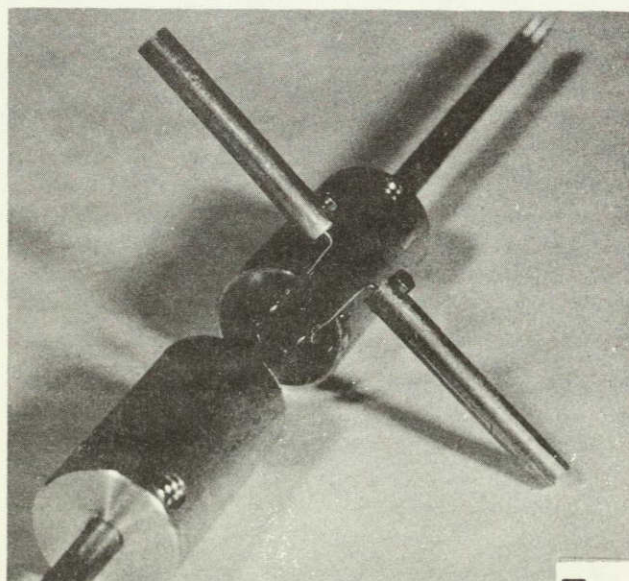
B



C



D



E

Figure 3 - 21

Various "dipode" configurations illustrating design and construction features which have been added to improve the collection and rectification efficiency of the device:

- (a) original device where rectifier bridge circuit makes up part of half wave dipole.
- (b) rectifier bridge circuit bent in "U" to permit use of conventional half wave dipole input.
- (c) chokes resonant at second harmonic frequency installed at dc output terminals of bridge circuit rectifier.
- (d) diameter of legs of half wave dipole increased.
- (e) most advanced configuration in which short section of matching transmission line has been inserted between dipole and rectifier circuit.

Table 3-4 indicates the improvement of efficiencies that were successively effected through 1) a change from completely planar geometry (Figure 3-20 (a) in Table 3-4) to a bent configuration (Figure 3-20 (b) in Table 3-4), 2) the use of second harmonic filters in the dc collector busses (Figure 3-20 (c) in Table 3-4), and 3) use of larger diameter legs in the dipole (Figure 3-20 (d) in Table 3-4). There was also a change in the waveguide configuration involved. It will be noted, however, that with all these configurations there was a notable amount of power reflected and a notable difference between overall efficiency and dipole efficiency. It may be noted that the match was better with the largest expansion of the waveguide. Ultimately, the design was improved to eliminate the reflection losses and to bring the overall efficiency of the dipole to a figure of 74%. The improvement in match was obtained by adding a section of transmission line between the dipole and bridge rectifier. The configuration is shown in Figure 3-20 (e) and the experimental results included in Table 3-4.

At the time this work was done, there was no measuring equipment to examine the input impedances to the bridge rectifier and to the dipole antenna. Standard VSWR measuring equipment is not suitable for this purpose. However, toward the conclusion of this phase of the contract, a VSWR detector for a balanced line system had become available. A check on the bridge rectifier with a short section of transmission line attached and with a dc output load resistance of 450 ohms gave an impedance point on the Smith Chart shown as point No. 1 in Figure 3-21. Also shown in Figure 3-21, as point No. 2, is the rf impedance looking into the input terminals of the dipole antenna as it was positioned in the waveguide test fixture. The capacitive reactance of the dipole input impedance is largely cancelled out by the inductive reactance of the input impedance to the rectifier and a good match results. However, if the short section of transmission line is removed from the input to the rectifier, a slight capacitive reactance is obtained and there is no cancellation of the reactance of the dipole antenna. A mismatch of 8.5 dB exists in the system causing a reflection of about 20% of the power input.

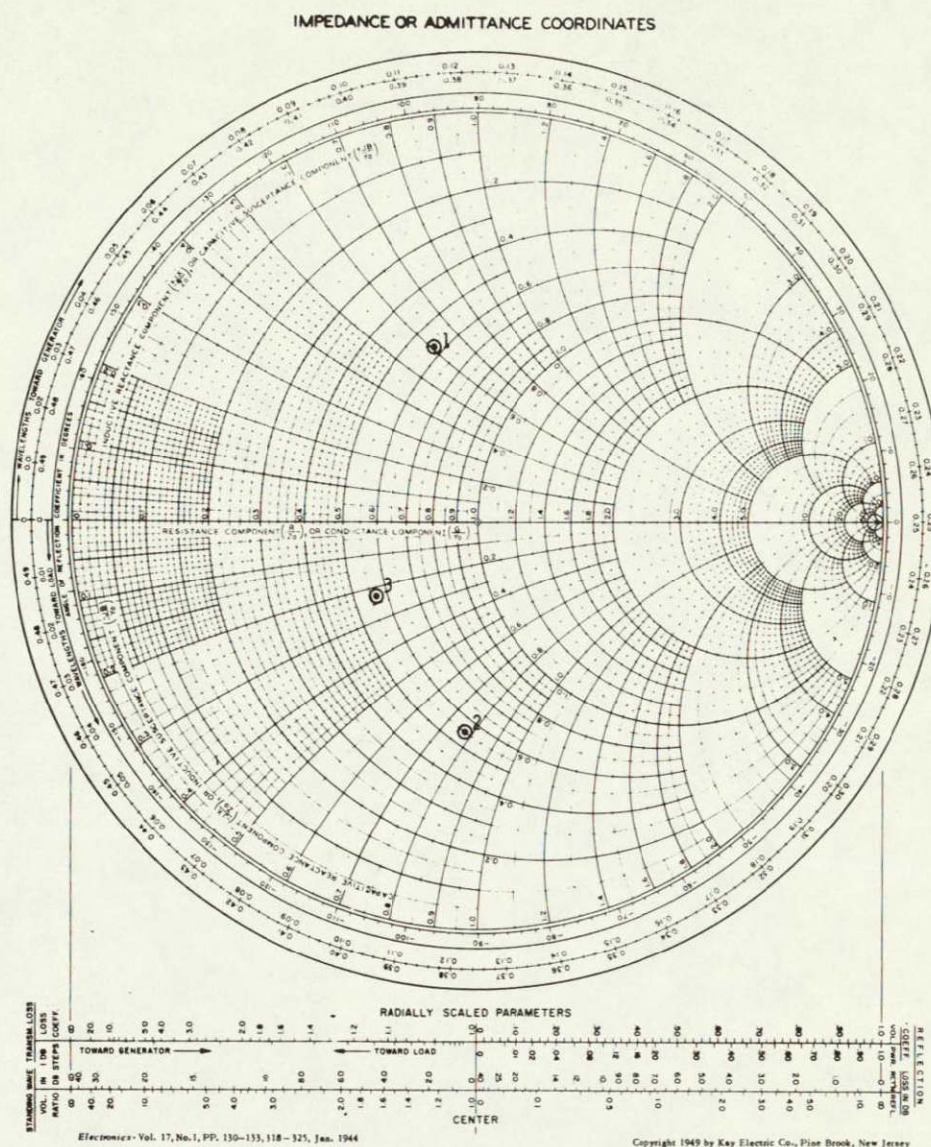


Figure 3-21. Smith Chart Plot of Bridge Rectifier Input Impedance (Point 1) and Dipole Input Impedance (Point 2) Showing How the Reactive Portions of the Input Impedance Tend to Cancel Each Other Out and Provide a Good Match. Point 3 is the Bridge rectifier itself with no input transmission line. Mismatch between points 3 and 2 is 8.5 dB. All impedances are normalized to the characteristic impedance of the transmission line of the test equipment which is 158 ohms.

With the successful use of the closed system for measuring the efficiency of the individual rectenna element, it was logical to think of arranging a number of such elements in a format identical with their arrangement in the complete rectenna, and to check out a small array in a closed system. Since the final objective was to construct a large rectenna, it was necessary to consider the desired format of the individual element from the viewpoint of manufacture and then assembly in the large rectenna. Consequently, a number of minor changes were made including redesign of the chokes in the dc collection leads and the use of a "bow tie" dipole configuration rather than the 1/8 in. diameter dipole. This final design is shown in Figure 3-22.

Several dipole and rectifier combinations (dipodes) were then assembled, as nearly identically as possible, and tested in the rectangular waveguide. There was a gratifying amount of similarity in the performance of the various diodes. The efficiency measurements of the units are shown below.

<u>Dipode Serial Number</u>	<u>Efficiency (%)</u>
1	71.5
2	70.8
3	70.0
4	71.0
5	72.0
6	72.8
7	69.0
8	71.0
9	72.8

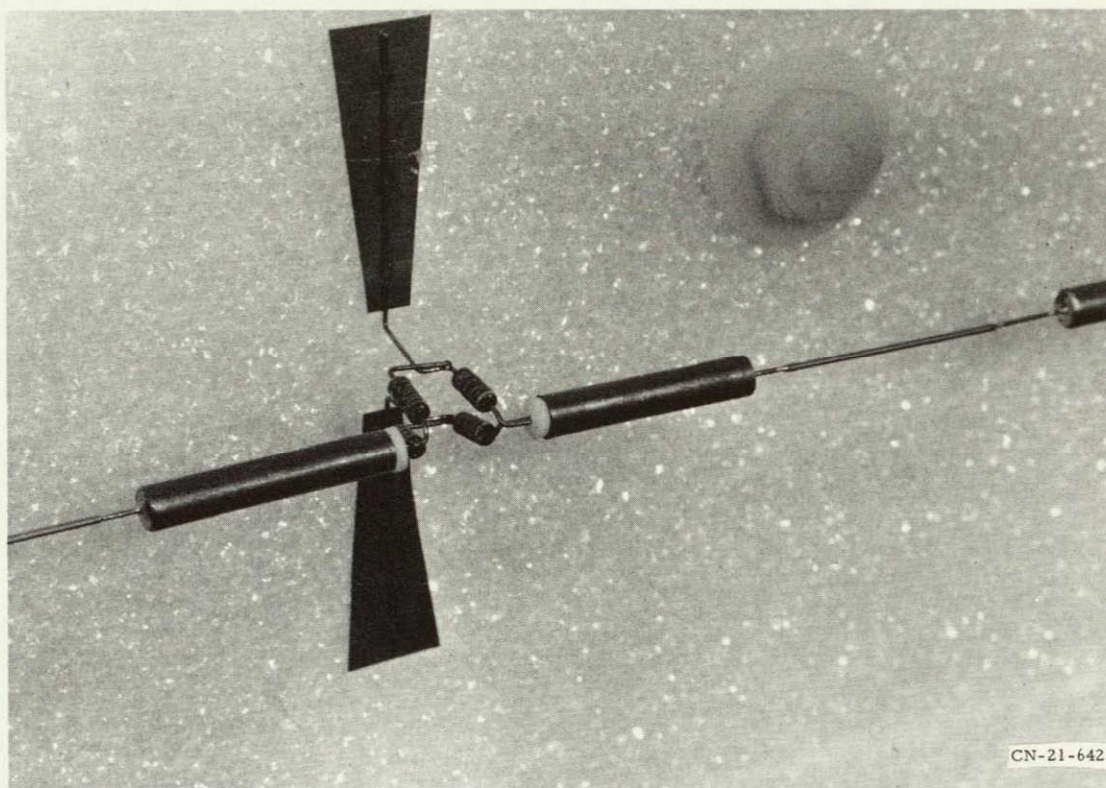


Figure 3-22. Rectenna Element

These dipodes were then assembled into a rectenna array as shown in Figure 3-23. In order to obtain a reliable measure of efficiency, a closed system was again used. In this case, a standard 2-1/4 in. x 4-1/2 in. waveguide was expanded into a large pyramidal horn of square cross-section with an opening about one foot square. The characteristics of the horn near its output are very similar to that of space and it is, therefore, logical to insert a rectenna shown in Figure 3-23 into the throat of the horn as shown in Figure 3-24. This constitutes a closed system where again the ratio of rectified dc output to the rf power input can be very carefully measured. The method does have some shortcomings in that if there is reflection of energy from the rectenna then higher order modes will be set up in the horn and may result in a distribution of energy inside the horn which departs from the simple sinusoidal distribution of electric field across the horn. If, however, the rectenna is well-matched, the reflections and therefore the mode difficulty are minimized. An overall efficiency of 66% was achieved.

The design work and measurements that have just been described have significance in that it is the first example of a rectenna array to be measured in a closed system so that the overall efficiency could be accurately obtained. It is also significant that the 66% efficiency achieved is significantly above the efficiency of the rectenna of 51% previously reported upon by Professor George of Purdue,⁶ and which made use of a measurement technique in which edge effects were difficult to estimate. Although efficiencies of the order of 70% and even higher have been predicted for the overall capture and rectification efficiency of the rectenna, these are the first efficiency measurements to have approached that figure.

In summarizing this section, it is believed that important steps have been taken to demonstrate high efficiency of rectenna elements, in the range of 70 to 75%. These steps have consisted of designing closed system measurement techniques as well as configuring the elements themselves. Finally, an efficiency of 66% was measured on a collection of nine such elements in a rectenna configuration but in a closed system of measurement.

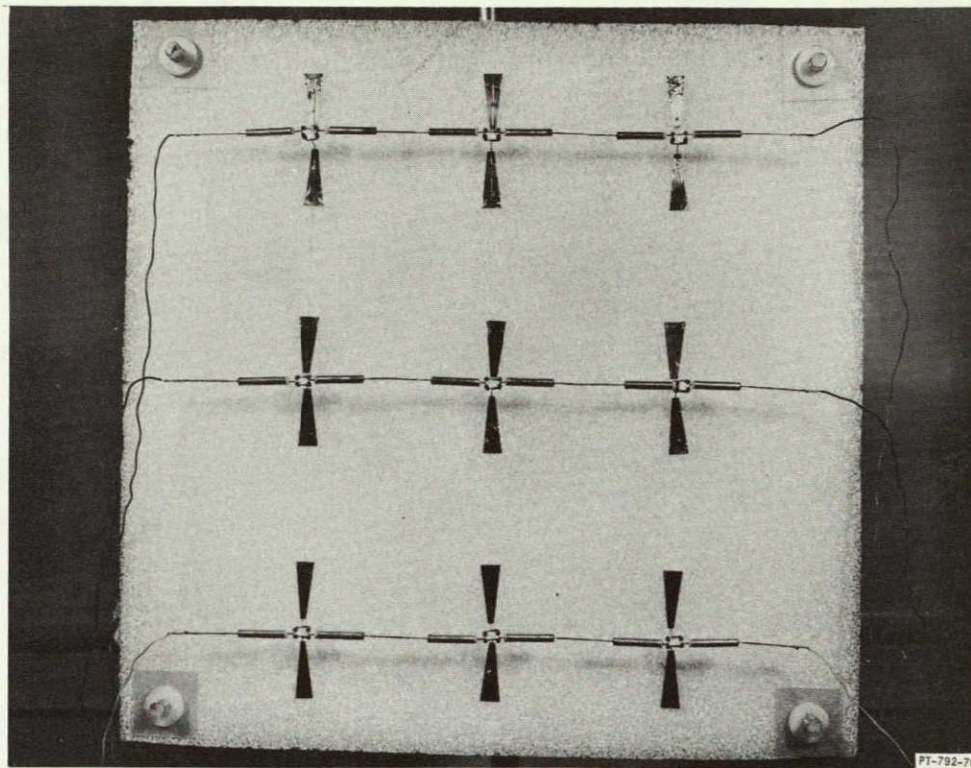


Figure 3-23.

A small segment of a rectenna array consisting of nine dipodes. Each dipode consists of a half-wave dipole matched into a bridge-rectifier consisting of 4 HPA 2900 Schottky barrier diodes. The dc output of each rectifier is fed through quarter wavelength chokes at the second harmonic frequency. In the arrangement shown above the outputs of three diodes are connected in series. The rectenna was tested in a pyramidal horn as shown in Fig. 3-24. The output of each group of three dipodes was fed into a 500 ohm resistor. The ratio of dc power output to rf power fed into the throat of the pyramidal horn was 0.66--for an overall rectenna efficiency of 66%. The power output at this efficiency was typically 2 watts.

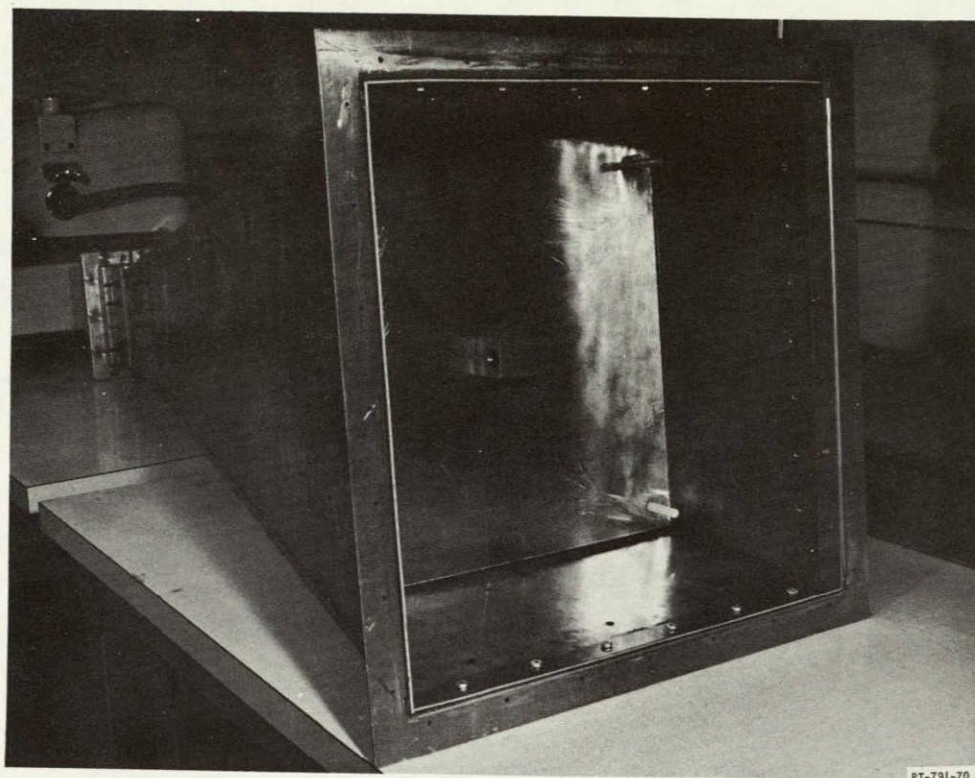


Figure 3-24. Closed system arrangement for measuring efficiency of nine-element section of rectenna. Back of rectenna may be seen inside pyramidal horn. Horn is excited from standard 4-1/2 in. x 2-1/4 in. waveguide.

Measurements on the completed 134 element rectenna modeled after the nine element section shown in Figure 3-23 is discussed in Section 3.4.2.2.

3.4.2.2 Complete 126 Element Rectenna Design and Test

Working from the nine element array shown in Figure 3-23 which had been tested and found to operate at an efficiency of 66% within a closed system, a complete rectenna consisting of 126 elements spaced identically with those in the nine element array was constructed. This rectenna, shown in Figure 3-25, was utilized in a complete microwave power transmission system in which the overall dc-to-dc efficiency was 28%. These measurements are reviewed in Section 2.0.

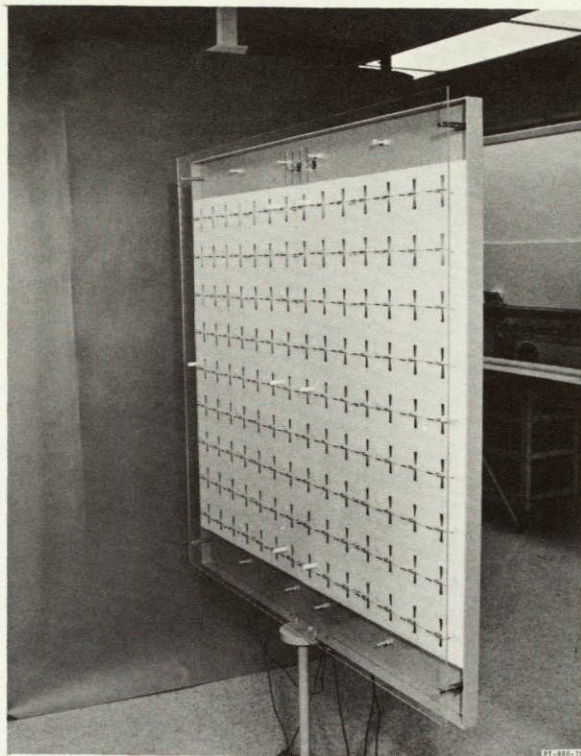


Figure 3-25. 126-Element Rectenna

It soon became evident that the rectenna was not working at an overall efficiency of much more than 50%. Initial measurements of reflected power from the rectenna indicated that about 25% of the incident power was being reflected, which would degrade the overall efficiency by a factor of one-fourth.

Subsequently, an attempt was made to measure the amount of the reflected power by using standing wave measurements made with the aid of a probe moved in front of the rectenna. These measurements were made under various conditions, including the situation where the rectenna surface was nearly uniformly illuminated and where the power density of the illumination varied by a factor of at least ten from the center of the rectenna to the edge of it. It would be expected that under the latter circumstance, various portions of the rectenna would operate at different matching efficiencies and that the standing wave ratio would vary across the surface of the rectenna. To understand the reason for this, it is necessary first to recall that the capture efficiency of the individual element of the rectenna depends upon the effective dc load seen by the device, and secondly to note the way in which the individual elements in the rectenna are coupled into a common dc load.

Figure 3-26 indicates the manner in which these individual elements are connected. Near the center of the board, three elements are connected in series, while, on the outside of the board, four elements are connected in series. The clusters of series-connected elements are then all connected in parallel across a common load resistor, as shown in the diagram. Each of the series-connected strings has a current jack in it so that the current can be measured in that string. Figure 3-26 indicates how the connections are made.

It should not be inferred from Figure 3-26 that this is the only possible connection of the series-connected elements. The rectenna design affords a considerable flexibility with respect to the way in which it is operated. For example, each of the 36 clusters of series-connected elements could be terminated in a separate load resistor and the current and voltage associated with that load resistor independently measured. However, there was not enough time to operate the rectenna under other than the common load format shown in Figure 3-26.

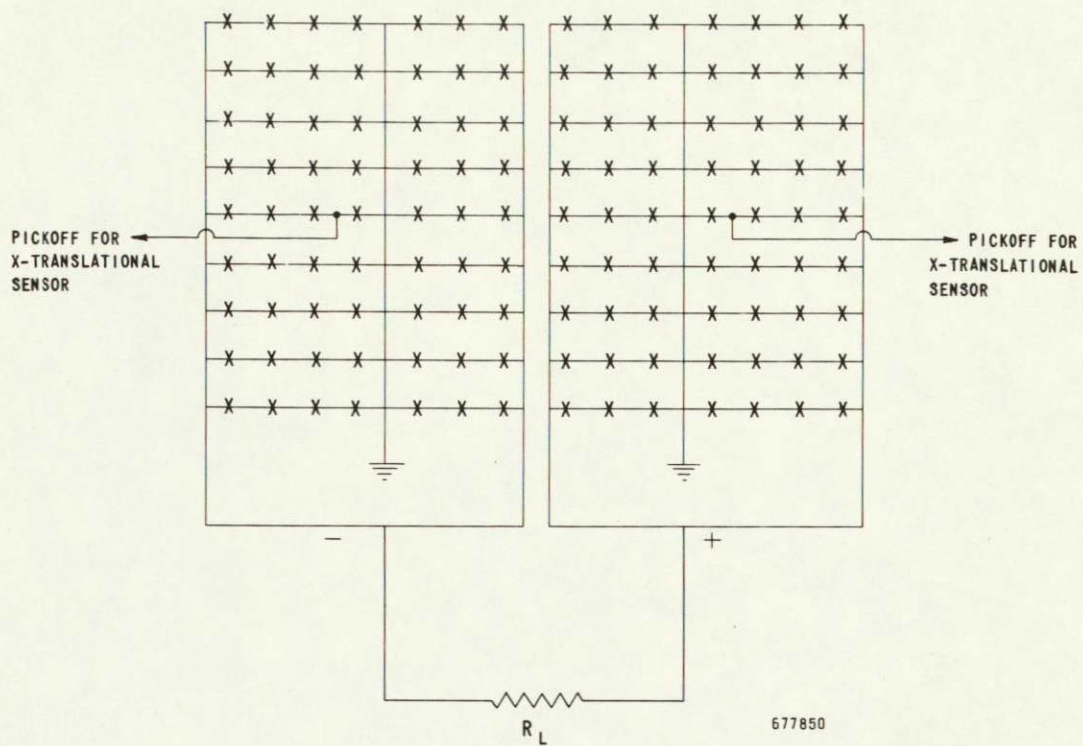


Figure 3-26. Schematic diagram showing how the 132 elements of the rectenna are coupled into one common load. In the diagram each "X" indicates an element. The additional function of two of the elements as position sensors is also indicated.

When we look at the impedances into which the various portions of the rectenna operated when the rectenna was illuminated at a distance of 57 inches from the mouth of a pyramidal trapezoidal horn we find a considerable variation. The data below follows the configuration of Figure 3-26. That is, the impedance of 92,000 ohms given as the top number in the most left-hand column corresponds to the load seen by the uppermost cluster on the left-hand side of the rectenna as depicted in Figure 3-26. Operating dc output level was 37 volts and 187 milliamperes.

92,000 ohms	3,700 ohms	4,650 ohms	12,300 ohms
5,300	1,480	1,850	3,100
2,300	880	975	1,540
1,370	710	785	1,150
1,320	660	690	1,090
1,320	685	750	1,150
1,950	900	1,030	1,760
3,400	1,270	1,325	3,100
∞	2,700	3,700	37,000

By way of contrast, the load is much more evenly distributed when the rectenna is located at a distance of 16 feet from the transmitter, because the rectenna intercepts only the central portion of the microwave beam. Operating level for the performance below was 64.5 volts and 255 milliamperes for the 16 foot separation condition.

2,900	2,700	2,500	2,930
2,500	2,500	2,300	2,560
2,150	2,000	1,800	2,160
2,300	2,000	1,900	2,300
2,000	2,300	2,000	2,150
2,000	2,000	1,950	2,150
2,150	1,950	1,850	2,150
2,500	2,600	2,150	2,500
2,950	2,900	2,500	4,000

In the first set of data, we note a variation of impedance level of over 10 to 1, while in the second case there is a variation of only 2.2 to 1. Yet, in both cases there was a substantial reflection of power from the surface of the rectenna. The first case was the one in which an overall efficiency from rf output to dc output from the rectenna of 40.5% was obtained as reported in Section 2.0. The reflected power from the central portion was about 30%, while about half way between the center and edge it was about 10%.

The second case in which the dc operating impedance level was nearly uniform over the surface closely corresponds to the impedance levels which produced high overall efficiency and very low levels of reflected power in the case of an individual element tested in a closed system and again in the case of the cluster of nine individual elements also tested in a closed system. The VSWR measurements in front of the rectenna indicate a ratio of about three to one. This would mean a reflection of 25% of the power, and this in turn means that the overall efficiency is degraded by 25%. The degradation in overall rectenna efficiency associated with the measured VSWR is consistent with estimates of overall rectenna efficiency obtained by other means. These measurements, based upon estimates of the amount of the microwave beam which impinges upon the rectenna surface, indicate an overall rectenna efficiency of from 50 to 54%, downgraded from the 66% obtained from measurements on the nine-element cluster tested in a closed system.

By analogy, with a reflective load terminating any transmission system, it should be possible to reduce the reflections by shunting the proper value of reactance across the transmission system at the proper distance from the reflective load. An inductively-reactive impedance sheet was made up from parallel aluminum rods, mounted in a position parallel to the plane of the rectenna, and moved back and forth with respect to it. The experimental set-up is shown in Figure 3-27. While the movement of the inductive sheet causes a cyclical variation in dc power output, as was expected, the

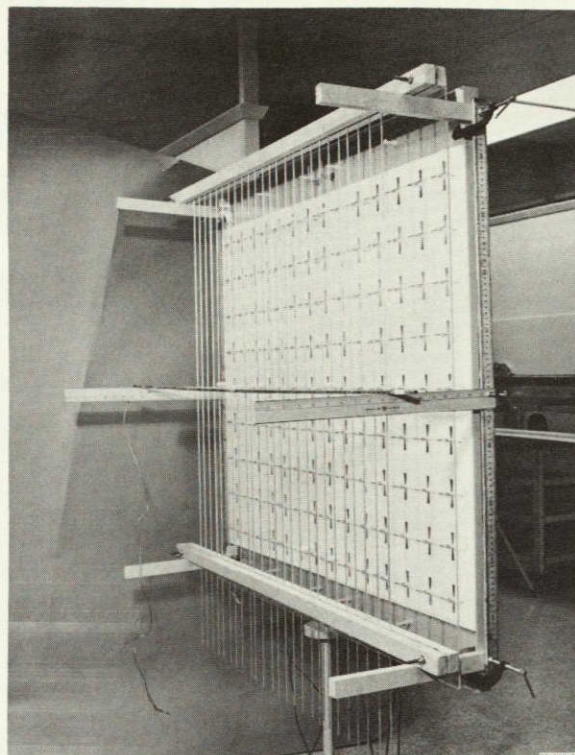


Figure 3-27. Experimental set-up for checking the effect of an inductive grating upon the amount of power reflected from the rectenna and upon the rectenna overall efficiency.

maximum power during the cycle was no greater than the dc power output without an inductive grating in the system. There are several possible explanations: 1) the resistive loss associated with the inductive grating is considerable, 2) there are substantial losses introduced at the open ends between the inductive grating and the array, and 3) the reflective loss is of a nature which cannot be compensated for by an inductive grating, that is, the simple transmission line analogue does not hold.

In summary, the rectenna which has been constructed, is not optimally designed. There are substantial reflective losses which should be removed. The nature of these losses is not completely understood. More study and measurements are necessary.

3.4.2.3

Preliminary Investigation of a Flexible Rectenna

The concept of a flexible rectenna was investigated as part of the study. In this area the help of the microelectronics laboratory of the Bedford Laboratory of the Raytheon Company was enlisted. This laboratory has equipment for the bonding of beam leads, normally to a substrate consisting of a thin application of gold to alumina.

The flexible rectenna involves the concept of a flexible printed circuit which consists of both microwave circuits and dc-buss circuits to which are bonded the diode rectifiers. The general concept of the flexible printed circuit is shown in Figure 3-28. The proposed rectifiers are beam leaded devices made by integrated circuit techniques. One common configuration would be a bridge circuit of four diodes on a single chip with four beam leads 90° apart. Two of the beam leads connect to the dipole antenna and two connect to the dc buss. The bonding process itself is essentially a combination of pressure and temperature. A wobbling motion is imparted to the bonding tool.

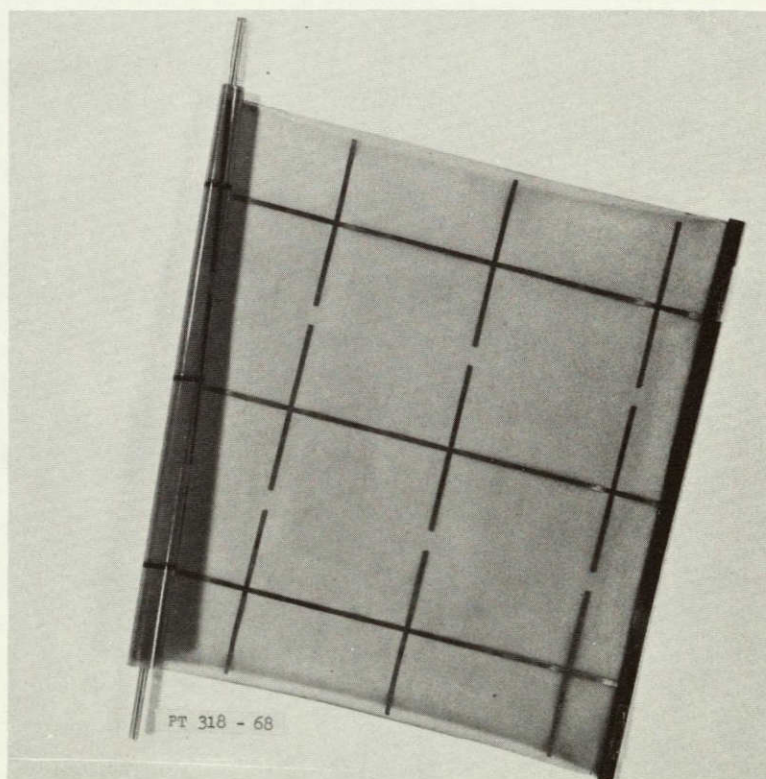


Figure 3-28. A possible physical configuration which future rectennas may assume. Rectenna is made in flexible form by employing printed circuit techniques on dielectric film material such as Kapton. Rectifiers perhaps made by integrated circuit techniques are bonded to the flexible printed circuit at appropriate points.

The first experiments involved attempting to bond mechanical samples of beam leaded devices to a substrate consisting of a 1/2 mil thick copper sheet laminated to two mil thick Kapton. This initial attempt was not successful because the force applied to the beam leads caused them to indent the copper, forcing the copper down into the Kapton substrate. The result was that the wobbling bonding tool rode on the surface of the copper as well as on top of the beam leads. In addition, it was felt that a gold plate on the copper would be desirable for future experiments.

To remedy the problem with respect to the indentation of the copper, a new Kapton-copper laminate was obtained in which the copper thickness was three mils, so that the copper would act as a heavy beam and would not bend. The Kapton, in this instance, was three mils thick. The surface of the copper was gold plated by the Techniques Laboratory in the Microwave Tube Operation of the Raytheon Company.

The experimental results with this new material were much more successful. A number of beam leaded devices were bonded. However, the bond fell short of perfection. In a standard test of the strength of the bond, in which a shear force is exerted on the beam lead device, only about 1/3 of the beam leads pulled away from the device and adhered to the gold plated surface of the copper. Upon inspection it was found that although the copper was not bonding, a coining operation was being performed in which the beam leads were actually being pressed down into the copper, the displaced copper flowing around the beam leads. Again, the limitation on the bonding was the riding of the bonding tool on the surface of the gold plated copper.

As a control experiment we then used the same pressure and temperature to bond a beam leaded device successfully to a "standard" substrate consisting of a gold film deposited on an alumina substrate. Because of the hardness of the alumina there was no coining of the substrate.

One way to overcome the coining difficulty would be to utilize a harder material, say, iron, on which a gold film had been deposited. The poor heat conductivity of the iron, however, might not be satisfactory from a heat dissipation point of view. Another better approach is to utilize a dispersion hardened copper which retains good heat conducting properties but which has a hardness level several times that of ordinary copper.

No doubt a suitable material in both hardness and heat conductivity could be found from which to construct the printed circuit. However, in subsequent discussion with D. Walters and R. Ilgenfritz of the Raytheon Bedford Laboratory, these experts in the bonding of beam devices expressed doubt as to the reliability of any assembly consisting of a flexible substrate with beam lead devices directly bonded to it. They highly recommended an intermediate step in which the beam lead device would be bonded to a thin small chip of alumina. This would not only solve the bonding problem, but the alumina chip would have a mechanical strength many times greater than the beam leads themselves. The alumina would have sufficient strength to help hold the flexible rectenna together so that large areas of the Kapton could be cut from the structure and more than make up for the additional small weight of the alumina. A good feel for the relative strength of the alumina chip versus the beam lead can be obtained by comparing the cross-section of the alumina chip which might be 0.060 inch square and ten mils thick with a beam lead which is 1/2 mil thick and 8 mils wide. The ratio of cross-sections is 150 to 1, and the alumina is probably stronger.

The information obtained from the experiments described above provides a basis for further investigation of the flexible rectenna concept.

3.4.2.4 First Tests on Gallium Arsenide "Flip-Chip" Schottky-Barrier Diodes as Rectifiers

The recent development of a new kind of Gallium Arsenide Schottky-barrier diode with special properties may be of great significance to the future development of the rectenna. These diodes which were developed by the Micro State Operation* of the Microwave and Power Tube Division of the Raytheon Company were developed for improved microwave oscillators and amplifiers. The diode has the properties of a higher operating temperature and much higher power handling capability than conventional Schottky-barrier diodes. In great part the higher power handling capability is made possible by the "flip-chip" type of construction in which the epitaxial layer in which most of the power is dissipated is bonded to the heat sink. In the typical diode, the heat has to flow through the semiconductor material which is a poor heat conductor.

Although these diodes had not been developed with microwave power rectification in mind, the staff at Micro State thought that they might be useful for this purpose and provided several of these diodes without charge for checking their power rectification properties. Testing these diodes necessitated making a special test set up, which was made without cost to the contract. After a careful calibration of the test equipment, a number of the diodes were checked. It was determined that the power handling capability of these diodes was more than an order of magnitude above the conventional silicon Schottky-barrier diode and that their efficiency was of the order of 75% at this high power operating condition. Typically, five to seven watts of power could be obtained from these devices.

To further examine the behavior of these diodes as rectifiers, the following set of data in Table 3-5 on diode No. 8-22-13552A-9 may be useful.

* This activity has since been incorporated into the Special Microwave Devices Operation of the Microwave and Power Tube Division of the Raytheon Company.

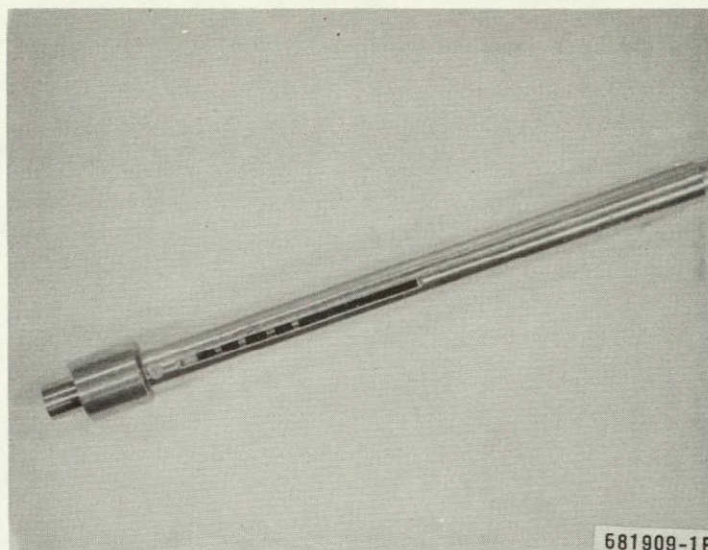
Table 3-5. Data on a Single Gallium Arsenide "Flip-Chip" Diode
Operated as a Rectifier at 2.45 GHz

Input RF Power (W)	RF Power Reflected (W)	Rectified DC Potential (V)	Rectified DC Current (mA)	Rectified DC Power (W)	Efficiency (after sub- tracting reflected power) (%)
4	0.04	18.2	158	2.97	72.5
6	0.08	23.0	198	4.55	77.0
8	0.16	26.3	228	6.0	76.5
10	0.26	29.3	252	7.37	75.6

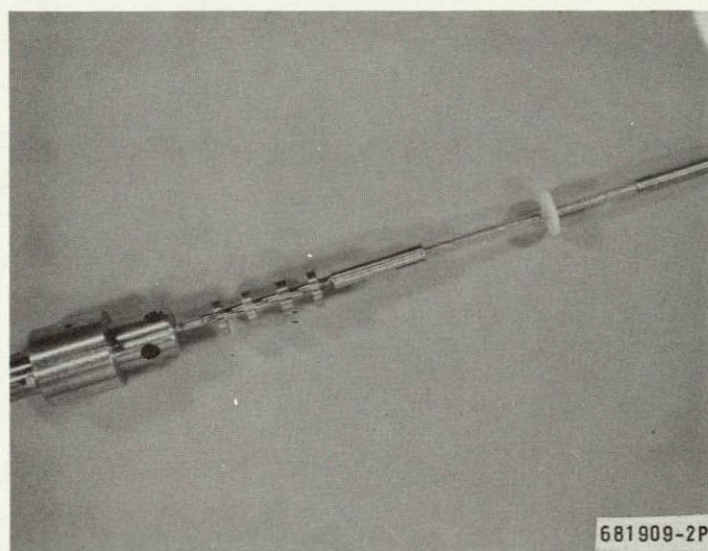
The test fixture consisted of a section of 50-ohm coaxial line, terminated by a low-pass filter (constructed in coaxial line format) and the diode. (See Figures 3-29a and 3-29b.) The diode was mounted at the center of one end of a large cylinder of copper which effectively was an rf short between the center and outer conductors of the coaxial line as shown in Figure 3.29c. It was isolated for dc from the outside shell of the coaxial line by means of a strip of Mylar insulation which also behaved as an rf by-pass. The dc load resistance was connected between the outer conductor of the coaxial line and the mounting block.

The rest of the test set up consisted of an rf power source at 2450 MHz, directional couplers for monitoring forward and reflected power and the test fixture. A NARDA power meter, connected to a carefully calibrated 30 dB directional coupler through a 6.1 dB attenuation pad, was used to read the forward power. There was a similar set up for reading the reflected power. Because the reflected power was quite small, the significant sources for measurement error were limited to the measurements of forward rf power and dc power output. The various meters and equipment in these measurements were carefully calibrated from secondary standards and it is believed that accuracy of the efficiency figures is within 3%.

a



b



c



NOT REPRODUCIBLE

Figure 3-29. Test Fixture for Measuring Efficiency of GaAs "Flip-Chip" Schottky-barrier Diode

The efficiency figures given above are somewhat higher than those measured on other representative diodes by about three or four percent and are undoubtedly due to some special characteristics of this diode.

Other work carried out with these diodes included the construction of a bridge rectifier made out of four of these diodes. Typical performance of this bridge rectifier was a dc output of fifteen watts. However, the test set up was such that an appreciable amount of power was reflected. At fifteen watts of power output, 8.1 watts of the 30 watts of incident power was reflected. It follows that the overall efficiency was fifty percent, while the rectification efficiency was 68%.

In summary, the importance of this investigation is two-fold. First, a greatly improved diode in terms of power handling capability and operating temperature has been discovered. Power levels are more than a magnitude higher. The higher operating temperature permits a higher operating temperature of the rectenna surface. The amount of heat radiated is proportional to the fourth power of the absolute temperature. Secondly, a test arrangement which will be of importance in subsequent investigations has been devised and checked out.

3.5 Study Summary and Recommendations

3.5.1 System Component Summary and Recommendations

Given the study objectives as outlined in Section 3.1, the following summary and recommendations with respect to system components are presented below and in Figure 3-30.

1. The Microwave Generator (See Section 3.2.4.)

At power levels of a few kilowatts, the preferred approach to the microwave generator portion of the system is a coaxial magnetron oscillator, for reasons of high efficiency, mechanical and electrical simplicity, and ability to radiate its dissipation into space. (See Section 3.2.4.1.)

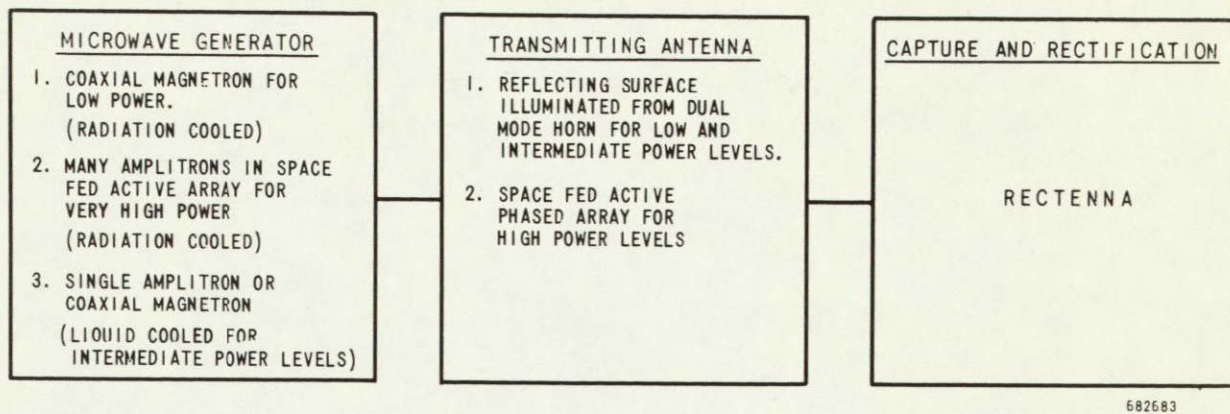


Figure 3-30. Summary of Recommendations for Microwave Power Transfer System

For very high power levels, the preferred approach is a space-fed active phased array employing a multiplicity of hybrid amplifiers whose final stage is a high-efficiency Amplitron of modest power level. Each Amplitron feeds one phased array element or a few elements at most. The Amplitrons' dissipated power is radiated directly into space. (See Section 3.2.4.2.)

For intermediate power levels where a phased array is impractical but where the power level does not permit the use of a tube which can radiate its power directly into space, the recommended approach is either a highly efficient Amplitron or a coaxial magnetron which is cooled by means of heat pipes or a liquid-cooling system. (See Section 3.2.4.3.)

2. The Transmitting Antenna

The conclusions reached in this study indicate either a space-fed active phased array in the case of a high power system or a reflecting surface illuminated by gaussian distributed energy derived from a dual-mode feed horn. By either of these means, illumination efficiencies of over 95% can be achieved. In the case of the high power system, the phased array is composed of active elements consisting of an Amplitron with perhaps additional low level gain from solid-state devices. The amplifiers radiate their dissipation directly into space. (See Section 3.3.)

3. Capture and Rectification of Microwave Power at Receiving Point

The conclusions reached in this study indicate the use of a rectenna for both intercepting and rectifying the microwave power. The rectenna makes effective use of the only existing highly efficient and reliable microwave rectifier, namely, the solid-state Schottky-barrier diode. The rectenna is also highly unidirectional, making attitude control simple, and permitting very relaxed mechanical tolerances in its construction. Being a very efficient device and having a very large number of rectifiers distributed evenly throughout the structure, the device can be both very light in weight and can get rid of any power dissipation by directly radiating the heat into space. (See Section 3.4.)

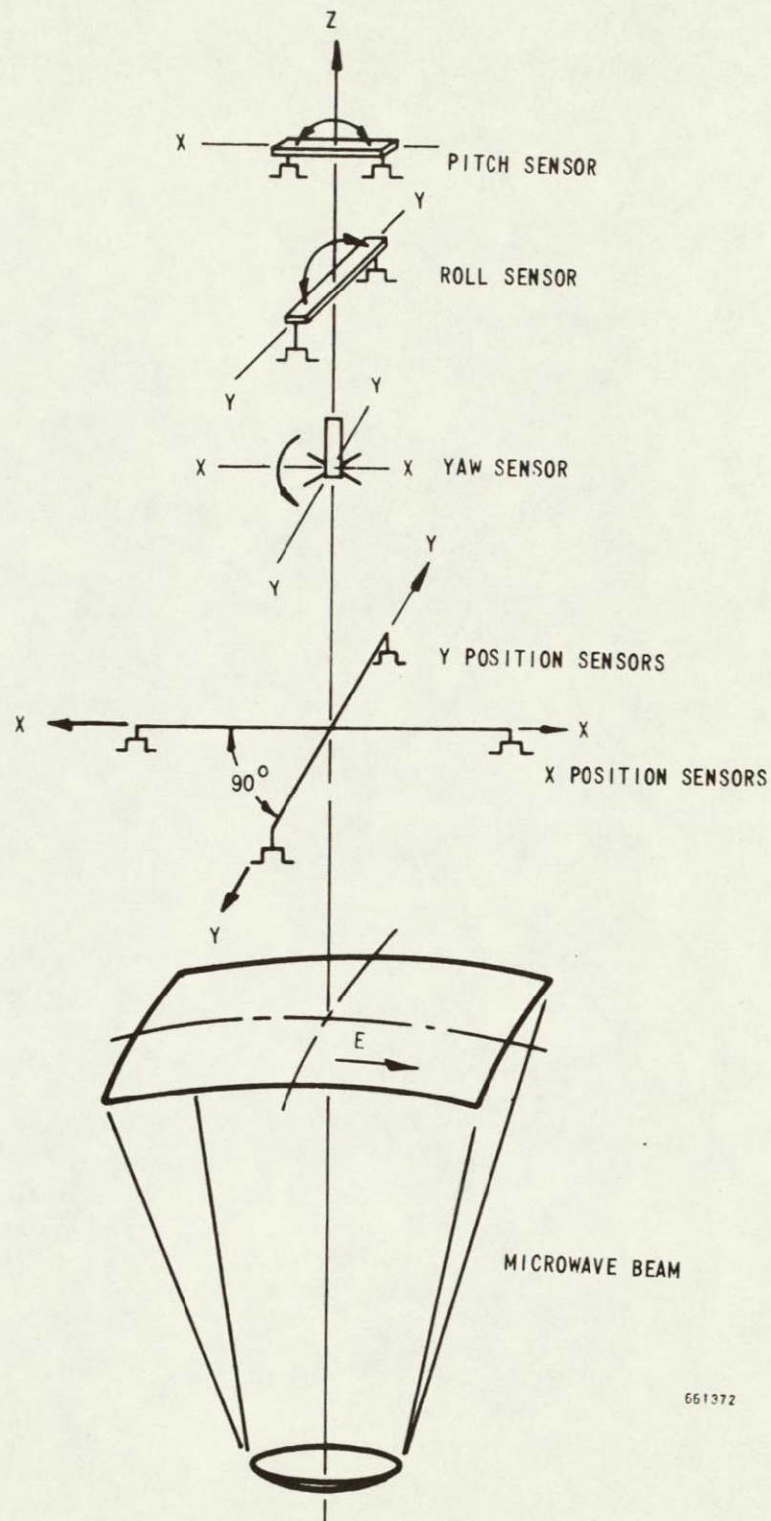
4.0 POSITIONING AND DOCKING SYSTEMS UTILIZING THE MICROWAVE BEAM

One of the important auxiliary features of the use of a microwave beam for power transfer purposes is that it can also be used as a position reference in five of the six degrees of mechanical freedom which the receiving antenna in space possesses. Hence, if the rectenna or the vehicle to which the rectenna is attached has the proper position sensors and the proper control system the position of the rectenna can be slaved to the microwave beam.^{31,32} In this section we will discuss the nature of the receiving sensors and of the closed loop positioning systems of which the sensors are a key element.

The way in which a microwave beam may be used to supply position information is examined with the aid of Figure 4-1. Roll and pitch information is obtained from the phase front of the microwave beam by means of two-port sensors which are phase sensitive. Yaw or bearing information is obtained from the polarization of the beam and a two-port sensor which is amplitude sensitive. The translational position of the receiving vehicle is obtained from the variation of the power density of the beam along a plane normal to its axis and a set of two-port sensors which are amplitude sensitive.

With the position error information provided by the interaction of the microwave position sensors with the microwave beam, a control system can be designed so that the space vehicle will tend to stay on or near the center of the beam.

The microwave beam and position sensing system outlined in Figure 4-1 have been successfully applied to automatically position a helicopter in a microwave beam. For reference purposes, a photograph of the beam-riding helicopter which demonstrated the use of a microwave beam as a position reference is shown in Figure 4-2. In the flight shown in the photograph, the helicopter is automatically positioning itself and the complete control system is carried on board the helicopter. The attached cables are supplying raw electrical power and monitoring the position sensors.



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Figure 4-1. General Configuration of the Five Sensor Elements Utilizing a Microwave Beam as a Position Reference

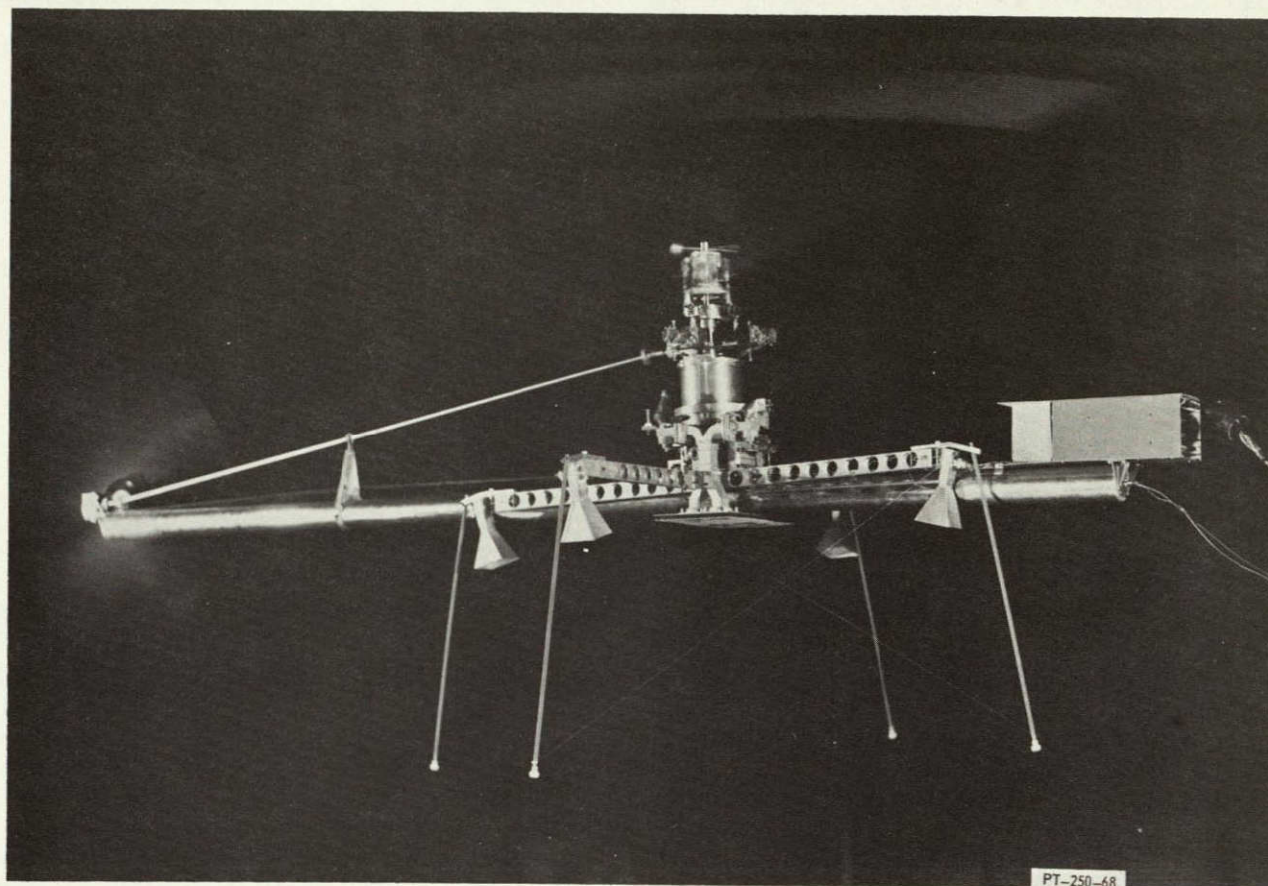


Figure 4-2. Position-stabilized Helicopter in Free-flight Making Use of a Microwave Beam as a Position Reference

The overall control loop in the helicopter is greatly complicated because of the close coupling between pitching motion and longitudinal motion and the close coupling between rolling and lateral motion. This is not the situation in a space vehicle where these motions can be separated from each other if all thrusting devices act through or around the center of gravity of the vehicle. Furthermore, if a microwave beam with a flat wave phase front is assumed there is virtually no intercoupling of the position sensors. This latter statement assumes that the rectenna will be continuously oriented with respect to the microwave beam so that position error information tends to be held at zero. This must also be the case to prevent intercoupling of the thrusting devices.

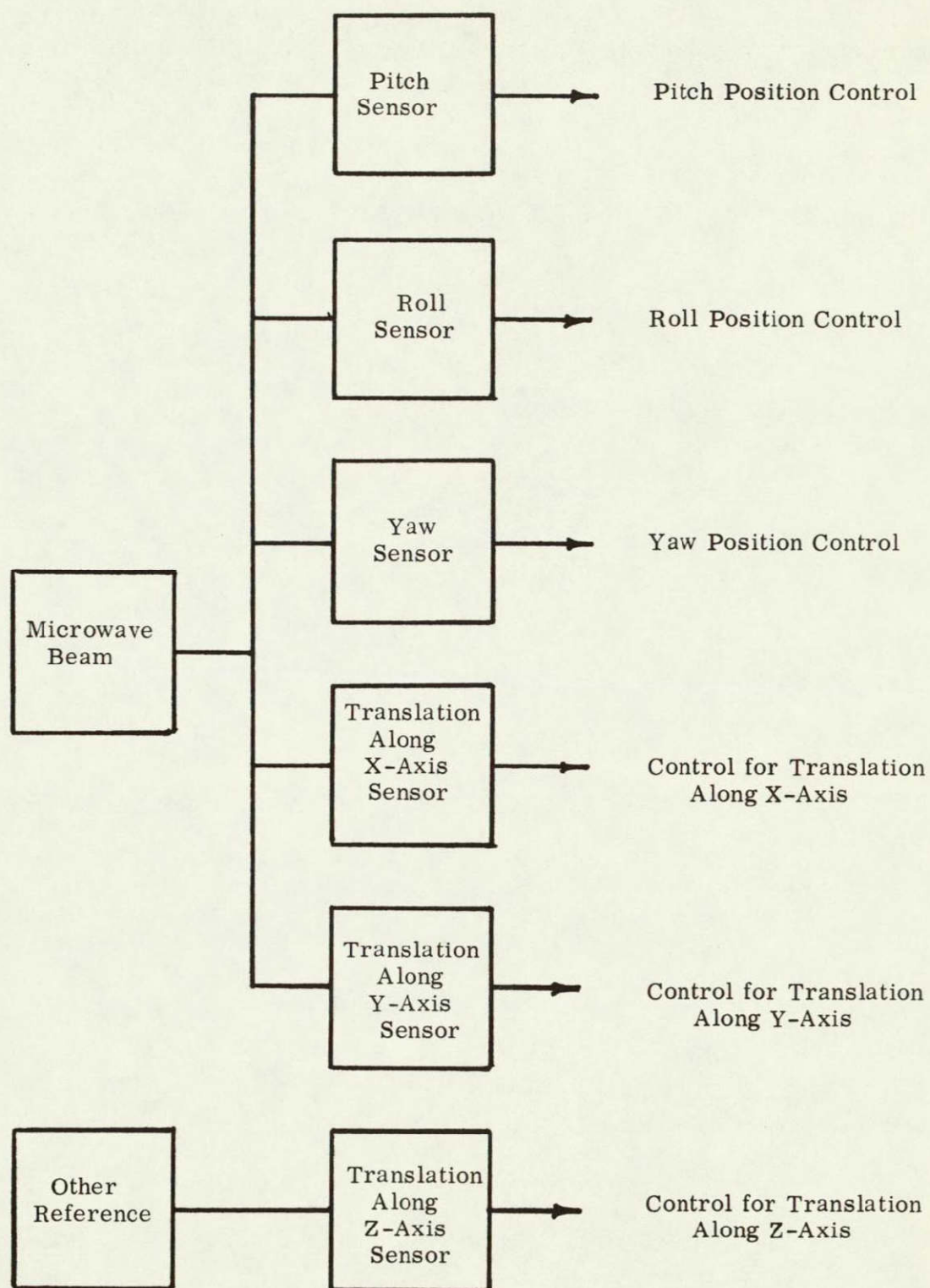
We may formalize the above discussion with the aid of a block diagram shown in Figure 4-3. It will be noted in Figure 4-3 that the microwave beam, at least in an unmodulated form, does not provide a good position reference for motion along the axis of the beam itself. Since there are several acceptable means of obtaining range information, we will pass over this aspect of the guidance problem.

The five control systems shown in Figure 4-3 are similar to each other, so that if we explore one in detail, we have essentially looked at all of them. However, before examining a specific control system, it may be helpful to discuss control systems from a more general point of view.³³

A block diagram for a general control system is shown in Figure 4-4. In general, we are interested in the response of the controlled variable (location of the receiving antenna in our case) to a change in the input reference (microwave beam position in our case). This is called the system response. Mathematically, it is expressed as

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1 + G(s) H(s)} \quad , \text{ where all items are expressed } \quad (1)$$

in LaPlace transform notation.



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Figure 4-3. Schematic showing the relationship between the microwave beam and position control of a space vehicle making use of microwave beam as a position reference.

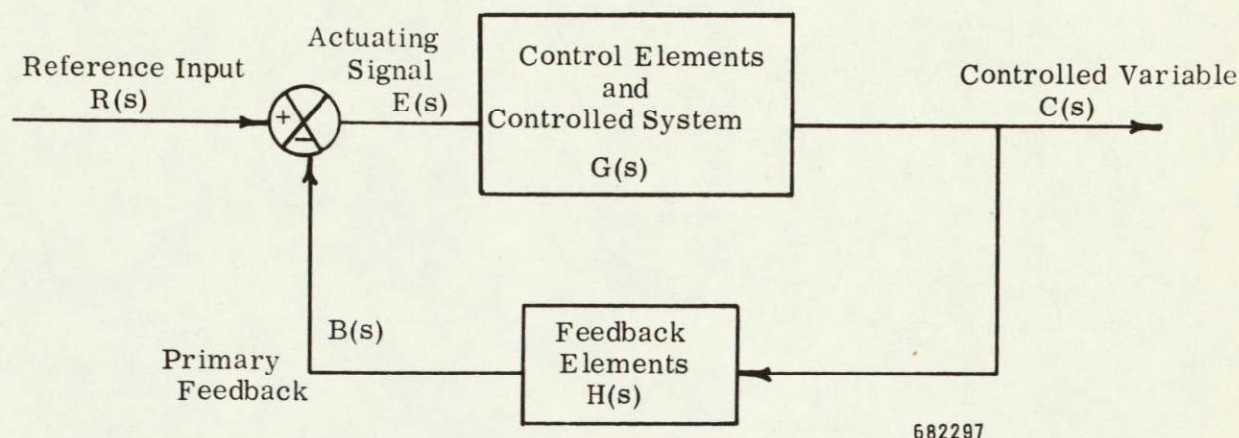


Figure 4-4. Basic Feedback Control System

Now we return to our specific problem and relate it to the general expression (1). All that is necessary is to find the $G(s)$ and $H(s)$ that correspond to our particular problem. In our particular case a good control system can be made by setting $H(s)$ equal to unity, or 1. This is known as a unity feedback system. Hence, expression (1) becomes

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1 + G(s)} \quad (2)$$

Now let us select the roll position control as representative of all of the six position controls. The error $E(s)$ is generated by a phase detector which compares the roll position of the receiving antenna with the phase front of the microwave beam. The error signal is then fed through a network to improve the response characteristics of the control loop. The processed signal then actuates a device which provides a force to accelerate the receiving antenna in a direction to minimize the error. The acceleration is integrated twice to provide a displacement which the sensor actually detects.

If we utilize standard control theory procedures the corresponding block diagram is shown in Figure 4-5. From Figure 4-5 we see that

$$G(s) = K_{\theta} G \frac{(s+a)}{(s+b)} K_1 g \frac{I_{\theta}}{s^2} \quad (7)$$

The various proportionality constants in equation (3) may be represented by the symbol K ,

$$K = K_{\theta} G K_1 g I_{\theta}, \text{ so that}$$

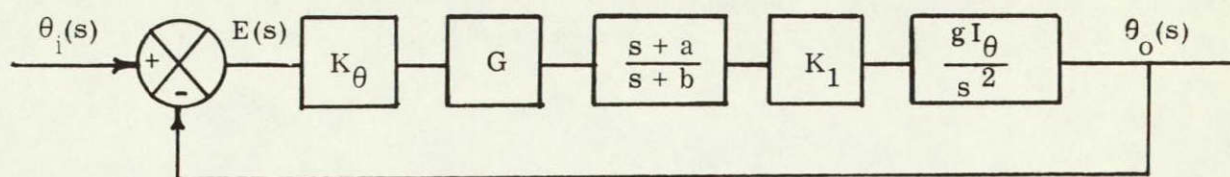
$$G(s) = \frac{K}{s^2} \frac{(s+a)}{(s+b)} \quad (4)$$

The control ratio, $\frac{C(s)}{R(s)} = \frac{\theta_o(s)}{\theta_i(s)} = \frac{G(s)}{1+G(s)}$, so that after substituting the right hand side of equation (4) for $G(s)$, we obtain

$$\frac{\theta_o(s)}{\theta_i(s)} = \frac{K(s+a)}{s^3 + bs^2 + Ks + a} \quad (5)$$

The control ratio given in equation (5) corresponds to that of a so-called type 2 system³³ in which the steady state response follows without position error either a step input or a ramp input function. This is a point of considerable interest since the accuracy of the positioning system in an environment without external forces would be determined by the noise level of the system.

One of the questions which arises is whether a microwave beam which is being used for power transfer can simultaneously be used as a position reference. To help answer this question as well as to demonstrate the use of a microwave beam for guidance purposes, an experimental vehicle was constructed and successfully operated. This vehicle is described in Section 5.0.



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- K_{θ} = volts from sensor per radian of θ movement.
 G = voltage gain of amplifier.
 $\frac{s+a}{s+b}$ = lead compensator (damping)
 K_1 = torque generated per unit of input, ft-lbs/volt.
 I_{θ} = moment of inertia of receiving antenna about roll axis.
 $\theta_i(s)$ = roll position reference input (phase front of microwave beam).
 $\theta_o(s)$ = roll position output.
 g = earth's gravitational constant 32.2 ft/sec^2 (relates force to mass in English system).

Figure 4-5. Control system for maintaining roll position of space vehicle with respect to a microwave beam position reference.

5.0 AN EXPERIMENTAL MICROWAVE BEAM RIDING VEHICLE

An addendum to the contract made provision for an experimental demonstration that the position of a vehicle could be controlled by means of a microwave beam at the same time that power was being transferred to the vehicle by means of the same microwave beam. The general principles of utilizing a microwave beam as a position reference are set forth in Section 5.0 which shows that a microwave beam contains position information for five of the six degrees of freedom which an object in space possesses. The experimental work, however, was limited to using the microwave beam as a position reference for two degrees of freedom only. One of these was a translational position; the other was a rotational position.

In general, there are two types of sensors which detect position errors between that of the microwave beam and the controlled vehicle. The sensors are either phase or amplitude sensitive. Both of these types were demonstrated in the experimental effort.

Figure 5-1 shows the completed vehicle together with the rectenna in position. The position sensors to be described later are mounted on the rectenna. A view of the complete system, including the transmitting antenna, is shown in Figure 5-2. Another view, Figure 5-3, shows the same system looking toward the transmitting antenna.

In demonstrating the system, the transmitting antenna is rotated. This causes an error signal to be produced in the sensor. The error signal is fed into the control system which activates an electric motor in a direction to cause the vehicle to move laterally toward the center of the beam.

As the angle between the direction of the travel of the vehicle and the line between the transmitting antenna and the vehicle departs from 90° , an error signal is created in the other sensor. The second error signal is fed into a control system which causes the rectenna to rotate so that its face is always pointing toward the transmitting antenna. In this manner, the rectenna is always positioned for a maximum transfer of power between the transmitter and the rectenna.

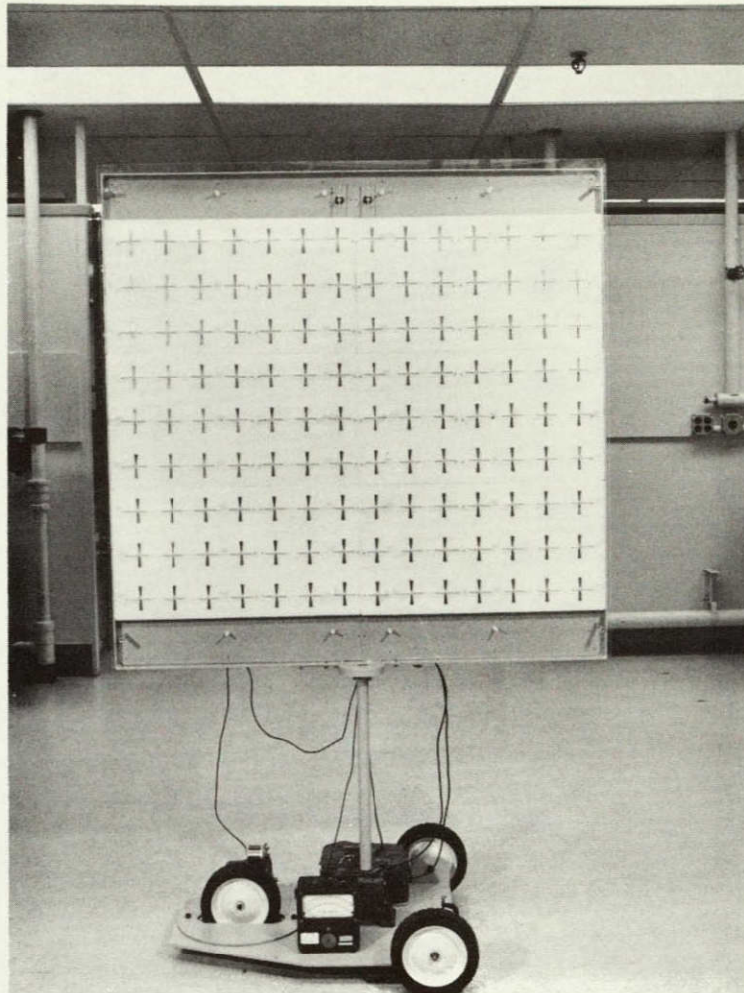


Figure 5-1. Three-wheeled vehicle and rectenna constructed to demonstrate rectenna positioning for optimum power transfer by means of a sensor and control system which makes use of the microwave beam as a position sensor.

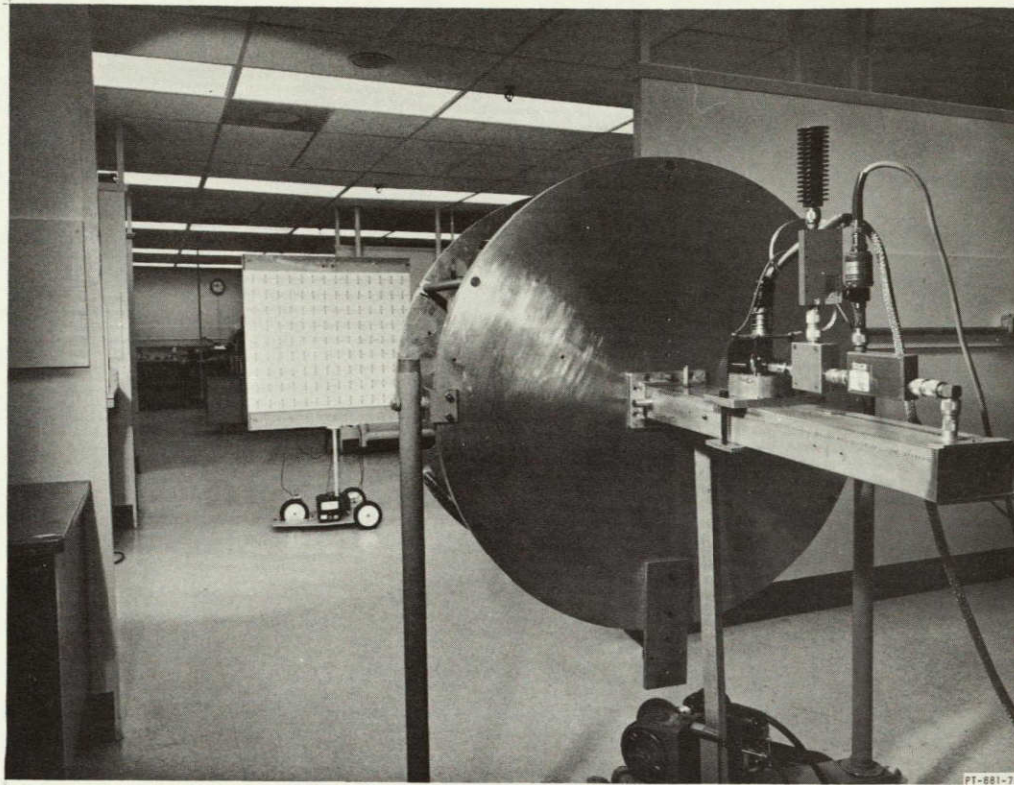


Figure 5-2.

Shown above in the background is a three wheeled vehicle supporting a rectenna. While there is an active transfer of power to the vehicle, by means of the microwave beam, the vehicle also automatically shifts its position to stay centered on the beam as the transmitting antenna in the foreground is rotated. This is accomplished by microwave sensors mounted on the rectenna. One set of sensors moves the vehicle and rectenna laterally while the other set rotates the rectenna on the vehicle so that the rectenna is always facing the transmitter.

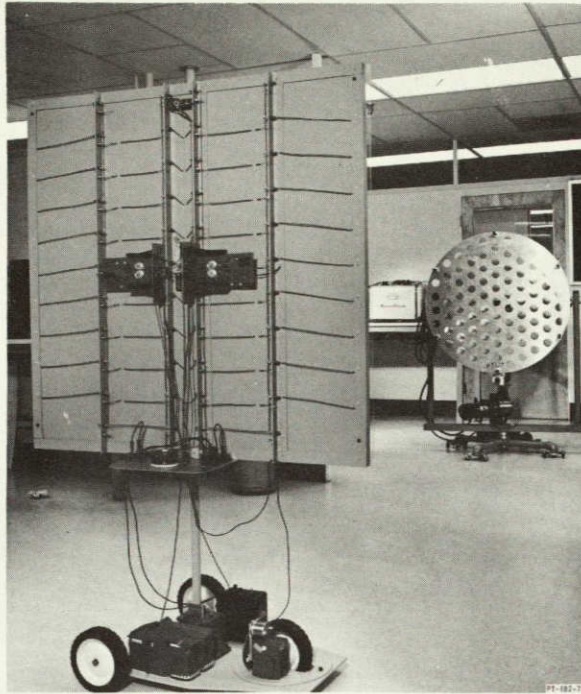


Figure 5-3. Rear view of experimental set-up demonstrating use of microwave beam as a position reference to control positioning of rectenna for optimum power transfer.

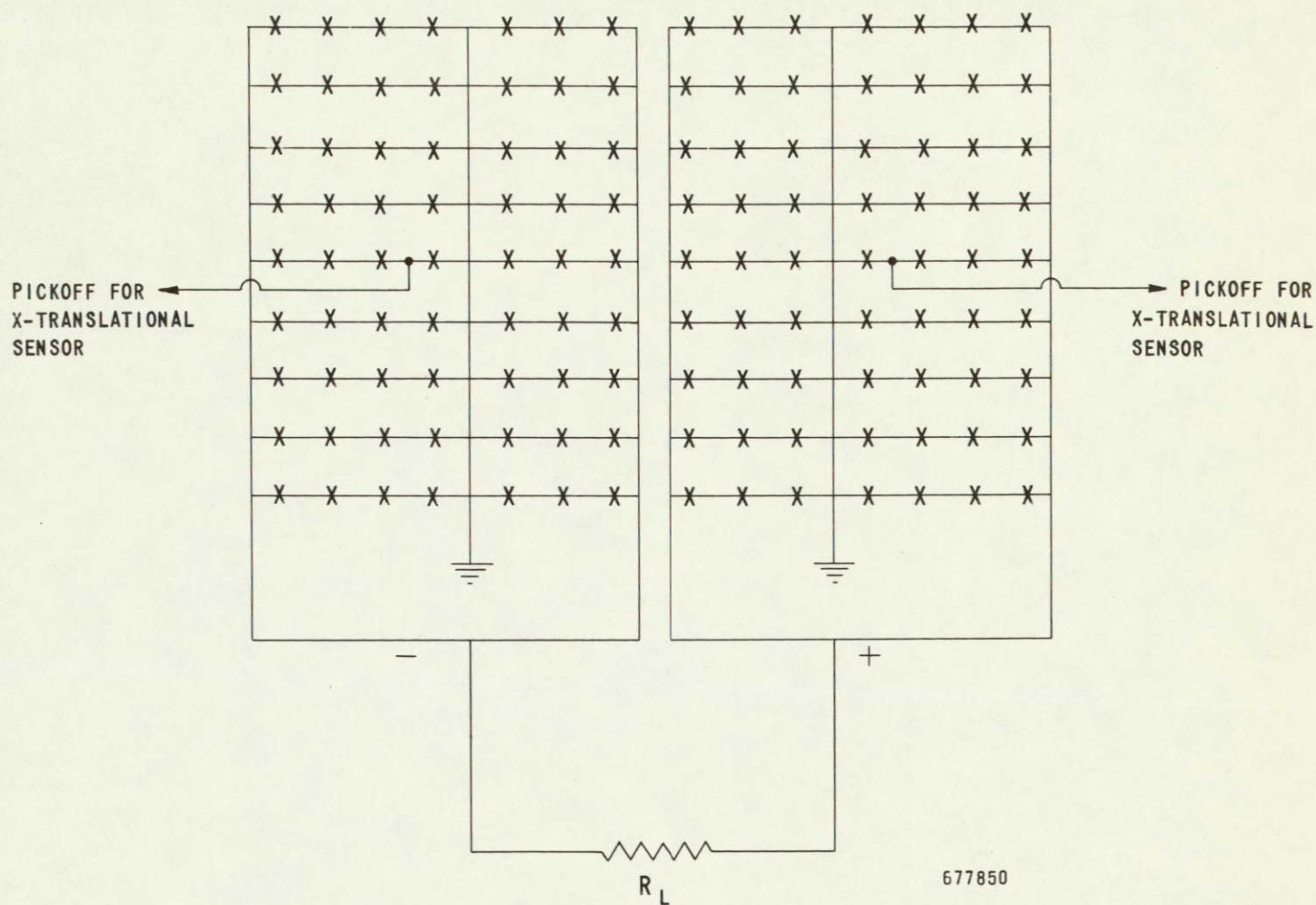
As previously stated, the two sensors are mounted on the rectenna and operate while power is being transferred by means of the microwave beam. Figure 5-4 shows how the sensing information with respect to the lateral positioning is obtained. The voltages across two of the rectenna elements are placed in series as shown in Figure 5-5. When the rectenna is symmetrically located with respect to the beam, the voltages are equal and the error signal is zero.

Figure 5-6 shows the phase sensitive detector which utilizes the phase front of the beam as a position reference. This detector is mounted just above the elements of the array as shown in Figure 5-1. Its normal and preferred position would be on the axis of the beam but in this location it would interfere with the power collection system. However, it seems to work well in the off axis position. Such behavior may be considered as an indication of the non-criticality of these sensors.

The device shown in Figure 5-6 may be of sufficient interest to merit additional discussion. Figure 5-7 shows the microwave electrical schematic of the device. It is a ring-circuit magic-T directional coupler. Normally such a structure is made in the coaxial line. The structure used here uses parallel transmission line structure. It was designed and built by W. Brown and supplied, without charge to the contract, by the Raytheon Company.

The output voltage as a function of the rotational position of the sensor with respect to the phase front of the microwave beam is shown in Figure 5-8. Note that the output response is highly linear with respect to the phase shift in the region of zero phase shift.

The schematic diagram of the complete control system is shown in Figure 5-9.



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Figure 5-4. Schematic diagram showing how the 132 elements of the rectenna are coupled into one common load. In the diagram each "X" indicates an element. The additional function of two of the elements as position sensors is also indicated.

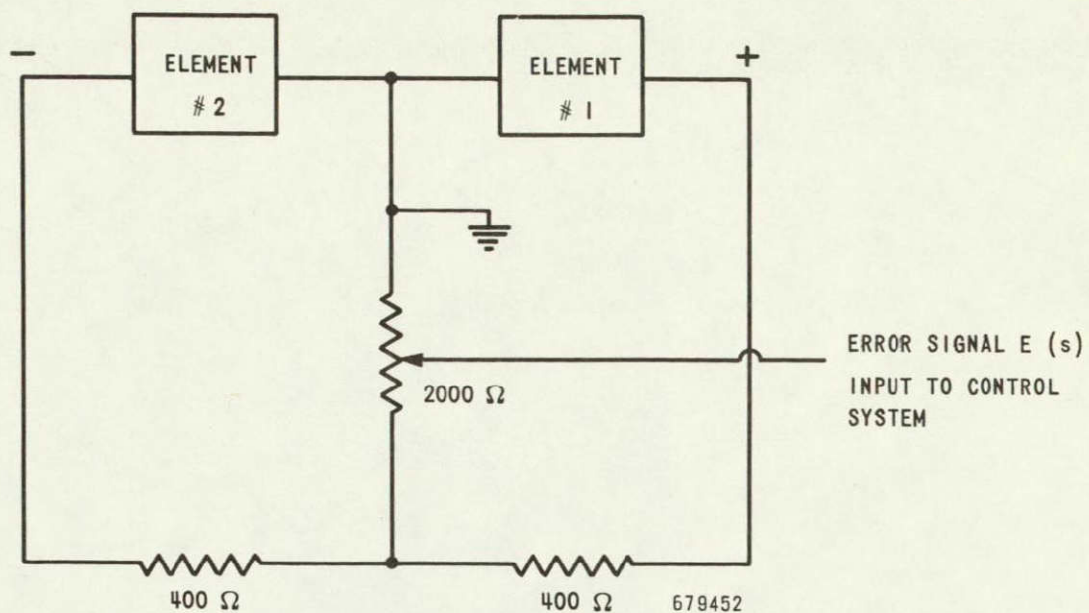


Figure 5-5. Schematic showing how position sensors are connected to supply an error signal.

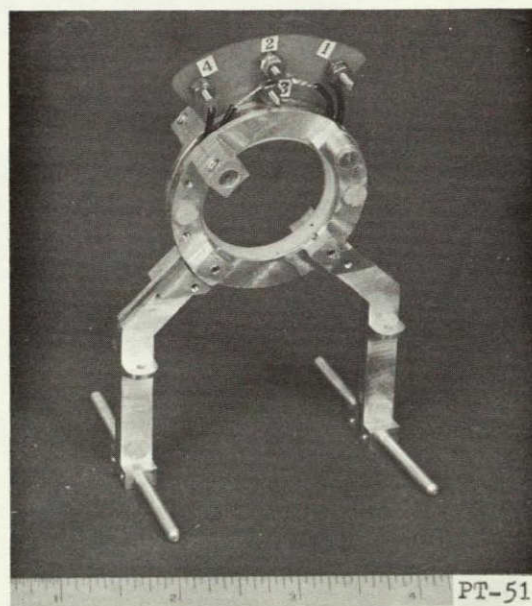


Figure 5-6. Phase sensor for determining degree of pitch or roll with respect to the reference provided by the microwave beam.

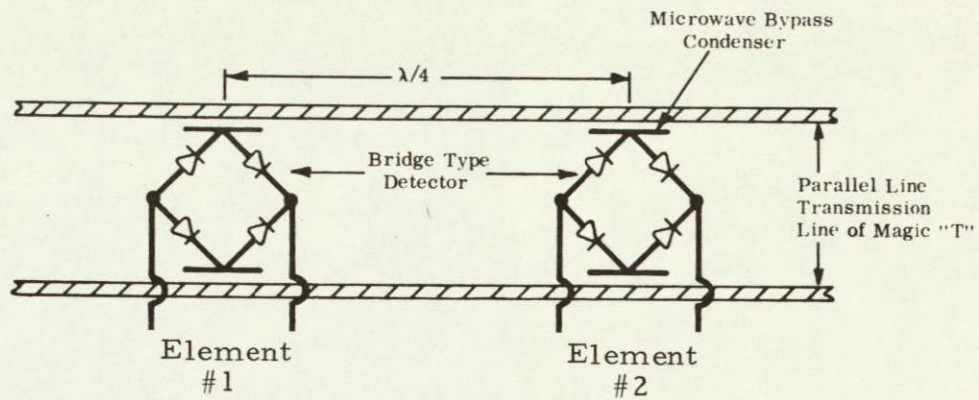


Figure 5-7. Schematic of Phase Detector Sensor

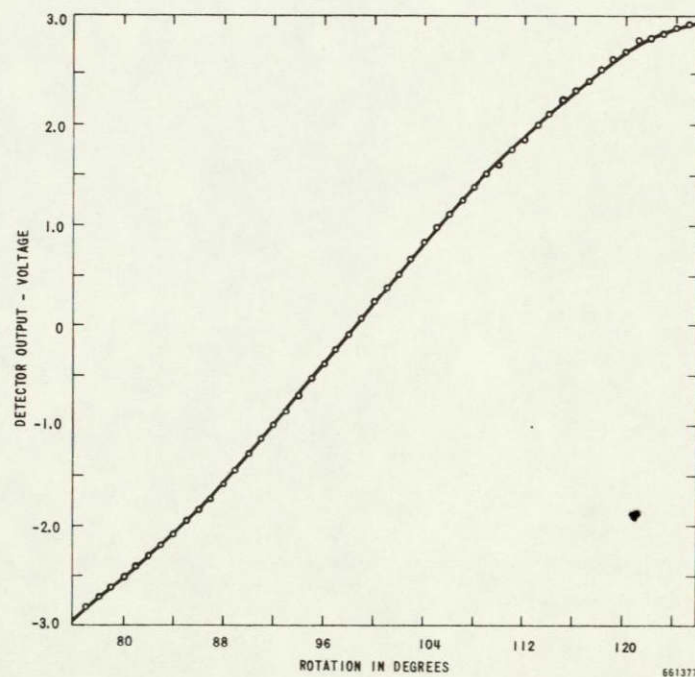


Figure 5-8. Performance data on phase sensor. Zero output voltage corresponds to the dipoles of the phase sensor located in a plane normal to the beam axis.

It follows from the diagram that the control ratio is:

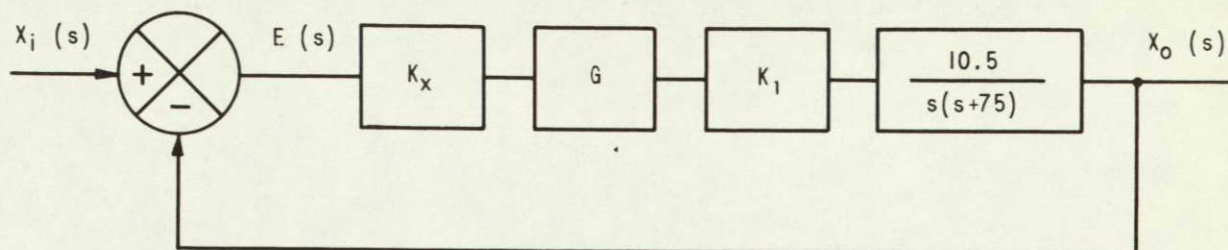
$$\frac{X_o(s)}{X_i(s)} = \frac{G(s)}{1 + G(s)} = \frac{10.5 K}{s^2 + 75 s + 10.5 K} \quad (1)$$

where

$$K = K_x K G_1 .$$

This is a very simple control system, without any kind of compensation. The schematic of Figure 5-9 neglects friction or any external forces. This would be nearly the real situation in space. If there are no external forces, then a lag form of compensation is not needed. If fast response time is not a factor, then no lead compensation is needed. The control ratio given in (1) is of the so-called type 2 system³³ in which the steady state response follows without position error (in the absence of external forces) either a step input or a ramp input function.

The form of the gain, G , in the control system is that of a dc operational amplifier. The two operational amplifiers may be seen in Figure 5-3 as the items in the middle of the back of the rectenna. The amplifier consists of a linear integrated circuit operational amplifier which takes the error signal, amplifies it with a voltage gain of 30, and a power amplifier consisting of four transistors.



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- K_x = VOLTS FROM SENSOR PER INCH OF X-TRANSLATIONAL MOTION
 G = VOLTAGE GAIN OF AMPLIFIER
 K_1 = TORQUE GENERATED PER UNIT OF INPUT, INCH/OZ VOLT
 $X_i(s)$ = X POSITION REFERENCE WHICH IS THE AZIMUTHAL POSITION OF THE MICROWAVE BEAM
 $X_o(s)$ = X POSITION OUTPUT
 $E(s)$ = ERROR SIGNAL = $X_i(s) - X_o(s)$

Figure 5-9. Schematic of the translational control system. Rotational Control system is Identical Except for the Values of the Constants Involved.

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APPENDIX A

PROGRESS IN THE DESIGN OF RECETNNAS

PROGRESS IN THE DESIGN OF RECTENNAS

by

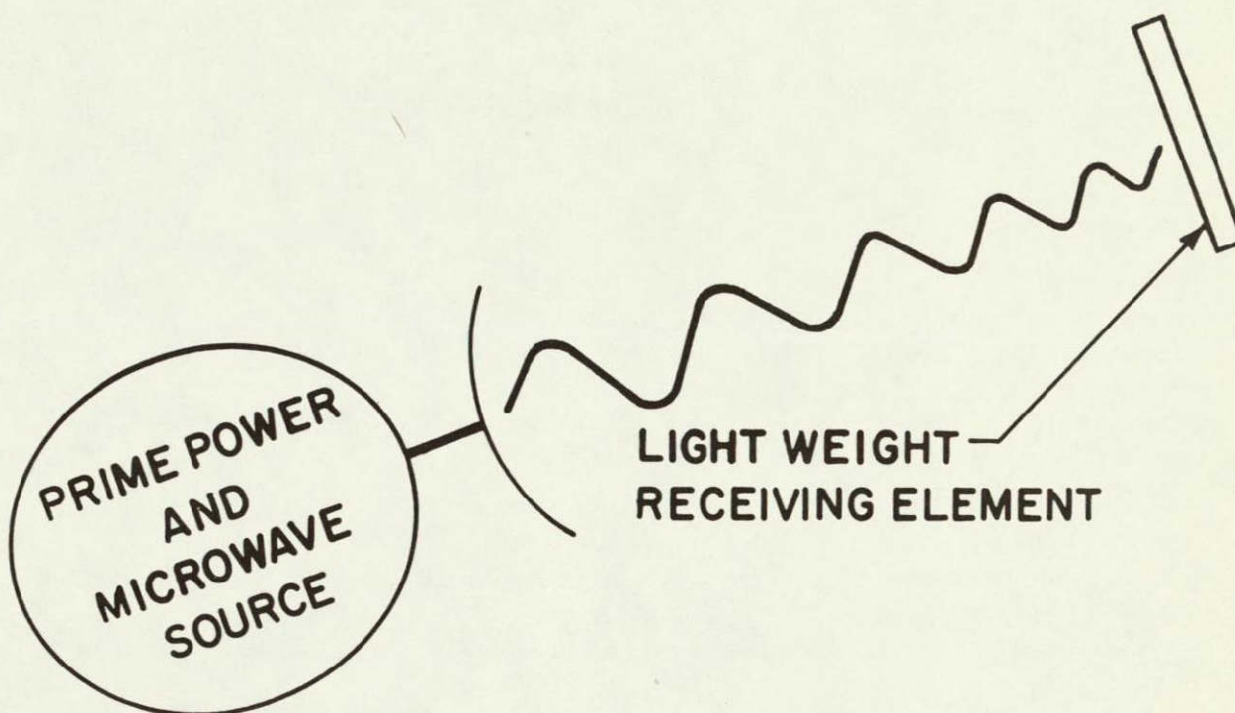
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ABSTRACT

This paper reviews the progress in the design of rectennas which are used to collect and rectify the microwave energy at the receiving end of a microwave beam power transmission system. A new lightweight rectenna which provides 20 watts of power but weighs only 20 grams is described. Future trends in construction are discussed.

The "rectenna" is a device used to collect and rectify the microwave energy at the receiving end of a microwave beam power transmission system--particularly in aerospace applications. The term "rectenna" is formed from the two words "rectifier" and "antenna," and as the name implies the device combines the functions of the receiving antenna and the microwave rectifier. The rectenna concept arose as a solution to a number of difficult requirements in the transmission of power for aerospace applications, and it may be constructive to examine what these requirements are.

As Figure 1 indicates, an aerospace microwave power transmission system involves a microwave beam source which may be located on the surface of the earth, moon, or on a large space vehicle. The receiving antenna may be on a station-keeping balloon, a helicopter, or another space vehicle. The receiving antenna and rectifier should have the following characteristics:



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Figure 1

Diagram of a generalized microwave power transmission system for aerospace applications.

1. Desirable Receiving Antenna Characteristics

Lightweight

Large aperture

Non-directive

Easy mechanical tolerance requirements

Low wind drag (for system in atmosphere typical of earth's).

2. Desirable Properties of the Rectifier

Lightweight

High efficiency

High power handling capability

Ease of heat dissipation

Long life and good reliability.

In addition to the desirable characteristics needed above, there are certain practical matters such as immediate availability of rectifier components as opposed to those requiring an R&D effort to make them available. Currently the only immediately available rectifier device is the semiconductor diode either in the form of a point contact diode or the Schottky barrier diode. Two such diodes in different size commercial glass packages are shown in Figure 2. However, these diodes meet all the requirements above with the exception of high power handling capability. Currently, available diodes will only provide about 250 milliwatts of power output per diode whereas in many aerospace applications a minimum of several hundred watts and a maximum of several hundred kilowatts are required. As we shall see, however, we need rectifiers of only modest power handling capability.

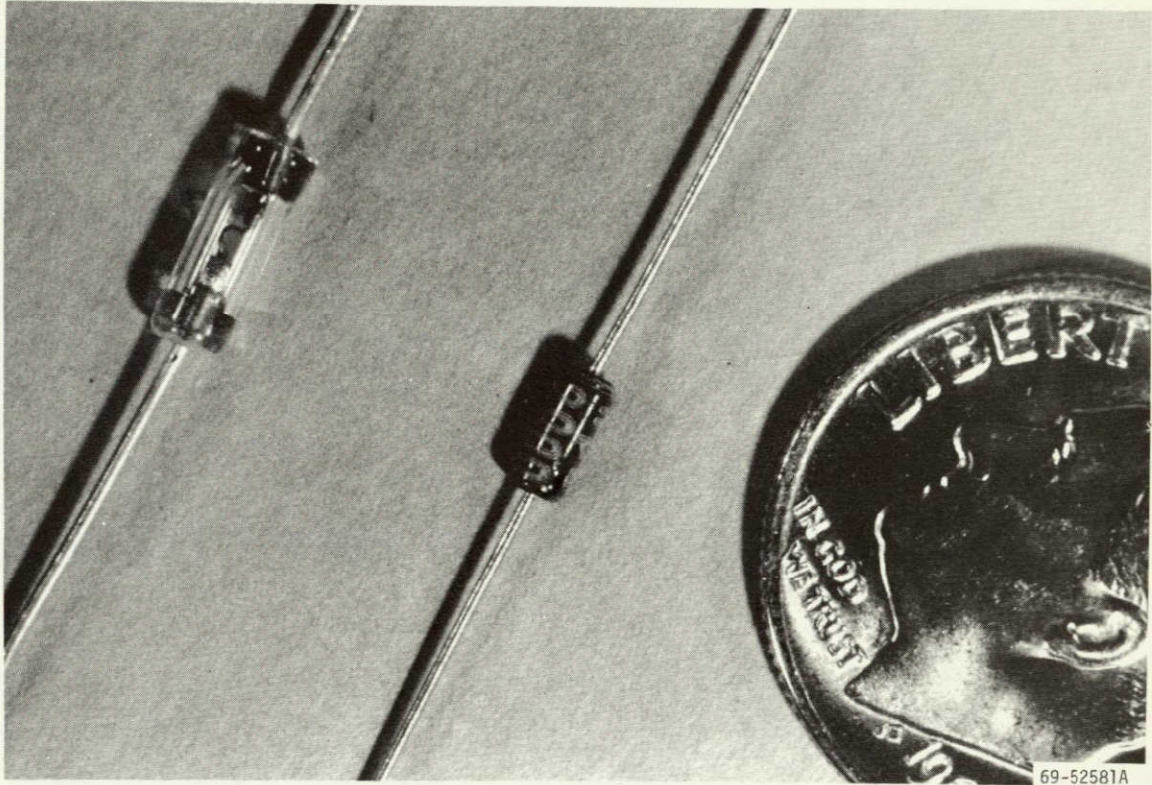


Figure 2

Point-contact and Schottky barrier diodes in glass packages compared in physical size to a dime.

Turning now to the receiving antenna we become aware of the difficulty of keeping an antenna aperture of large area with a correspondingly high directivity pointed towards the transmitter. The difficulty suggests that the total aperture be broken up into a large number of smaller ones each of which is terminated in its own rectifier. In that way, the total aperture directivity would be the same as that of the small aperture. In the case of many small apertures, therefore, it would be possible to utilize the semiconductor diodes as terminating elements even though their individual power handling capability is quite limited. When this approach of breaking up of the large aperture into a large number of small apertures each terminated by its own rectifier is taken, a structure is provided which meets all of the requirements for both receiving antenna and rectifier as listed above.

Within the constraints indicated above, and depending upon the state-of-the-art of the rectifier diode technology, there is a wide variation in the manner in which rectennas may be physically arranged and constructed. The aperture may be broken down into a large number of half wave dipoles each of which is terminated in a rectifier bridge. Or, it may involve a construction using strings or closely spaced rectifiers which are directly excited by the incident microwave energy. It is possible to build the rectenna in either a rigid or flexible form. To obtain a maximum efficiency from the rectenna, there must be a reflecting plane or some other form of matching device in order that the rectenna can absorb all of the incident power. A highly efficient rectenna must involve a minimum of two planes in its construction.

The first investigation^[1] of the rectenna device was performed at Purdue University under the direction of Professor R. H. George with the support of

the Raytheon Company. In this early work an array of diodes was arranged as shown in Figure 3 and the efficiency, power handling capability, and directivity properties of such an array were investigated. The array consisted of 28 half wave dipoles each terminated in a bridge rectifier made from four 1N82G point contact semiconductor diodes. The dipoles were separated from each other by approximately $1/2$ wavelength. A reflecting plane was placed $1/4$ wavelength behind the dipoles. The test frequency was 2.44 Gigahertz.

The directivity characteristics in one of these arrays is shown in Figure 4. It will be noted that the directivity is essentially that of a $1/2$ wave dipole and therefore dependent upon the size of the sub aperture rather than the overall aperture. The combined capture and rectification efficiency measurements were made using the setup shown in Figure 5. The results are shown in Figure 6. It must be noted, however, that because of edge effects accurate measurements of overall efficiency of the relatively small area are difficult to make.

The first application^[2] of the rectenna principle was in 1964 at the Raytheon Company in conjunction with a small tethered helicopter whose propulsion power was supplied by a microwave beam. The particular antenna construction utilized is shown in Figure 7 and consists of strings of rectifiers arranged to form the legs of a rectifier bridge as shown schematically in Figure 8. The particular form of array shown in Figure 7 was necessary because of the relatively large power density required for the experiment and the relatively small power handling capability of each point contact semiconductor diode. A total number of 4480 diodes were used to construct the two foot square rectenna. The maximum power output of this rectenna was

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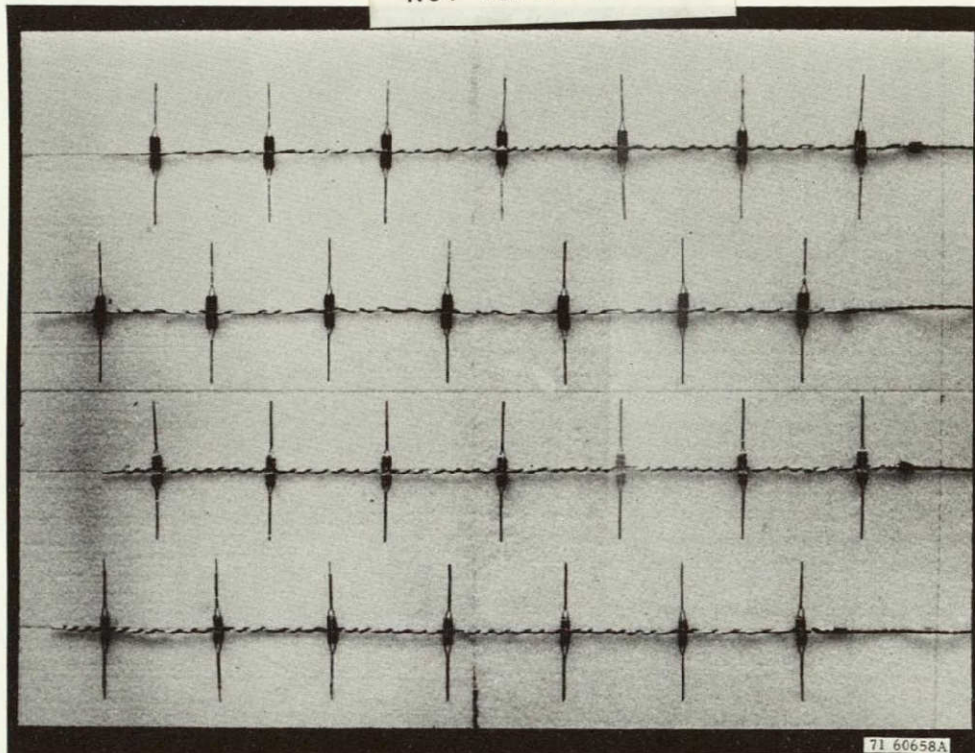
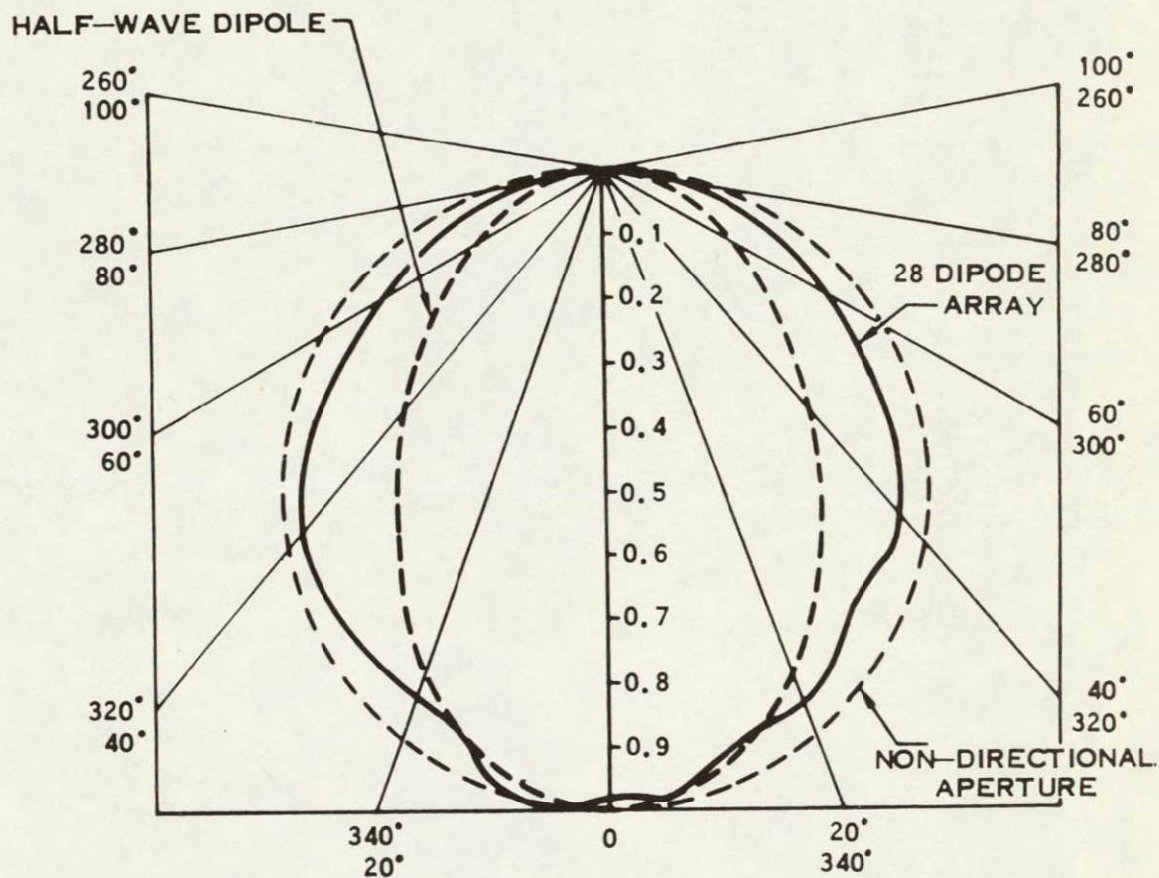


Figure 3 An early experimental rectenna composed of 28 half-wave dipoles spaced one-half wavelength apart, each dipole being terminated in a bridge-type rectifier made from four 1N82G point contact semiconductor diodes. A reflecting surface consisting of a sheet of aluminum was placed one-quarter wavelength behind the array.



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Figure 4

Directivity of the rectenna shown in Figure 3 compared with the directional properties of a half wave dipole and a non-directional aperture. Directivity is essentially the same about both axes of rotation.

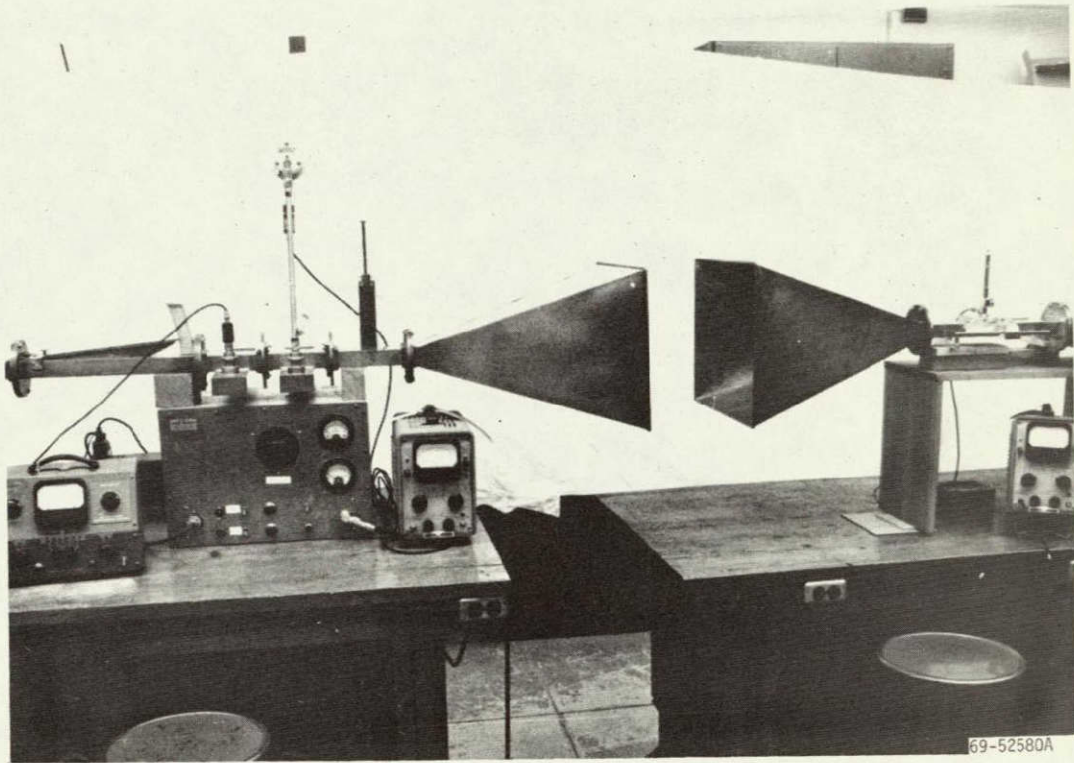
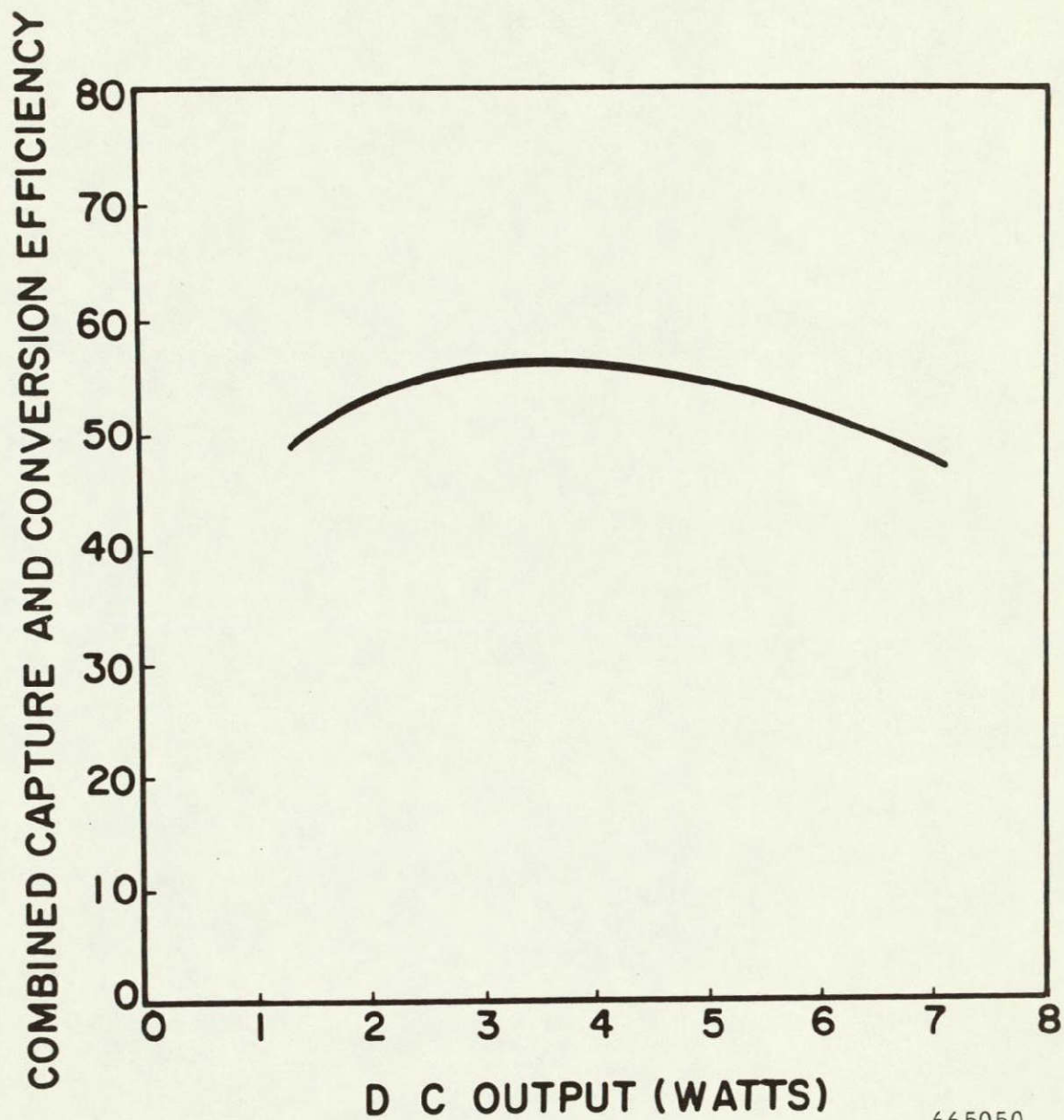


Figure 5

Experimental arrangement at Purdue University for checking combined collection and rectification efficiency of the rectenna shown in Figure 3. The amount of microwave power that enters the horn at the right is measured, and then compared with the DC power output of the rectenna when the rectenna is mounted immediately in front of the horn on the right.



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Figure 6

The combined capture and rectification efficiency of the experimental rectenna shown in Figure 3 when it is measured with the experimental arrangement shown in Figure 5.

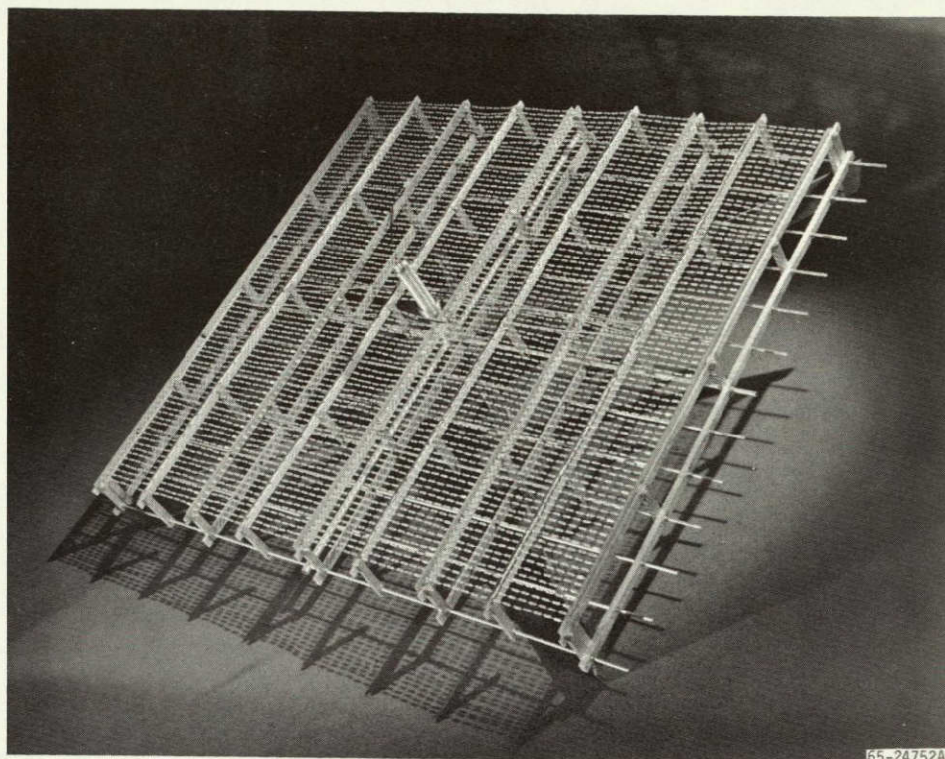


Figure 7

The special rectenna made for the first microwave-powered helicopter. Array is two feet square and contains 4480 1N82G silicon point-contact rectifier diodes.

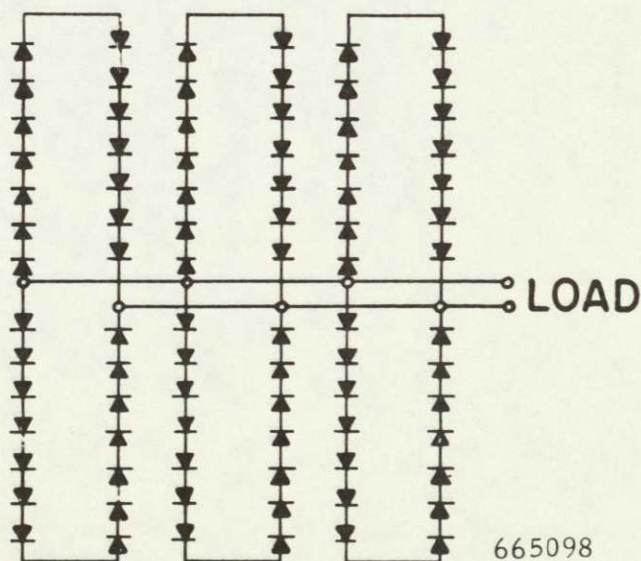


Figure 8

Schematic drawing showing arrangement of dipoles and interconnections within one of the sixteen modules forming the rectenna shown in Figure 7.

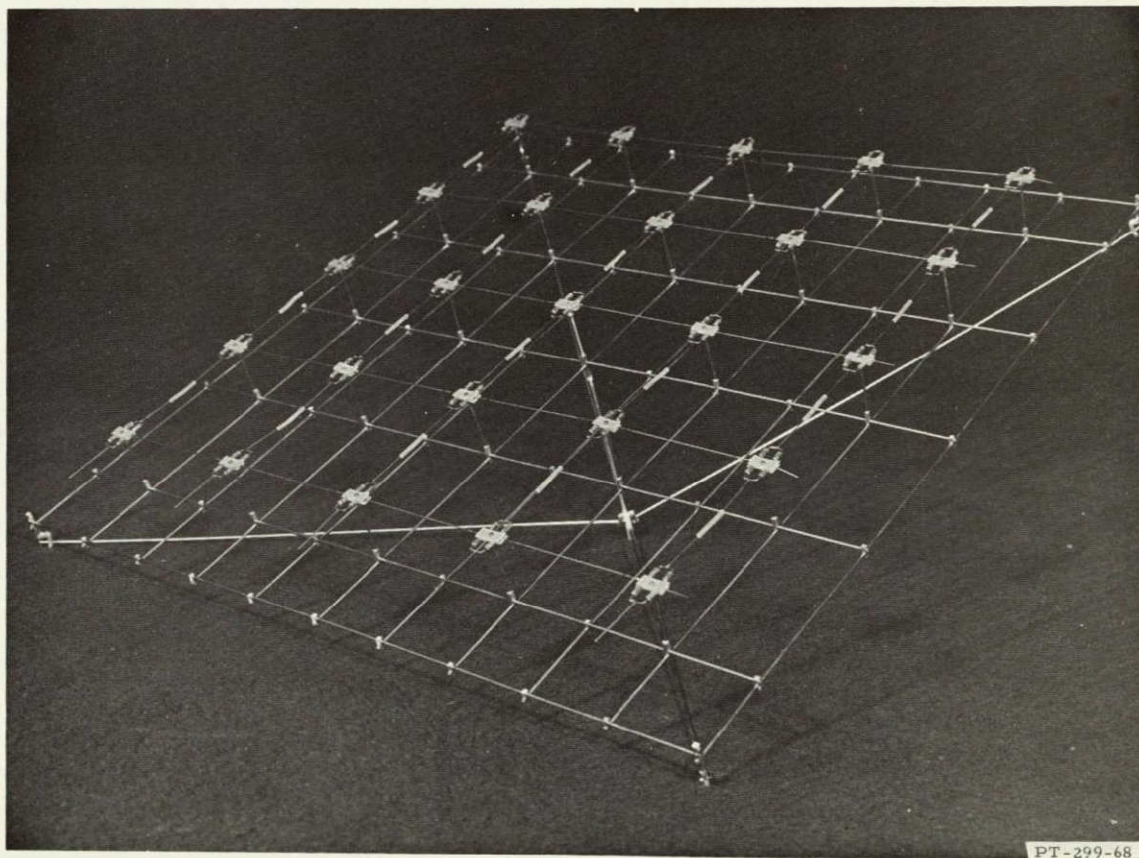
270 watts. The weight of the complete rectenna was 2.2 pounds so that the power output to weight ratio of the rectenna was 122 watts per pound. This ratio for an aerospace rectenna was undesirably low and a way to increase this figure was sought.

The introduction of the Schottky barrier diode in the miniature glass package shortly after this initial work in 1964 made it possible to predict and subsequently obtain a substantial increase in the ratio of the power output to the weight of the rectenna. Further, it was found that the Schottky barrier diode operates at a substantially higher efficiency. Typical efficiency performances of these diodes when they are measured by themselves at 2450 MHz without the presence of the rest of the rectenna is of the order of 80 percent. Typical performance data^[3] provided by R. H. George is listed in Table I.

In order to investigate the reduction in the specific weight of rectennas that could be accomplished by using commercially available Schottky barrier diodes, a one foot square rectenna was recently constructed and tested at 2450 MHz. This rectenna, shown in Figure 9, made use of lightweight construction techniques. The main construction members are made from 40 mil OD hard-drawn nickel tubing having a two mil wall. The one foot square array employs 25 dipoles spaced approximately $1/2$ wavelength from each other. Each dipole is terminated in a bridge rectifier made from four HPA 2900 Schottky barrier diodes. The outputs of the bridge rectifiers are connected in series. The DC connectors are placed normal to the electric field and hence do not disturb the interaction of the array with the incoming microwave beam. The weight of the diodes themselves in this array is five grams. The weight of the supporting structure is fifteen grams and the weight of the additional

TABLE I

TYPE NO.	GROUP NO.		2.44 GC/s DC OUTPUT/DIODE		EFFICIENCY %
			VOLTS	MILLIWATTS	
H-P-A	SB	6	10.0	240.5	82.2
"	"	6	10.0	300.0	75.0
SYL.	#31	7	10.2	107.0	89.1
"	#	7	10.2	137.2	85.7



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Figure 9

Greatly improved rectenna made from improved diodes (HPA 2900) which are commercially available. One foot square structure weighs twenty grams and can deliver twenty watts of output power.

trussing which would connect this section to another section in a module type of construction is five grams.

The rectenna shown in Figure 9 has been tested in a narrow microwave beam so that the power density illumination of the center portion of the rectenna was twice the illumination at the edges. The power output of the rectenna was therefore limited by the maximum power dissipation of those central elements receiving the highest incident power density. The array was tested up to a power output of 14 watts under these conditions. If the array were tested in a microwave beam such that the incident power upon the array was uniform over the one foot square area, at least 20 watts should be obtained. The power output to weight ratio of this array, therefore, is about one watt per gram or about 454 watts per pound. This is approximately four times better than that achieved with the rectenna in Figure 7. Further, by employing more diodes to terminate each dipole and by making corresponding changes in the matching of the antenna to space, it should be possible to obtain a power output to weight ratio of about one kilowatt per pound for the basic type of structure shown in Figure 9.

Valid efficiency measurements of the improved rectenna are not available, chiefly because of the existence of edge effects which make experimental efficiency measurements difficult. However, valid efficiency measurements of 69 percent for an individual dipole and rectifier combination similar to those used in the array of Figure 9 have been made. In these measurements the unit dipole was used to terminate a special waveguide in which the power flow could be carefully measured.

A consideration of rectenna design indicates that there are three

levels of successively more complicated structures that are involved. The first level corresponds to the individual diode and its characteristics. The second level is the incorporation of this diode with other diodes into a subelement of the rectenna structure; for example, the dipole terminated in a bridge array. The third level is the incorporation of these subelements into an overall structure.

At the individual diode level we are interested in the conversion efficiency and the equivalent circuit of the diode. In the rectification process harmonics will be generated and it is important that this harmonic power be subsequently converted in large measure to useful DC power. The measurements made by R. H. George^[3] and Paul Smith^[4] on individual diodes are believed to have been made in such a way that the harmonic power was not uselessly reflected or dissipated but was incorporated in large measure in the DC power output.

When the diodes are incorporated into a subelement of the rectenna structure their circuit characteristics and the handling of the harmonic content are of considerable importance. To illustrate this point a simple bridge configuration connected to a dipole and with the DC energy extracted without the use of RF filters in the DC leads gives a typical matched out efficiency of 50 percent when tested in a special waveguide with a shorting plate $1/4$ wavelength back of the dipole. On the other hand, a more complex configuration with chokes inserted on the DC collection leads to prevent the escape of second harmonic energy gave matched out efficiencies of as high as 69 percent.

Just as the introduction of the Schottky barrier diode in the small

glass package made possible large advances in rectenna performance, so is it likely that the current progress that is being made in fabricating Schottky barrier diodes with integrated circuit techniques will make additional advances possible in the area of rectenna construction.

It may be interesting to examine the possible future directions that rectenna development may take. It is quite likely that with the use of integrated circuit techniques and beam-lead technology that a complete bridge-type rectifier can be made on a very small chip. This small chip may in turn become part of a flexible antenna which is made by printed circuit techniques on a flexible dielectric film. Some of the experimental effort in this area is shown in Figure 10 which shows the half wave dipoles and DC connecting leads photoetched from a 1/2 mil sheet of copper bonded to a 2 mil thickness of Kapton material. The bridge rectifiers then made with the use of integrated circuit techniques would be bonded to the flexible rectenna at the point where the half wave dipoles intersect with the DC collection leads. The weight of such a construction would be very small indeed and the construction would have the additional advantage of being able to be rolled into a compact configuration for transportation purposes. Such a flexible rectenna without a second matching plane could absorb up to 50 percent of the incident microwave power. In those applications where maximum efficiency was needed, a reflecting plane could be positioned approximately 1/4 wavelength to the rear of the flexible face of the rectenna.

In summary it may be stated that the rectenna is a suitable device for receiving and rectifying microwave power in an aerospace application. The device has been experimentally demonstrated. Existing designs provide acceptable ratios of

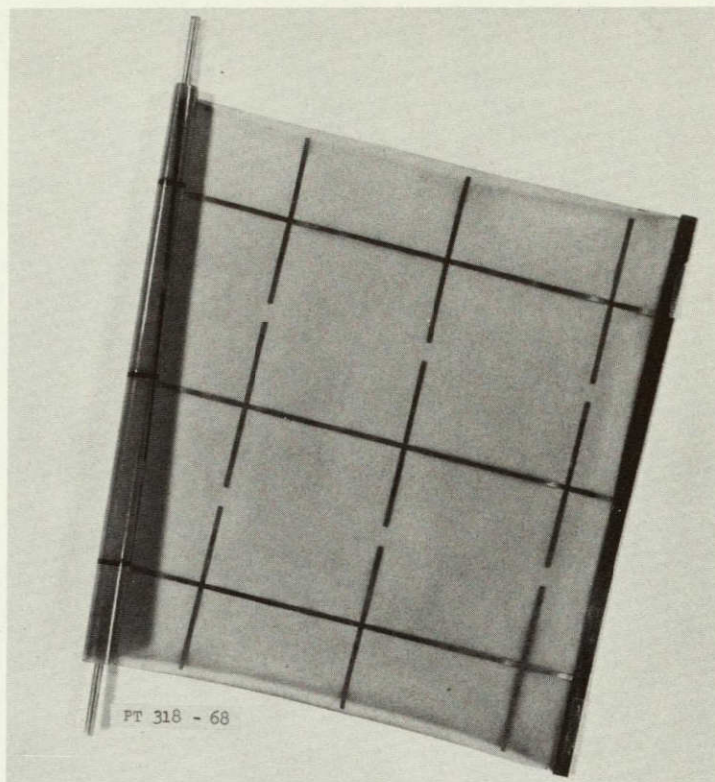


Figure 10

A possible physical configuration which future rectennas may assume. Rectenna is made in flexible form by employing printed circuit techniques on dielectric film material such as Kapton. Rectifiers perhaps made by integrated circuit techniques are bonded to the flexible printed circuit at appropriate points.

power output to weight for many applications. Impending developments in making Schottky barrier diodes with integrated circuit techniques may improve this ratio further.

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13. ABSTRACT A microwave beam is studied as a means of transferring power between satellites. Emphasis of the study is upon the basic elements of microwave power generation, transmission, and capture and rectification. Experimental work included an accurate measurement of overall dc to dc efficiency of 27% in a laboratory system, and a beam-riding vehicle capable of simultaneously receiving power and automatically positioning itself for maximum power transfer.			