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THE FEASIBILITY OF WIRELESS POWER TRANSMISSION FOR AN ORBITING ASTRONOMICAL STATION

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ABSTRACT

An examination is made of the feasibility of using microwave or laser energy for wireless transfer of power from a manned, Earth-orbiting central station to unmanned astronomical substations. This is a recent conception, and details of a power-transfer system have not been established. Therefore, the possibility of wireless power transfer is judged on the basis of the state of research and development in power generation, transmission, and conversion.

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SCIENTIFIC PAYLOADS DIVISION
SPACE SCIENCES LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

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THE FEASIBILITY OF WIRELESS POWER TRANSMISSION FOR AN ORBITING ASTRONOMICAL STATION

SUMMARY

An examination is made of the feasibility of using microwave or laser energy for wireless transfer of power from a manned, Earth-orbiting central station to unmanned astronomical substations. This is a recent conception, and details of a power-transfer system have not been established. Therefore, the possibility of wireless power transfer is judged on the basis of the state of research and development in power generation, transmission, and conversion.

Existing microwave power generation is more than adequate for the estimated 2 kW requirement of a satellite substation. Generators such as superpower Amplitrons have a laboratory output exceeding 400 kW of CW power at a wavelength of 10 cm. In an unoptimized power system (including generation, transmission, and conversion) with an overall efficiency of 18 percent, an Amplitron could supply power for several substations.

Microwave power transmission would require better efficiency than is acceptable for present radar and communication systems. One idea for improving efficiency is to form a convergent beam in an ellipsoidal transmission "envelope."

Calculations involving the relationship between antenna size and operating wavelength show that antenna size can be reduced as wavelength is reduced. However, generator efficiency also diminishes with shorter wavelength. The implication is that improvement of generator efficiency for operation at shorter wavelengths (less than 3 cm) would permit a significant reduction in antenna size.

Direct conversion of microwave to dc power is a more recent development than power generation. Semiconductor diodes and close-spaced thermionic diode rectifiers are considered the most promising components for aerospace applications.

A microwave power transfer system has already been used experimentally to operate a helicopter device; and a beam-riding system is under development. This is an attempt to use a microwave beam to control a distant helicopter as well as supply its operating power.

The present availability and performance of microwave components and the progress being made in research and development point to the feasibility of a practical wireless power-transfer system for aerospace use within a few years.

Laser high-power development, being newer, is behind microwave technology. The highest power attained in the laboratory has been 7 kW, with a CO_2-N_2-He medium. Despite the short history of its development, however, power generation is progressing rapidly; the 7 kW output represents more than a threefold increase within the year.

Laser power transmission and conversion still are in the research stage. One of the goals of research in power transmission is to obtain a long-lived refractor that will withstand high-power radiation. Lenses of doped germanium (Ge-Sb-Se) and of ultrapure germanium are being tested for this use.

Laser energy has been converted to electric power by means of photovoltaic detectors. These are semiconductor diodes with p-n junctions of Cd-Hg-Te alloys, and can be made for efficient operation at the CO_2-laser wavelength.

Calculations similar to those made for microwave antenna size show that transmission and receiving apertures would be much smaller for the laser beam. This offers a special advantage over a microwave system, which must compromise between transfer efficiency and antenna size.

INTRODUCTION

The objectives of future astronomical payloads (beyond the follow-on Apollo Telescope Mount) have been the subject of much discussion and planning [1]. To help fulfill these objectives, a concept of an Earth-orbiting astronomical station has been proposed. The concept envisions a large, manned central station and small, unmanned satellite substations several kilometers from the central station. Each substation would be designed for a specific program.

The central station would support an astronaut crew and provide electric power, a workshop and laboratory, data transmission systems, shielded film storage, docking facilities, etc. For the concept of untethered substations, which this report is concerned with, the electrical power obtained from a nuclear reactor generator would be converted to electromagnetic energy in the form of microwaves or monochromatic light. This energy would be transmitted to the substations, thus serving as a source of electrical power and, possibly, for guidance and control. All the substation power requirements would be met through suitable conversion of the electromagnetic energy received from the central station.

With this conception, changes in the scientific programs would require only the addition of a new substation having its telescope and recording equipment designed for the particular program. The cost of each new substation in time and money would be relatively small since such features as control and pointing systems, power source, and launch systems would be standard for all substations.

The concept of electric-power transmission through microwaves is not new, of course, being first attempted in 1899 by Tesla [2, 3]. Since that early, unsuccessful experiment, industry has successfully developed microwave equipment which generates hundreds of kilowatts for radar, heating, and other applications [4, 5, 6]. In a recent example of wireless power transmission, a helicopter device operated aloft, deriving its electric power from microwave energy beamed from a ground-based generator [2, 3, 7].

Laser generation and transmission of energy for conversion to electric power has not reached the same stage of development as in microwaves. The potentialities of lasers, however, warrant serious consideration of their use for power transmission. Consequently, although this report deals mainly with microwaves as a feasible power system, the possibilities of laser application are also considered.

An artist's conception of the orbiting astronomical station is shown in Figures 1 and 2, and the basic plan of electromagnetic energy transfer is illustrated diagrammatically in Figure 3. The research and developmental status of these basic elements in microwave and laser systems is examined in this report as the basis for determining the feasibility of wireless power transmission for the orbiting astronomical station.

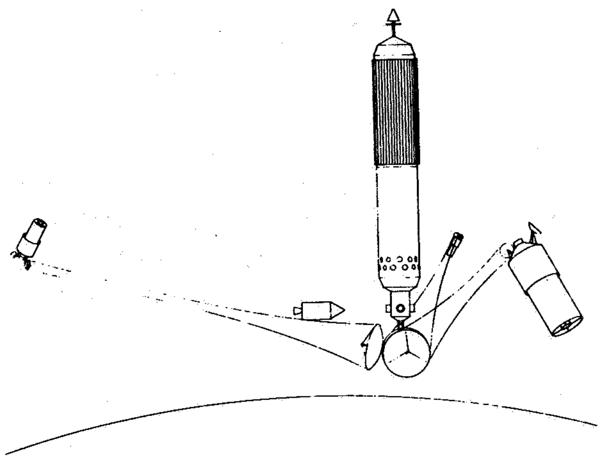

FIGURE 1. ARTIST'S CONCEPTION OF ORBITING ASTRONOMICAL STATION USING MICROWAVE BEAMS

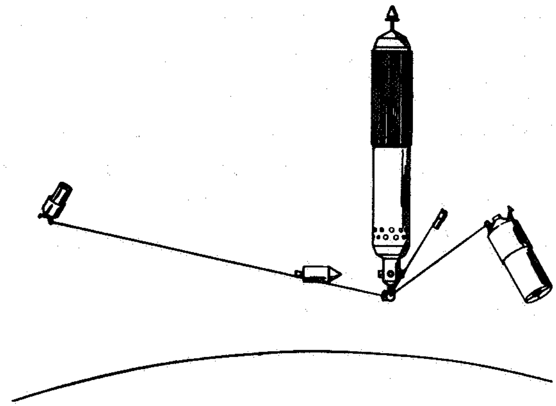

FIGURE 2. ARTIST'S CONCEPTION OF ORBITING ASTRONOMICAL STATION USING LASER BEAMS

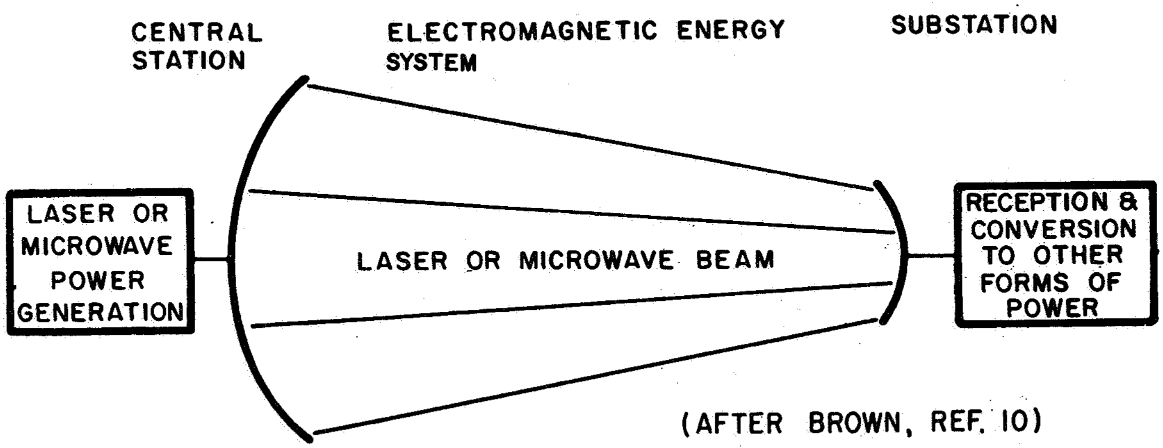

FIGURE 3. ELECTROMAGNETIC ENERGY SYSTEM

TRANSFER OF POWER BY MICROWAVES

A general outline of a microwave power transfer system is given in Figure 4, and the status of the constituent systems is discussed in the following text.

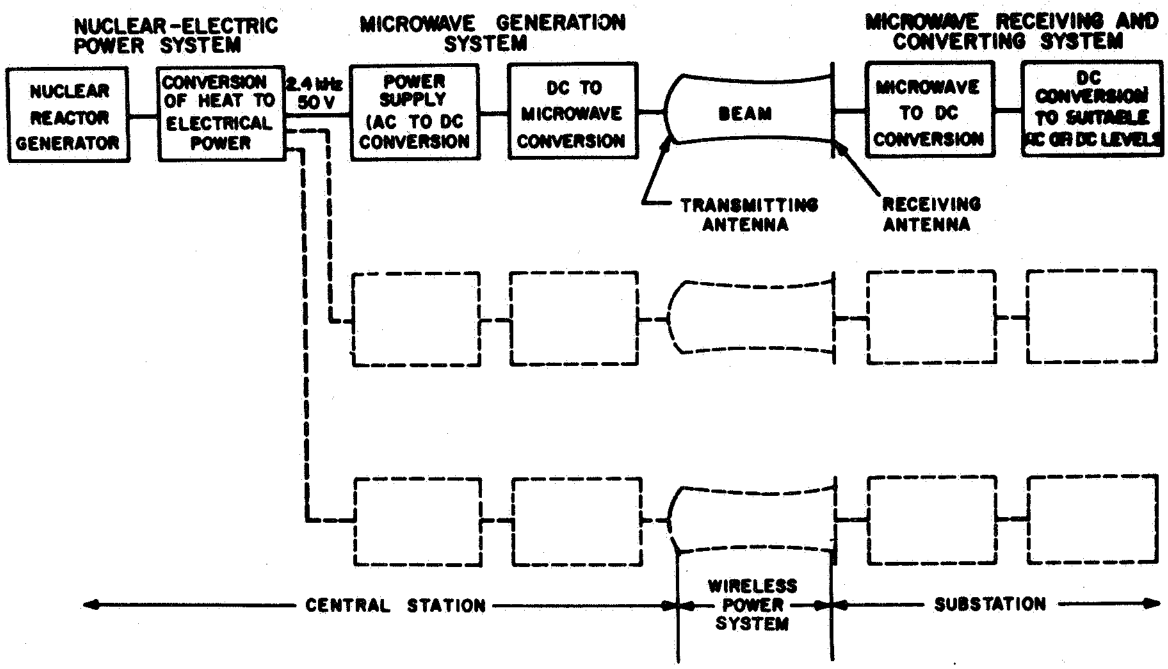

FIGURE 4. BLOCK DIAGRAM OF PROPOSED MICROWAVE POWER SYSTEM

Microwave Power Generation

Electric Power Supply Considerations. The electrical power needed for the microwave generator is calculated as 11.2 kW, based on an overall system efficiency of 18 percent and proposed satellite substation requirement of 2 kW. (Present attainable efficiencies are 85 percent for the microwave generator power supply,[1] 70 percent for the dc to microwave converter, 50 percent for antenna transfer in nonoptimized systems, and 60 percent for the substation rectifier [9]. Therefore, overall efficiency is $0.85 \times 0.7 \times 0.5 \times 0.6 \approx 18\%$.)

[1] Discussion with Mr. H. F. Fichtner, R-ASTR, MSFC.

A survey of electric-power systems in use on space vehicles shows a trend toward high frequency electrical systems as a means of reducing power loss, system weight, and component size.[2] Although frequencies higher than 2.4 kHz may be desirable for certain applications, this basic frequency is recommended as a practical compromise between design constraints of the nuclear power system and attempts to make optimum the capacity-to-weight ratios for electric-power equipment. High-performance materials for use at this frequency are becoming available for motors, transformers, etc., and the new equipment shows significant advantages over equipment operating at 400 Hz. Moreover, proven equipment designed for 400 Hz operation may be used, since 2.4 kHz is readily converted to three-phase 400 Hz power (using semiconductor static inverters and counting techniques for signal splitting).

An operating voltage of 50 V appears to be practical because of limitations in the speed of system rotary components and in high-temperature insulation. This voltage is acceptable for equipment now in use since semiconductor switches and other components can operate reliably at this potential. In addition, should static conversion equipment be required, this voltage would permit the use of static power modules without overstressing the components. When higher voltages are needed, they can be obtained with available high-performance, low-mass transformers.

DC Conversion to Microwaves. Efficient microwave tubes generating hundreds of kilowatts of continuous power in the microwave domain have been developed [8]. A scaled-down version for use in space power transmission may be adapted from one type, the Amplitron, first developed in 1955 by Raytheon Company [3, 4]. Present types of Amplitrons have demonstrated in the laboratory 400 kW output in the 10 cm band at 74 percent operating efficiency [9], and the efficiency is expected to improve to 90 percent [10].

The principle of Amplitron operation is a continuous crossed-field interaction, as in the conventional magnetron oscillator. Besides having the magnetron's high efficiency and simple construction, the Amplitron is able to amplify over a broad frequency band [4]. The details of its operation and construction are given in References 11, 12, and 13, so only a brief description is given here.

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[2] Discussion with Mr. R. Boehme, R-ASTR, MSFC.

The Amplitron consists of a "cold" cathode, a slow wave structure arranged concentrically around the cathode, a magnetic field through the axis of the cathode, and a dc electric field between the cathode and the slow wave structure [Fig. 5].

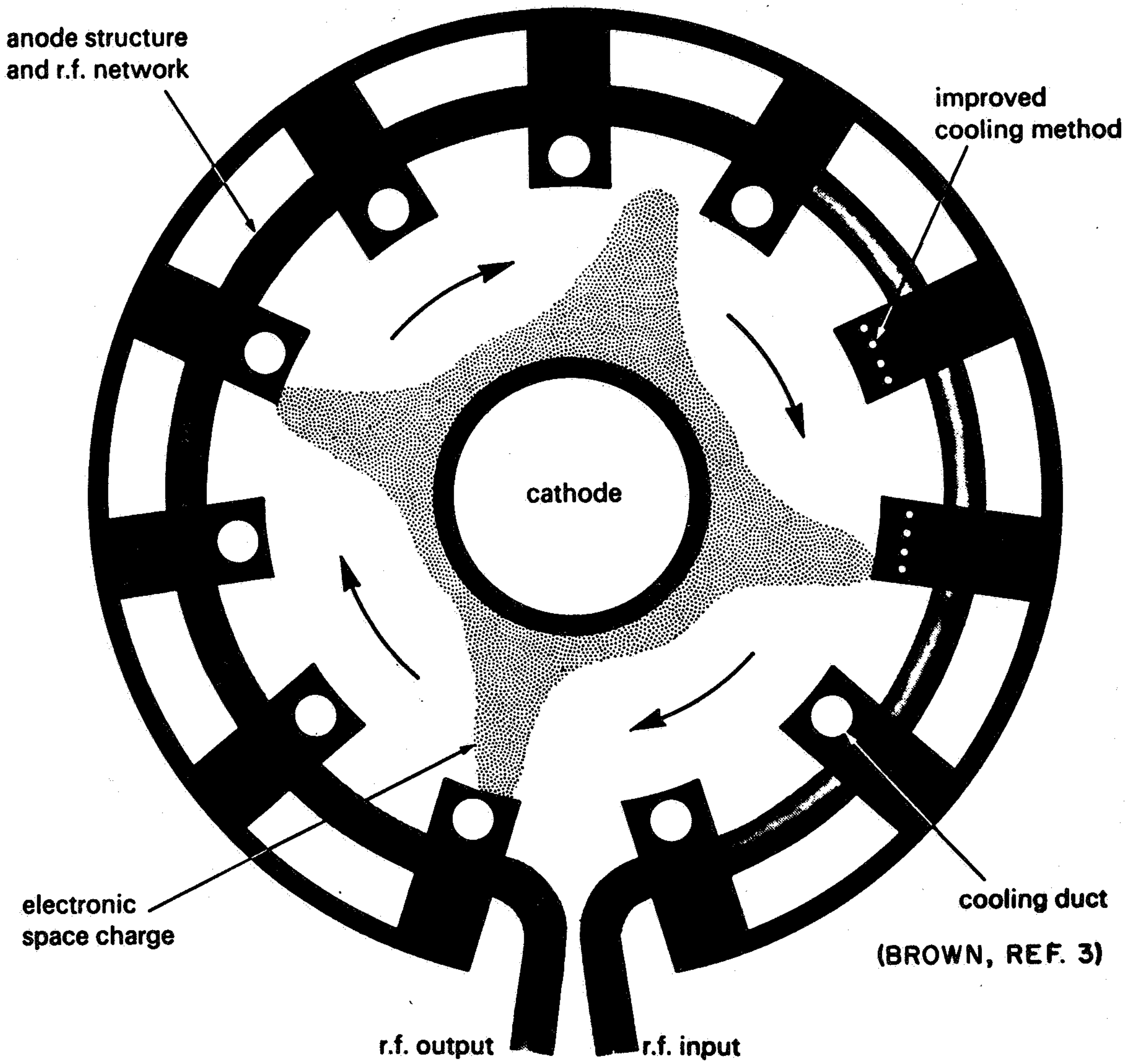


FIGURE 5. DIAGRAM OF BASIC AMPLITRON

To put the Amplitron into operation, a dc potential from an external source is applied, causing electrons to leave the cathode. Under the influence of the magnetic field, the electrons rotate in concentric circles around the cathode. When a traveling rf wave is introduced, it interacts with the rotating electrons or rotating space charge. As the dc potential is increased, a critical value is reached; the electron angular velocity is in synchronism with the rf wave fields. The electrons lose energy to the rf fields at the same rate at which they accept energy from the dc field. The power generated is proportional to the product of torque and angular velocity.

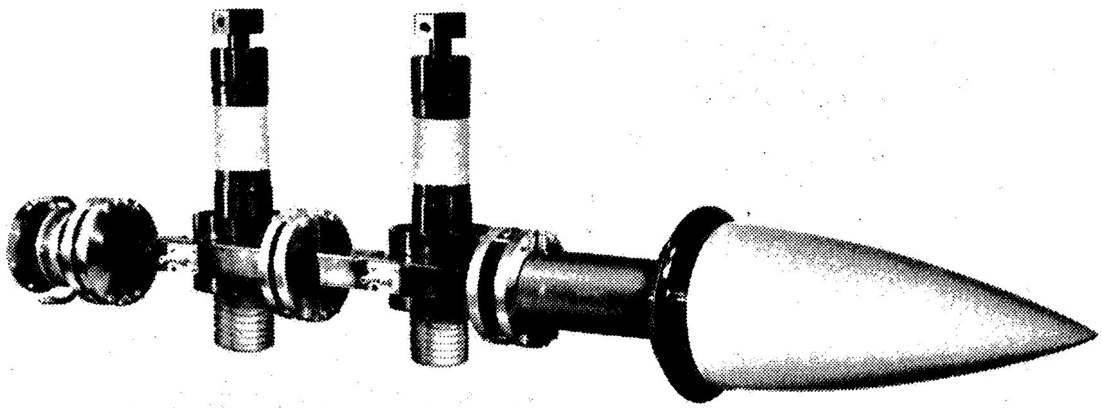
A double-stage Amplitron is illustrated in Figure 6. This cascade arrangement, producing 425 kW of continuous-wave power, radiates rf power into space directly through the radome vacuum window. A single-stage Amplitron, also illustrated in Figure 6, has a lower power output of 50 kW, having been derated for long tube life ($\approx$ 10 000 hours). The efficiency and power output relative to frequency are given in Figure 7, and a comparison of power generation with those of other single units is shown in Figure 8.

The development, application, and weight and cost per kilowatt of power generated is documented [14] for the experimental helicopter device powered by beamed microwaves (described in the next subdivision, "Status of Development"). Microwave power transmission in space would require a scaled-down Amplitron with about a 10 kW output for each substation. The QR 1224 Amplitron has an output of 400 kW at a wavelength of 10 cm, with 70 percent efficiency obtained at an operating potential of 20 kV. Its efficiency and power output are compared with frequency in Figure 7.

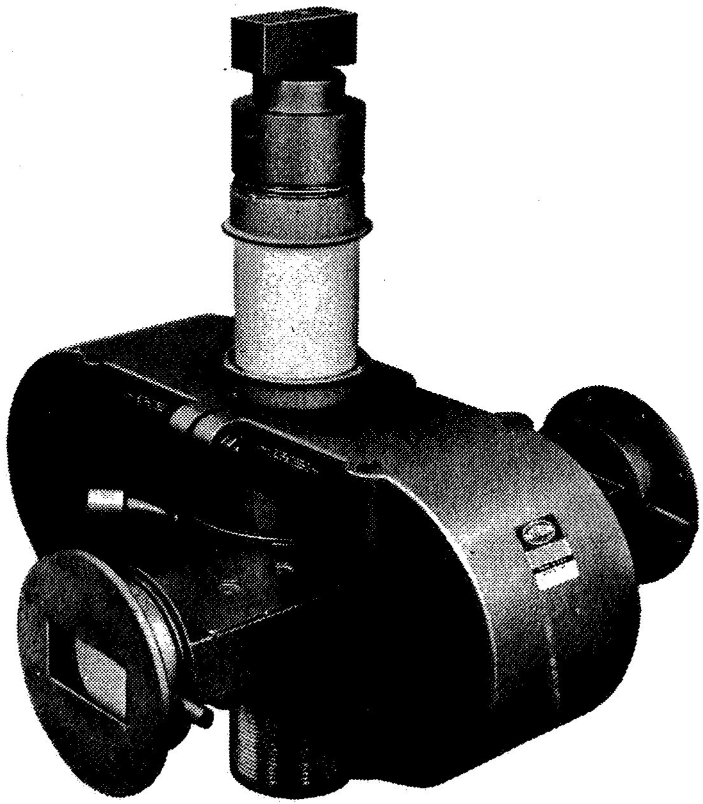
The optimum frequency range of the Amplitron is 1 GHz (λ = 30 cm) to 10 GHz (λ = 3 cm). The operating frequency must be considered not only in regard to optimum transmission but also with respect to potential interference with sensitive land-based radar, microwave (TV and telephone), and spacecraft telecommunication systems.

The power-supply requirement for the present high-power Amplitrons is 20 kV at 15 to 20 amperes. Therefore, one tube could supply the power for several microwave links. One Amplitron cannot work over the entire frequency and power ranges, but must be designed for a particular wavelength and power range. For example, a low-power Amplitron designed to operate on a frequency of 3.035 GHz (λ = 10 cm) and having an output of 10 kW, including 3 kW for reserve, would need a power-supply input of approximately 17 kW (calculations based on 85 percent efficiency for the power supply and 70 percent for the Amplitron).

DOUBLE – STAGE (QR849)



SINGLE–STAGE (QR 1262)



(BROWN, REF. 9)

FIGURE 6. SUPERPOWER AMPLITRONS

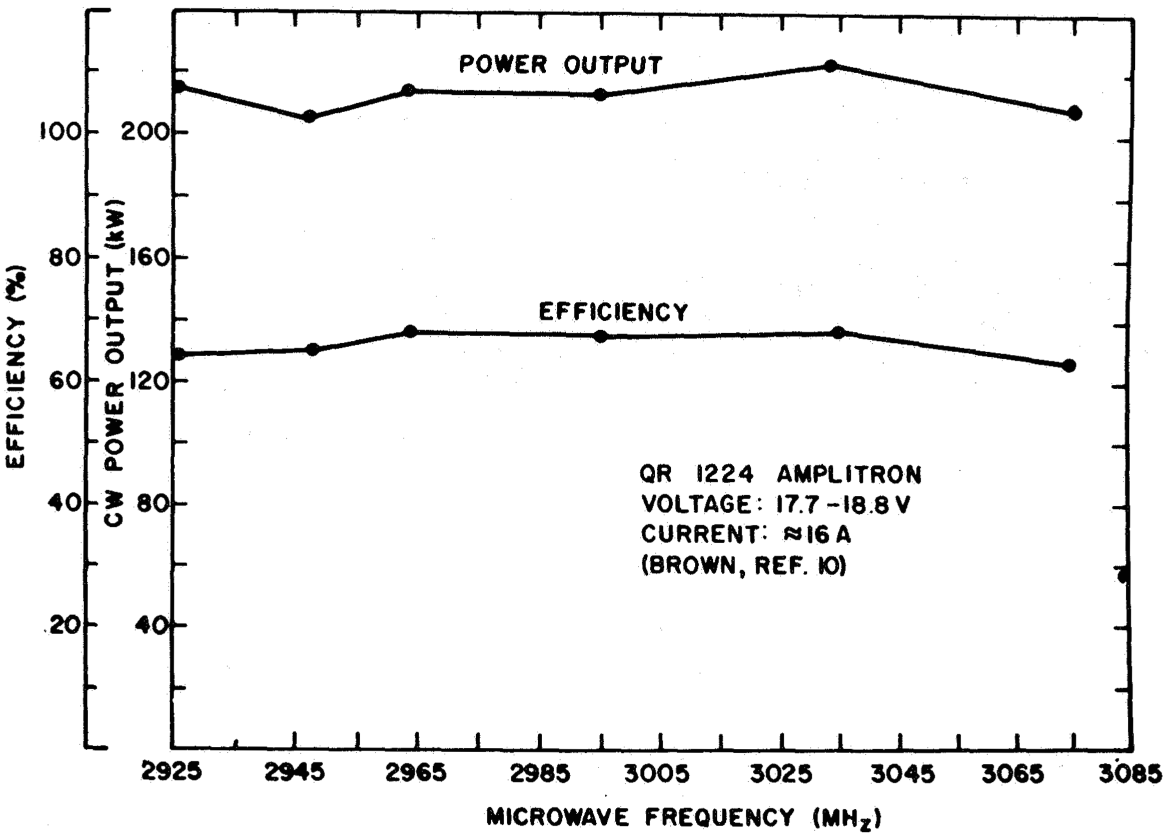


FIGURE 7. EFFICIENCY AND POWER OUTPUT RELATIVE TO MICROWAVE FREQUENCY

Status of Development. In Figure 8 are shown the efficiency and power outputs of single microwave generators working at a 10 cm wavelength, for the period 1940 to 1963 [3]. Although the average power output increased 50 times per decade, the rate of increase was low from 1950 to 1958. Then the Office of Electronics, U. S. Department of Defense, recognizing the need for higher-power devices, initiated several developmental studies in 1960. One of the objectives was to increase available power levels by several orders of magnitude. As a result of this support, by 1963 as much as 400 kW of continuous power at a 10 cm wavelength could be generated. This was 200 times the maximum available in 1948 and 20 times the amount available 3 years earlier. Microwave power of a few hundred watts was transmitted at 2450 MHz over a distance of 7.6 m (25 ft), in an experiment by Raytheon [2]. At the receiving antenna this power was converted to 230 W of dc power at an overall efficiency of 18 percent.

In 1963, Rome Air Development Center, Griffiss Air Force Base, supported a feasibility study for the construction of a microwave-powered helicopter device. A successful demonstration was made by Raytheon in October 1964 [2, 15], when a 2.3 kg (5 lbm) tether-guided helicopter with an excess lift of 0.7 kg (1.5 lbm) at sea level was kept aloft as high as 15.2 m (50 ft) for 10 hours. The helicopter (Fig. 9) had a rotor diameter of 1.8 m (6 ft), and was powered by a 0.1 kW (0.15 hp) electric motor that received its power from a rectenna (rectifier-antenna). The rectenna (Fig. 10), receiving microwaves at a frequency of 2450 MHz from a ground-based transmitter, was an array of diodes covering an area of 3700 sq cm (4 sq ft); its dc output was 230 W.

Work is continuing on a beam-riding system for a helicopter in which the tether wires will be eliminated [16]. In this project, the microwave beam will be used not only as a power source but as a reference for determining helicopter position in five degrees of freedom (pitch, roll, yaw, and X and Y translation). In addition, Raytheon Company has proposed an airborne vehicle of this type for

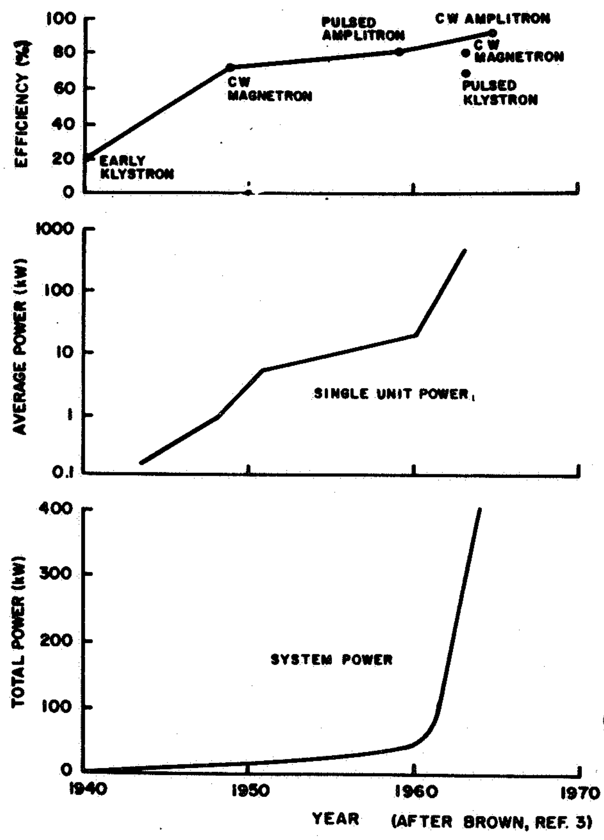


FIGURE 8. DEVELOPMENT OF EFFICIENCY AND POWER OUTPUT OF MICROWAVE GENERATORS WORKING AT A 10-cm WAVELENGTH

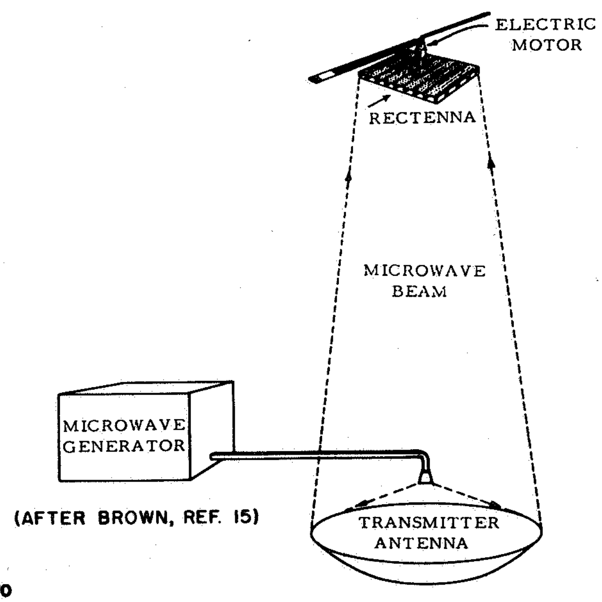
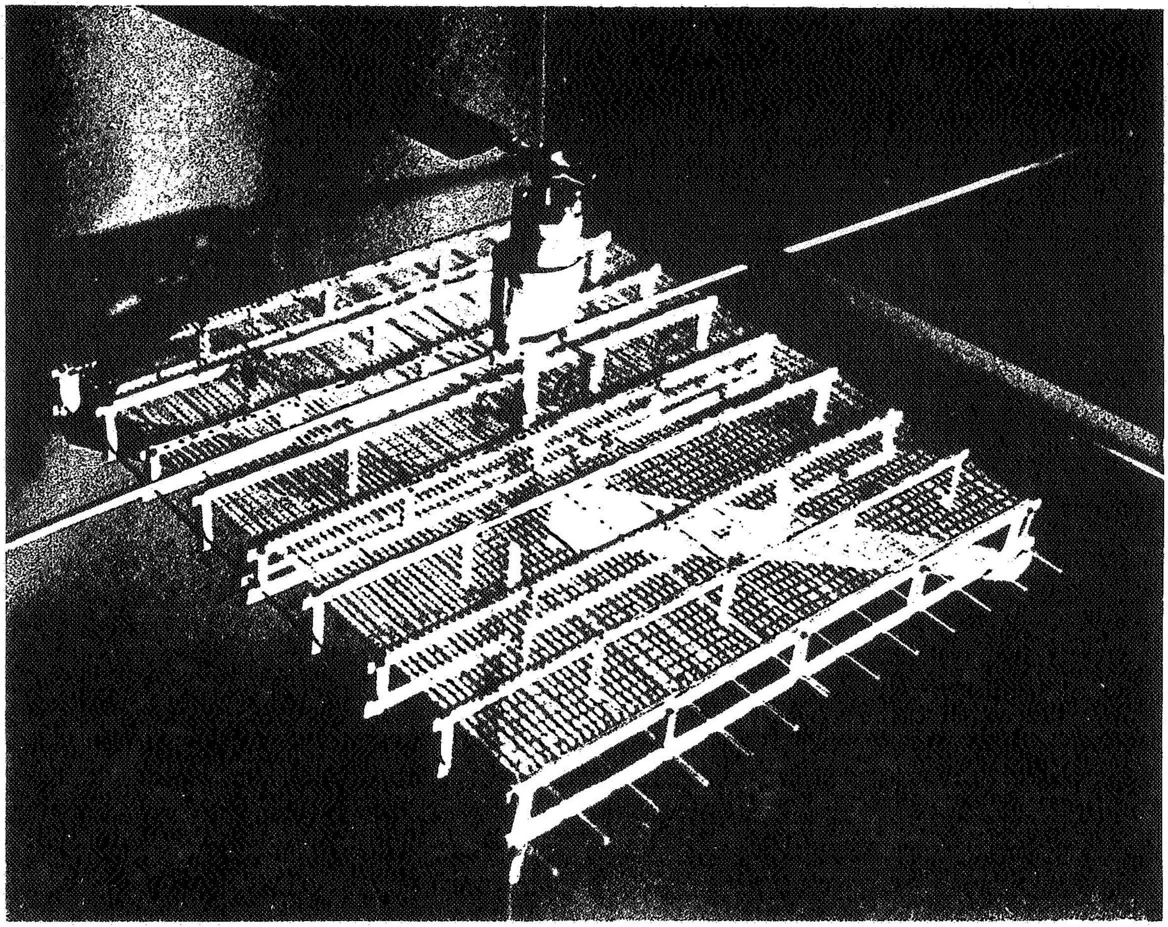
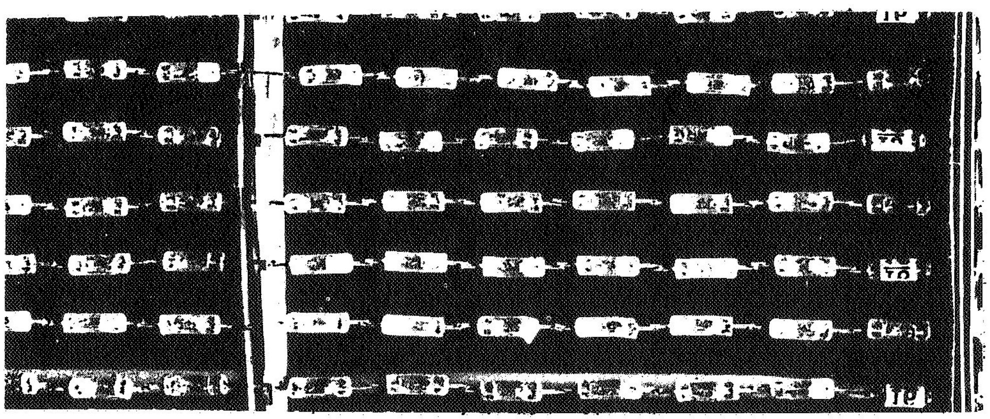


FIGURE 9. DIAGRAM OF MICROWAVE-POWERED HELICOPTER DEMONSTRATION



DETAIL OF RECTENNA DIODE ARRAY



(BROWN, REF. 3)

FIGURE 10. EXPERIMENTAL HELICOPTER

applications such as a surveillance or communications platform to fly above the cloud cover up to an altitude of 15.2 km (50 000 ft).

The work on a beam-riding system and the proposal for its application to a distant flying platform are relevant to the requirements for attitude control of an orbiting astronomical station. A successfully developed beam-riding technique could be applied to the stabilization of an astronomical substation position with respect to the central station (except for control of the separation distance). The facts that microwave power has been transmitted and converted to electricity to power a helicopter device, and that work is under way for similar power transmission at greater distances, with the addition of guidance and control, all support the feasibility of microwave power transmission between the astronomical satellites.

Special Engineering Considerations. Special considerations in the application of the microwave generator system relate to (1) heat generated within the power supplies and generator device,[3] and to (2) the possibility of electromagnetic interference with other services because of the high powers transmitted.

The selected frequency of operation would have to be determined through agreement with the Department of Defense, NASA, and FCC agencies to prevent interference with sensitive land-based radar systems, microwave TV and telephone systems, and spacecraft-to-Earth data links.

The present method of cooling a microwave amplifier is through water circulation. The heat removed could be radiated into space by means of heat pipes [17, 18], or could be used to warm the crew living quarters. The amount of heat to be removed is calculated on the basis of generator system efficiencies and residual power needs. Thus, with the assumption of 70 percent efficiency for the Amplitron or other microwave amplifier, 85 percent efficiency for the power supply, a 17 kW power-supply input, and about a 10 kW useful microwave output, approximately 7 kW of heat would have to be removed.

Microwave Power Transmission

Microwave power transmission to a satellite substation at a known distance from the central station will require better transfer efficiency than is obtained in present radar and communication systems. Experimental work to

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[3] Discussions with Mr. W. Snoddy and Mr. A. Byrd, R-SSL, MSFC.

determine the efficiency of microwave power transfer, using a convergent beam, has been conducted by Raytheon Company [10]. In a new approach, it has considered the configuration of an ellipsoid of revolution for the antenna system. In this arrangement, the transmitting antenna is at one apsis of the ellipsoid, the propagation source is at a focal point, and the detector at the other focal point. The basis for this configuration is the principle in which all energy waves emanating from a transmission focal point will traverse the same distance to the receiving focal point, and all energy waves radiated in phase will arrive in phase. The energy waves also will be in phase in a spherical surface having its center at the receiving focal point. This is illustrated in Figure 11, which shows the outer edge of the spherical surface coinciding with the aperture of the ellipsoidal antenna used as a reflecting surface.

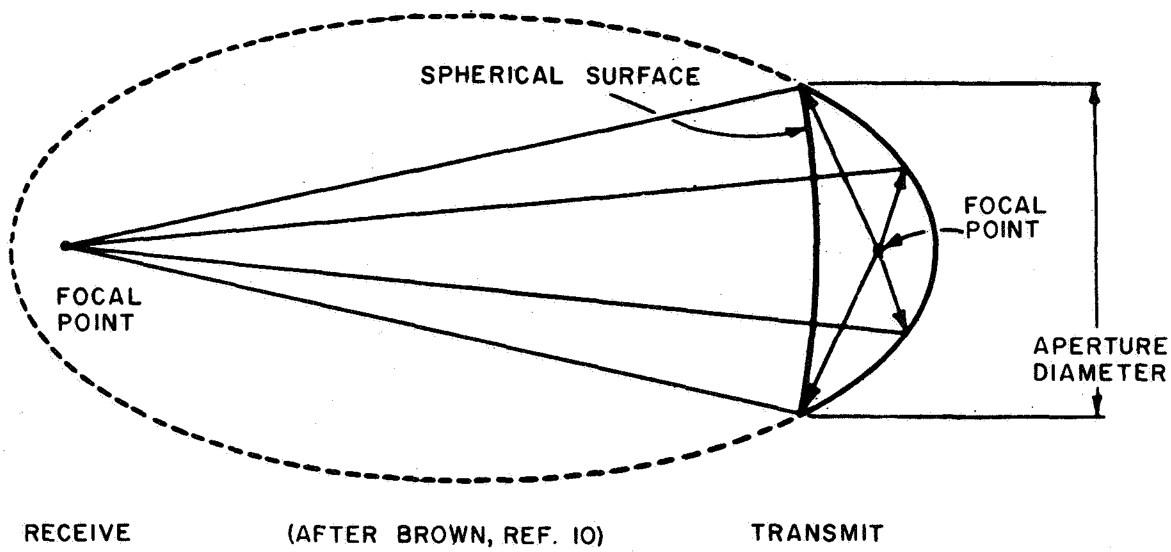
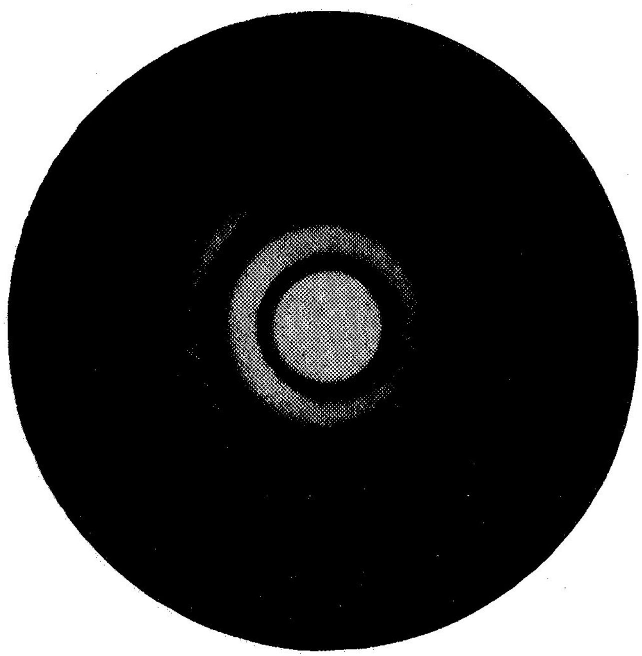


FIGURE 11. POWER TRANSFER IN AN ELLIPSOIDAL CONFIGURATION

In practice, because of energy diffraction, not all the radiated energy will converge at the receiving focal point. Instead, the energy will have a distribution about this focal point, determined by the wavelength, the diameter of the transmitting aperture, and the distance between the focal points. This energy distribution will follow a Fraunhofer diffraction pattern (illustrated in Fig. 12). Mathematically, the distribution is a Bessel function; the use of this relationship is discussed in the next subdivision, "Microwave Power Reception and Conversion."



(BORN & WOLF, REF. 25)

FIGURE 12. FRAUNHOFFER LIGHT-DIFFRACTION PATTERN

An ellipsoidal reflector was used in an experiment to verify this theoretical power-distribution pattern. The results of the experiment are compared with a theoretical power distribution in Figure 13, which shows the close correlation of theory with experimental data. In this experiment, in which an operating wavelength of 8.2 mm was used, the overall power-transfer efficiency was 52 percent ±2 percent. (The individual component efficiencies are stated in Reference 12, in which the experiment is discussed in detail.)

The following calculations have been made for a hypothetical example of microwave power transfer in an ellipsoidal configuration. When the wavelength is 10 cm, a transmitter antenna diameter of 122 m (400 ft) is needed to project 84 percent of the microwave power 16 km (10 miles) to a receiving antenna with a 30.5 m (100 ft) diameter. This is illustrated in Figure 14.

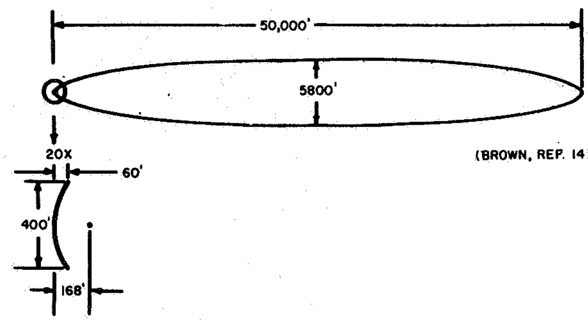


FIGURE 14. DIMENSIONS OF ELLIPSE IN HYPOTHETICAL MICROWAVE POWER TRANSFER

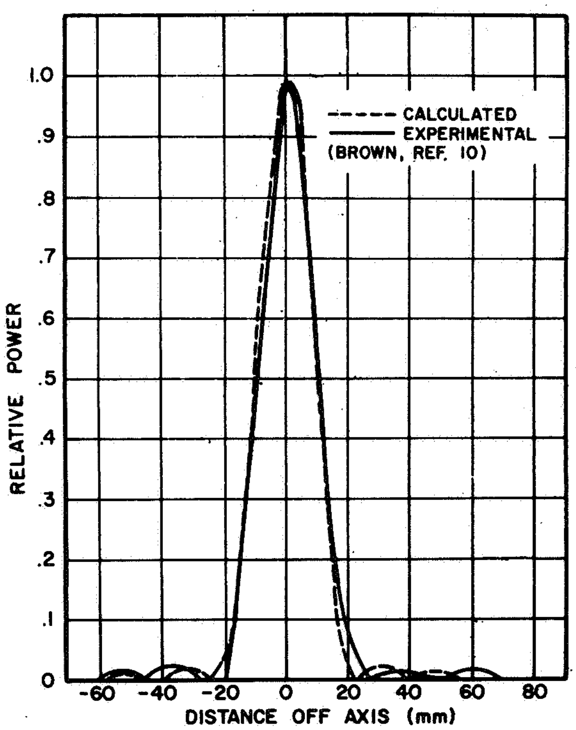


FIGURE 13. COMPARISON OF EXPERIMENTAL AND CALCULATED POWER DISTRIBUTIONS

Information on microwave energy transfer at a proposed settlement on the Moon has been estimated [8]. This information is presented in Table I, which shows how the diameter of the antenna and the mass of the antenna, transmitter, and receiver would vary as a function of distance of power transfer and radiation wavelength. The transmitting and receiving antennas are the same size for these estimates, and the power transfer is between an unshielded nuclear-power source and a distant central station. For power transfer between the central station and outposts which may have to be shifted at times, it was suggested that the main center have a large antenna and the receiving sites have small ones, possibly a few feet in diameter and with a mass of half a kilogram (1 lbm).

TABLE I. ESTIMATED MASS OF COMPLETE MICROWAVE ENERGY TRANSFER SYSTEMS*

Distance of Power Transfer km (mi)	Power Level (kW)	Wavelength of Radiation (cm)	Antenna Diameter ** m (ft)	Transmitter Mass kg (lbm)	Antenna Mass kg (lbm)	Receiver Mass kg (lbm)	Total Mass kg (lbm)
1.6 (1)	35	10	15.2 (50)	31.8 (70)	90.7 (200)	15.9 (35)	138.4 (305)
		3	9.1 (30)	31.8	22.7 (50)	15.9	70.4 (155)
		1	4.9 (16)	31.8	4.5 (10)	15.9	52.2 (115)
	100	10	15.2	90.7 (200)	90.7	45.4 (100)	226.8 (500)
		3	9.1	90.7	22.7	45.4	158.8 (350)
		1	4.9	90.7	4.5	45.4	140.6 (310)
	1000	10	15.2	680.4 (1500)	90.7	454 (1000)	1225.1 (2700)
		3	9.1	680.4	22.7	454	1157.1 (2550)
		1	4.9	680.4	4.5	454	1138.9 (2510)
16 (10)	35	10	45.7	31.8	2449.4 (5400)	15.9	2497.1 (5505)
		3	27.4	31.8	616.9 (1360)	15.9	664.6 (1465)
		1	15.2	31.8	90.7	15.9	138.4
	100	10	45.7	90.7	2449.4	45.4	2585.5 (5700)
		3	27.4	90.7	616.9	45.4	753.0 (1660)
		1	15.2	90.7	90.7	45.4	226.8
	1000	10	45.7	680.4	2449.4	454	3583.8 (7900)
		3	27.4	680.4	616.9	454	1751.3 (3860)
		1	15.2	680.4	90.7	454	1225.1

* Data after Brown [8]

** Antenna Diameter based on 75% capture efficiency

In a related study on microwave power transfer (a microwave-powered helicopter to be used as a communication platform 1 to 2 miles above the Earth's surface) [16, 19], information has been developed on factors of cost, size, and weight. This information is applicable to the present conception of an astronomical station since considerations of distances, power levels, equipment, and antennas apply to both. Wavelength is an important parameter in both applications. As the wavelength is reduced, antenna size and cost decrease. However, reliability of components and efficiency of microwave power sources and rectifiers also decrease, but the cost does not diminish proportionally.

Microwave Power Reception and Conversion

Receiving Antennas. The transmitting-antenna diameter, wavelength, and the distance to the receiving antenna are the critical parameters that determine the receiving-antenna diameter at the substation. We get some idea of the antenna sizes by using the equation that describes the distance across the central bright disk in the Fraunhofer diffraction pattern (Fig. 12).

The equation for receiving-antenna diameter is determined from the relationship $r_n = 1.22\lambda h/D_t$, the terms of which are shown in Figure 15. The bright central disk of the Fraunhofer diffraction pattern represents 84 percent of the transmitted energy. Since r_n is the radius of this central disk, $2r_n$, the diameter of the disk, represents the diameter of the receiving aperture D_r. The applicable equation, therefore, is:

$$2r_n = D_r = 2.44\lambda h/D_t ,$$

where h is the distance between the transmitting and receiving antennas.

The family of curves (Fig. 16) derived from this equation shows calculated antenna diameters for values of λ suitable for efficient Amplitron operation (10 cm - 3 cm), and for values of h representing the distance between the central station and substation (1 km - 5 km).

Conversion of Microwave Power to Electric Power. The development of high-power microwave generators made transfer of electrical power by microwave much more attractive as a potential method of wireless power transfer. In early attempts to transfer power, microwave energy was converted to heat, then to electricity. The best overall efficiency of this indirect

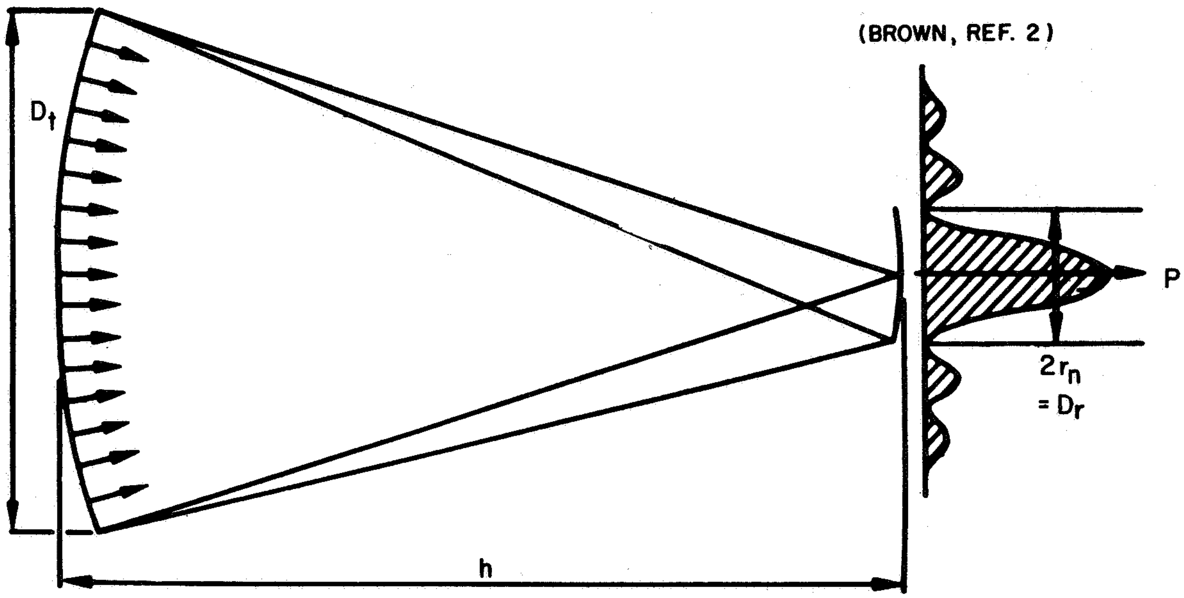


FIGURE 15. ENERGY DISTRIBUTION AS A BESSEL FUNCTION

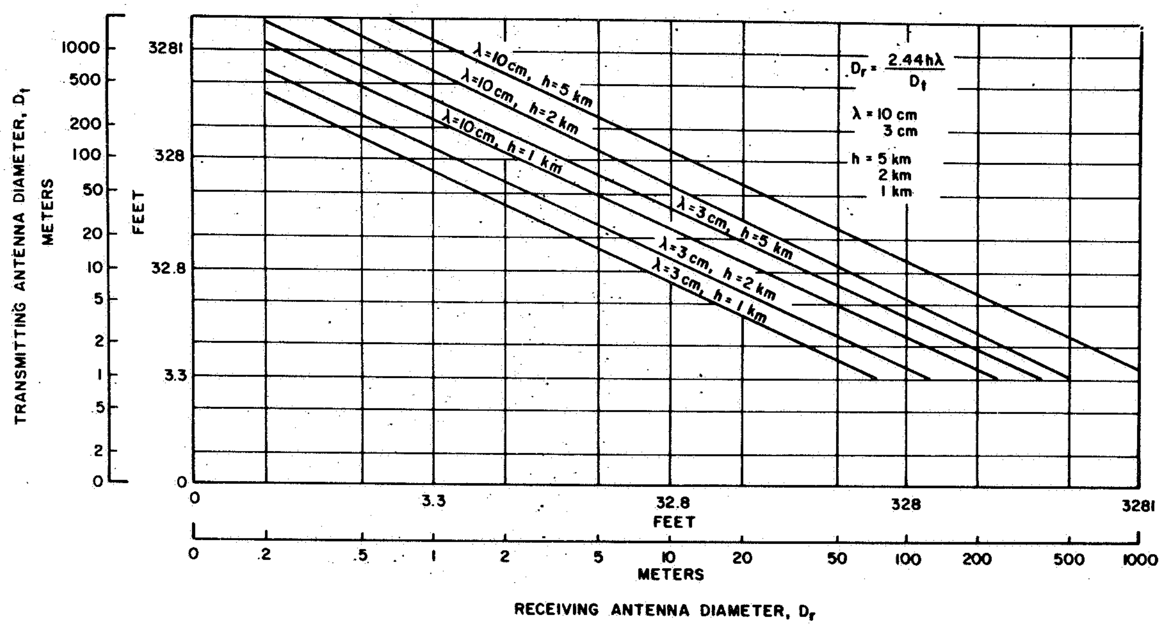


FIGURE 16. CALCULATED ANTENNA DIAMETERS FOR THREE SEPARATION DISTANCES AND TWO MICROWAVE WAVELENGTHS

conversion was less than 25 percent [7, 10]. The need for direct conversion resulted in a number of investigations. Several of the microwave rectifiers investigated appeared promising, such as the semiconductor diodes and close-space thermionic diodes. Data on these and others such as klystrons, traveling-wave tubes, and various types of diodes are shown in Table II, in which the power outputs and efficiencies are compared. The injected-beam crossed-field

TABLE II. COMPARISON OF POWER OUTPUT AND EFFICIENCY OF MICROWAVE RECTIFIERS*

Class	Subclass	Maximum Experimental Efficiency (%)	Maximum Experimental Power (watts)	Frequency Band
Colinear Beam	TWT	-----	-----	-----
Colinear Beam	Klystron	-----	-----	-----
Crossed-Field	Injected Beam	42	162	S
Crossed-Field	Magnetron	22	25 000 (peak)	L
Crossed-Field	Cyclotron	12	12 000	L
Diode	Multipactor	-----	-----	-----
Diode	Thermionic	55	900	S
Diode	Point Contact Semiconductor	70	0.1	S

* Data from Brown [10]

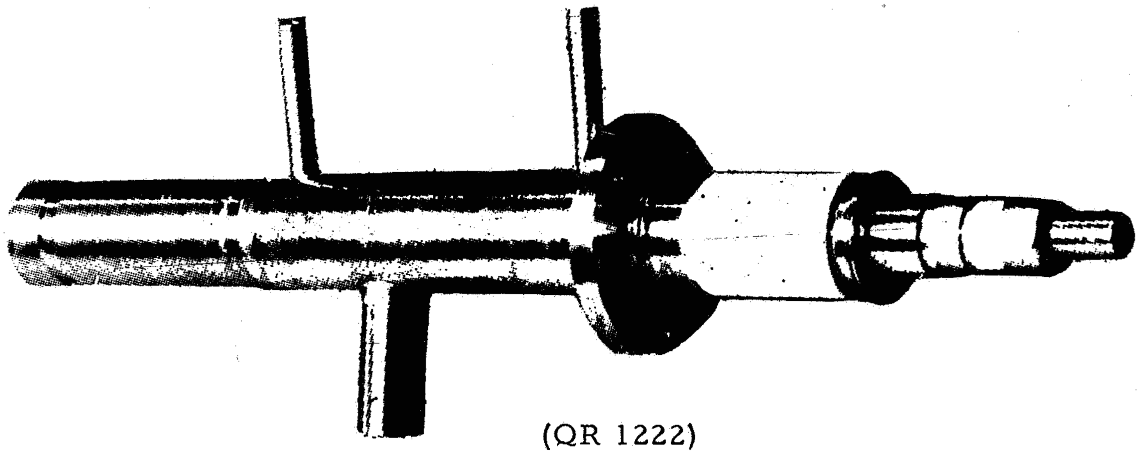
device, with a relatively high efficiency of 42 percent for a 162 W output, does not seem suitable for aerospace applications because it is too heavy and its output impedance is too high for matching to the impedance of electric motors. On the other hand, the point-contact semiconductor diodes and the thermionic diodes are well suited to aerospace applications. Their special advantages are an ability to operate continuously, an output impedance compatible with that of electric motors, and a high power-handling capability relative to their weight. The last feature is not contradicted by the low power-handling capability of single diodes (50 to 100 mW), since these are easily combined to form modules that handle a considerable amount of microwave power. For example, a method was devised for mounting standard subminiature diodes (type IN 830) in series-parallel to form a single-phase full-wave rectifier. The efficiencies and outputs of this array, at 2440 MHz, are summarized as follows:

Efficiency (%)	Power Output (W)	Operating Voltage (V)
70	9.0	24
65	18.7	30
60	25.2	32 - 36

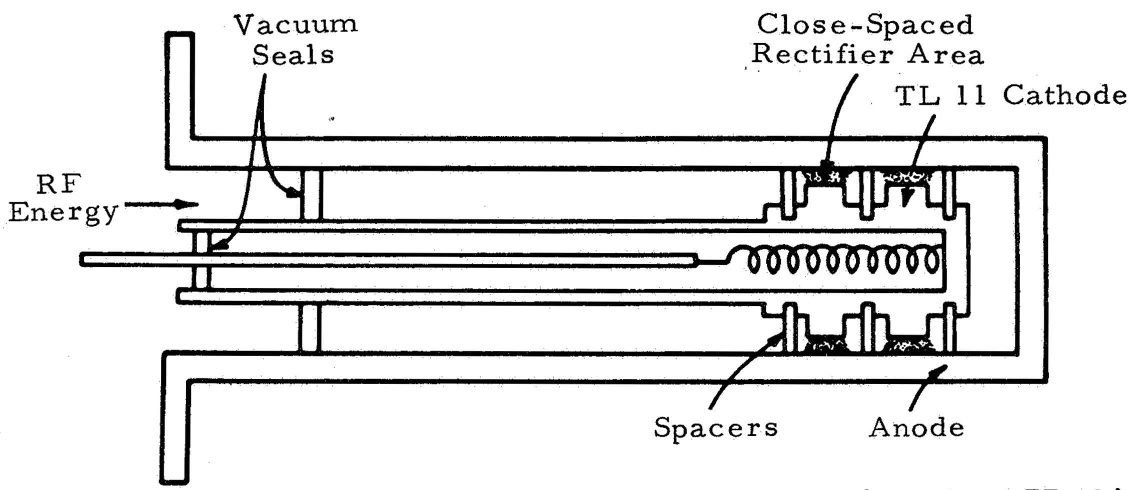
The ratio of power-handling to mass of the diode array is 250 W/0.45 kg for Sylvania IN 830 and Japan Radio IN 82G point-contact diodes. Much better power-to-mass ratios have been obtained with Schottky barrier diodes [9]. These operate at efficiencies of 80 percent with a 200 mW output. When these diodes are arranged in a comparable antenna structure, the ratio is 3000 W/ 0.45 kg.

The close-spaced thermionic diode rectifier still under study at Spencer Laboratory [10], is the highest power microwave rectifier developed. Handling microwaves at a frequency of 2450 MHz, it has produced up to 900 W of dc power at 55 percent efficiency. The QR 1222 close-spaced thermionic diode rectifier is illustrated in Figure 17.

Microwave Power Supply Converters at the Substation. The electric power output (of the rf converter) at the astronomical substation will be assumed to be dc. This will have to be converted to a suitable form for the most efficient operation of the substation instruments. For example, the dc power may be converted to an alternating current of 2.4 kHz, 400 Hz, or other, for distribution to the servo system, the telescope, and other instruments.



(QR 1222)



(BROWN, REF. 10)

FIGURE 17. CLOSE-SPACED THERMIONIC DIODE RECTIFIER

Since 2.4 kHz power supplies already are in use (Apollo and Mariner), there may be no special substation dc power-conversion problem. It is expected that these power supplies will be needed in most of the substation experiments and that the efficiencies will be from 85 percent to 90 percent.[4]

Beam-Riding System. The satellite substations will be unattended except for occasional servicing, changing of instruments, or recovery of film

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[4] Discussion with Mr. H. J. Fichtner, R-ASTR, MSFC.

[1]; therefore, their position may be controlled automatically by beam sensors and a servo-controlled electric thruster system. The recent development of a microwave beam-sensing technique [19] may be applicable to the control of the substation receiving antenna.

Raytheon Company is under contract [No. AF 30(602) 4310] to Rome Air Development Center to design a control system that automatically keeps an electrically powered helicopter positioned on a microwave beam [15]. The beam-riding capability will be provided through the use of the E vector of the beam as a reference for determining position in five degrees of freedom: pitch, roll, yaw, and X and Y translation (Fig. 18). In this technique, the information from the sensors is processed to apply the proper amount and direction of cyclic pitch of the helicopter rotor to maintain the helicopter towards the center of the microwave beam.

There are two types of sensors: amplitude- and phase-sensitive. The amplitude type is used as reference for yaw and for longitudinal (X) and lateral (Y) translational motion. The phase sensors are used as reference for roll and pitch. Properties of the microwave beam that make it suitable for use as reference are the decrease in beam intensity off the beam axis in the X and Y directions, a surface of equal phase normal to the beam axis, and polarization of the beam. The entire control system has been tested in a flight dynamics simulation using analog computers, and a test platform for evaluating five degrees of freedom of the helicopter movement has been completed.

Summary of Microwave Power Transfer

Transmission of power over a microwave beam has been demonstrated experimentally. Components are available for the transfer of several kilowatts over a distance of several kilometers. It should be feasible to adapt these components for use in the orbiting astronomical project.

Research and development in microwave generation have been going on for 25 years, and have resulted in equipment which can generate the microwave power required for the proposed astronomical station. An obvious implication of the calculations on antenna size and operating wavelength (Fig. 16) is that work on superpower generators should be directed toward efficient operation at shorter wavelengths (smaller than 3 cm). Research and development in microwave receiving systems constitute a relatively new field of endeavor.

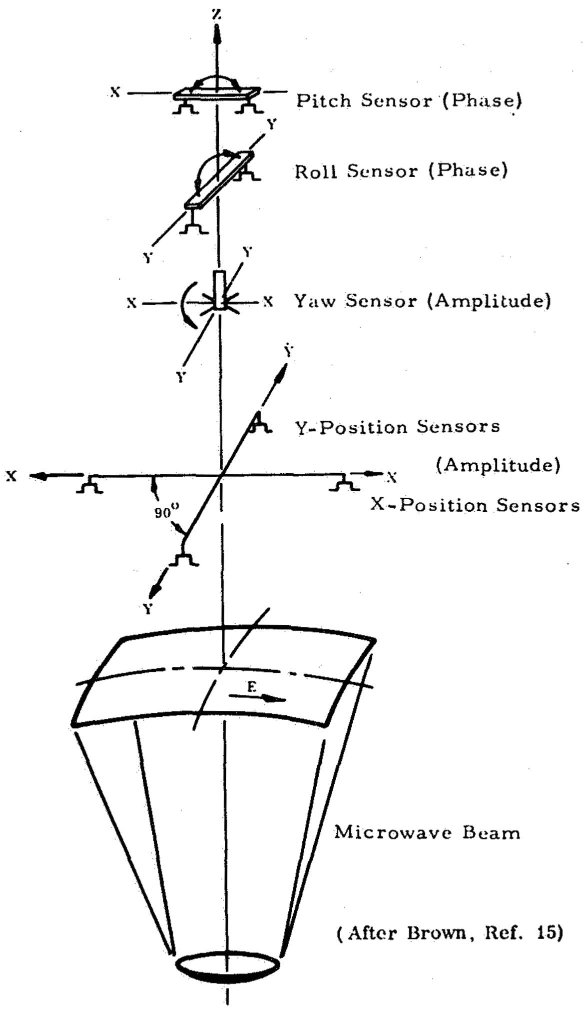

FIGURE 18. MICROWAVE BEAM AS REFERENCE FOR FIVE POSITION CONTROLS

While much promise is offered by the diode rectifiers being investigated, other components should be reexamined since continuing improvements in their efficiency may now make them as useful as the diodes. Other approaches also should be reevaluated. For example, using a local oscillator, heterodyning incoming microwave power down to a frequency of 2.4 kHz for distribution would eliminate a dc-to-ac converter and improve overall efficiency.

TRANSFER OF POWER BY LASERS

The development of lasers for high output powers is a relatively new field of investigation, with most of the effort being in the research phase. For this reason the possibilities of their use in wireless power transfer cannot be reported to the extent done for microwaves.

Laser Power Generation

Laser power output and efficiency have been improved rapidly since the first demonstration of the continuous-wave gas laser in 1961. At that time Javan's He-Ne laser had a power output of 0.1 W/m of laser tube, and an efficiency of about 0.1 percent [20]. In recent experiments with gas lasers (CO_2-N_2-He medium), continuous power of 1.2 kW was obtained in a 20 m tube, at 17 percent efficiency, and a linear power density of 80 W/m was obtained in a 3 m tube [21]. With a fixed volume of gas in a sealed-off tube, the maximum linear power density was 28 W/m, at 7 percent efficiency.

The highest power output known at present is 7 kW, obtained at Raytheon Company Research Laboratory (under contract to Physical Sciences Laboratory, Redstone Arsenal).[5] The laser in this investigation is made of nine modules, each 15.2 m (50 ft) long, arranged side by side to shorten the laser housing. It is expected that under improved operating conditions (increased pump capacity at each module and cooling of the module walls) and the addition of six more modules, the output will be increased to 10 kW.

The high-power CO_2 lasers are large and bulky, and require much supplementary equipment. Their quasi-theoretical upper limit of efficiency as energy generators has been estimated to be 40 percent[6] [21], in comparison with 70 percent - 80 percent for Amplitrons. Despite the present shortcomings, however, work on high output powers for lasers is heavily funded in military weapons studies. If progress continues at the same rate as in the past 5 years, engineering models of laser power generators should be available in about 5 more years [22].

Laser Power Transmission

In electromagnetic energy transmission, reflectors are used for microwave frequencies; and refraction techniques are usually used for the visible frequencies. The frequency of the CO_2 laser output (10.6μ, in the middle infrared) falls between the visible and the microwave frequencies. Both refraction and reflection techniques are being used in laser studies, but refraction systems, being much smaller and lighter, would be preferable.

The heating effect of the infrared wavelengths, however, presents special problems in the use of refractors (i.e., lenses). Rigden and Mueller [23] have pointed out that there are relatively few solids or liquids that do not have a high absorption for 10μ radiation. Consequently, most materials become incandescent and tend to burn up when exposed to the high-power beam of CO_2 lasers.

Several salts have been used as laser beam refractors. Irtran 4 has been the best of the zinc selenide types, but its efficiency of 94 percent is too low to allow its use for high-power beams. Refractor materials with an efficiency closer to 100 percent (for minimum absorption of destructive heat)

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[5] Discussion with Dr. H. Statz, Raytheon Company, Waltham, Mass.

[6] Discussion with Dr. J. A. Merritt, U. S. Army Missile Command, Redstone Arsenal.

are needed to withstand the very high temperature of beams in the kilowatt power level. The only high-efficiency materials which have been used in experimental work are NaCl and KCl (99% efficiency), but their eventual deterioration makes them unsuitable for long-term, practical operation [21]. (NaCl output mirrors, for example, have several disadvantages: NaCl is hygroscopic and soft, the surface cannot be cleaned, dust particles tend to settle on the surface and burn in, the internal surface becomes altered so that the optical quality deteriorates, it creeps under thermomechanical strain and so produces surface curvature, and it cracks after several hours of exposure to the laser beam.)

Ultra-pure germanium is being investigated as a lens material for high-power levels [21], but it, too, has an inherent disadvantage of poor operation because of heat absorption. A doped germanium lens (Ge-Sb-Se) with an efficiency of 98% also is being tested, but results have not been published.[7]

The technology of high-power transmission by lasers obviously is in too early a stage for conjecture on its practicality. Nevertheless, laser power transmission is being considered as a possibility in the orbiting astronomical concept because it has potential advantages over microwave transmission. As it will be shown, the laser beam requires a transmitting aperture that is very small compared with the microwave antenna, and the same advantage applies at the receiving end of the power link. In addition, a much narrower beam can be projected, even for great distances. This is an ideal condition for an electromagnetic link since the narrowness of the beam minimizes the engineering problems of compromising between antenna sizes and efficiency of power transfer.

The relationship between antenna diameter, wavelength, and separation distance, as used for microwaves, applies as well to laser power transfer. Thus, for a CO_2 laser wavelength of 10.6μ and the same distances between central station and substation (5, 2, and 1 km), the aperture diameters are very much smaller than for microwave transmission. This is illustrated in Figure 19, for the same 84% power capture as in the calculations of the microwave antenna diameters. The size of the antenna apertures increases with

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[7] Discussion with Mr. G. J. Hutcheson, U. S. Army Missile Command, Redstone Arsenal.

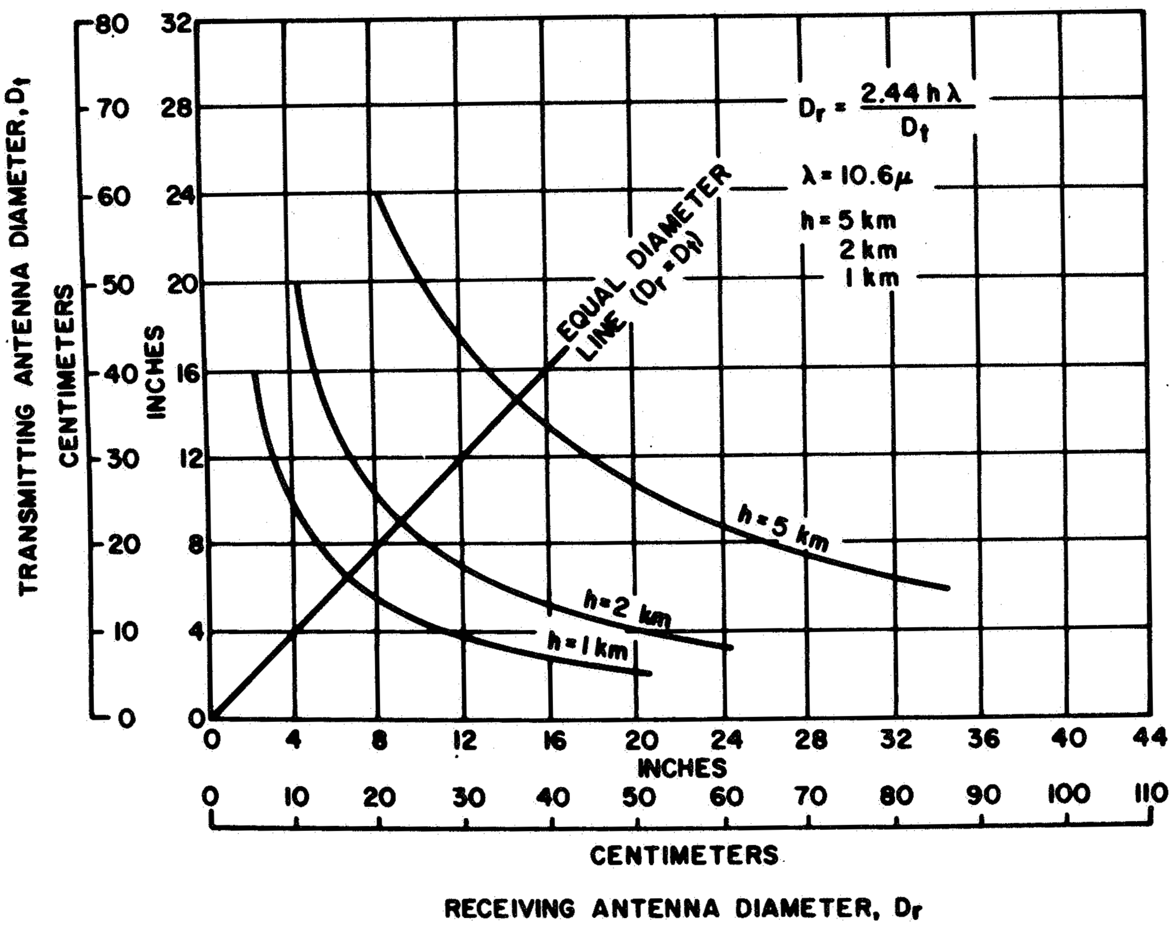

FIGURE 19. CALCULATED ANTENNA DIAMETERS FOR THREE SEPARATION DISTANCES AND A LASER WAVELENGTH OF 10.6μ

increasing length of the beam path, as it was shown in Figure 16 for microwaves. However, the beam path length is not a limiting factor for antenna size to the extent it is for microwaves.

Laser Power Reception and Conversion

Antennas. Just as for the transmitting aperture, the receiving antenna can be smaller than its microwave counterpart (at least an order of magnitude). Therefore, where receiving-antenna size may be strictly limited for a small substation, the antenna size may not be a serious problem for a laser system. The substation may even be able to carry a receiving antenna sufficiently large for better capture than the calculated 84%.

Conversion of Laser Power to Electric Power. There are no detectors presently available for the conversion of high levels of laser power. The most promising possibility for the conversion of laser energy to dc power may be photovoltaic detectors.

A new method of doping p-n junctions has been reported by Vérié and Ayas [24]. The junctions are made of $Cd_xHg_{1-x}Te$ alloys, which are small bandgap semiconductors for certain values of x $(0.15 < x < 0.30)$. The special p-n junctions are produced through the diffusion of interstitial atoms of Hg in p-type $Cd_xHg_{1-x}Te$ single crystals. The result is a crystal with properties of electrical rectification, photovoltage, and electroluminescence. Photovoltaic detectors have been made with these crystals: they were operated at 77° K and showed responses from 3μ to 17.5μ. According to the investigators, the results indicate that $Cd_xHg_{1-x}Te$ p-n junctions should be usable for rectification of CO_2 laser radiation.

This development also indicates the probability of very good efficiencies. The bandgap of these semiconductors is very small and can be tailored to function at a wavelength of 10.6μ. The theoretical efficiency has been calculated to be close to 100%, and practical diodes with an efficiency of 70% may be possible.[8] Since the output power of a single detector diode would be very small, many diodes could be arranged in a suitable array to provide the proposed 2 kW requirement for an astronomical substation.

COMPARISON OF THE TWO METHODS OF WIRELESS POWER TRANSFER

Power Generation

Research in laser-power generation has progressed rapidly in the few years of its history, but it is too recent to have provided power levels competitive with microwave power generation. The efficiencies and power outputs for both methods are summarized graphically in Figures 20 and 21, respectively.

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[8] Discussion with Dr. H. Statz, Raytheon Co.

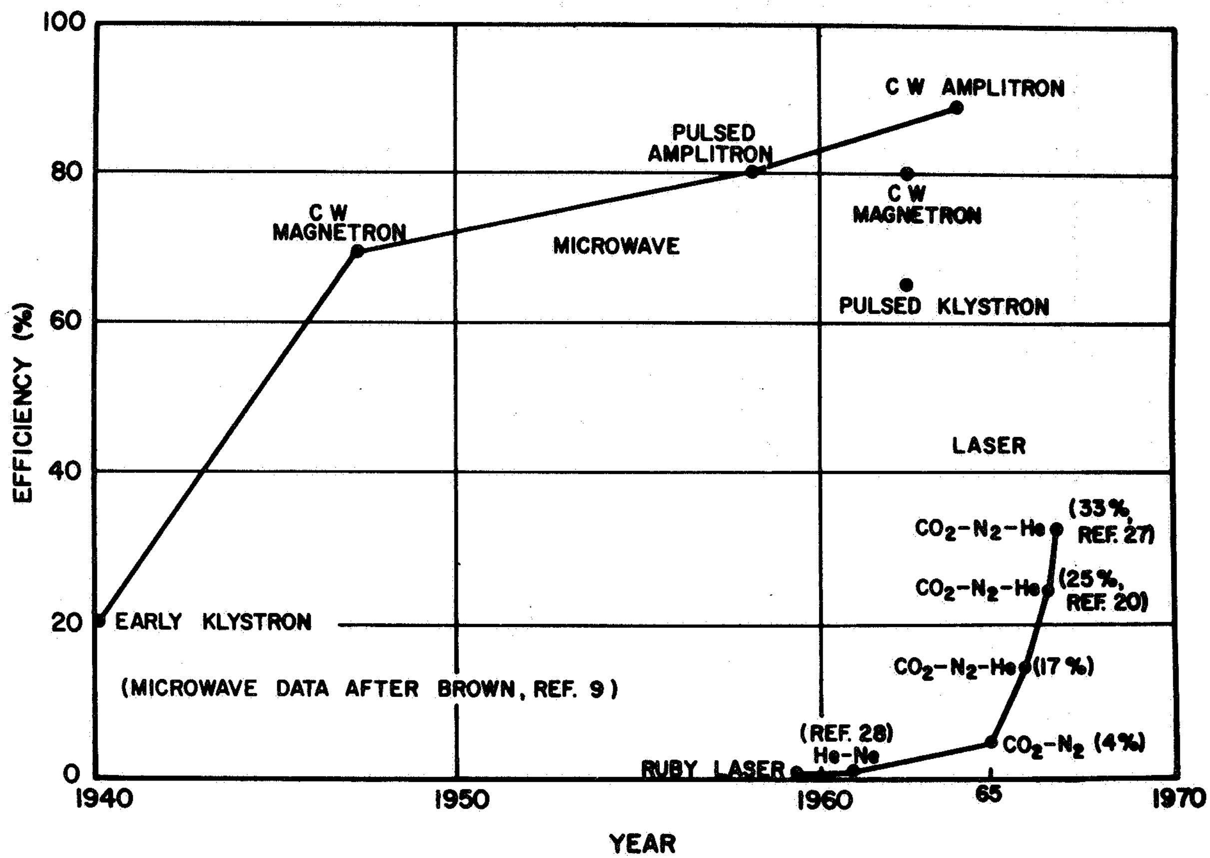

FIGURE 20. DEVELOPMENT OF EFFICIENCIES OF LASERS AND SINGLE MICROWAVE GENERATORS

Microwave power output (over 400 kW at 70% - 80% efficiency for Amplitrons) is more than adequate for the 10 kW - 20 kW estimated requirement of an orbiting astronomical station; moreover, it is generated by long-lived, relatively small, proven industrial components. The maximum output power of lasers, 7 kW, is insufficient for the estimated requirement, and is obtained with bulky laboratory equipment. However, since investigations on high-power laser output are being actively supported, there is good reason to believe that the needed power output will be available before 1975.

An assessment of the feasibility, in the next few years, of power generation for an electromagnetic link points to microwaves as the likely source of energy. For longer-term feasibility (within 10 years) lasers are expected to supply the required energy.

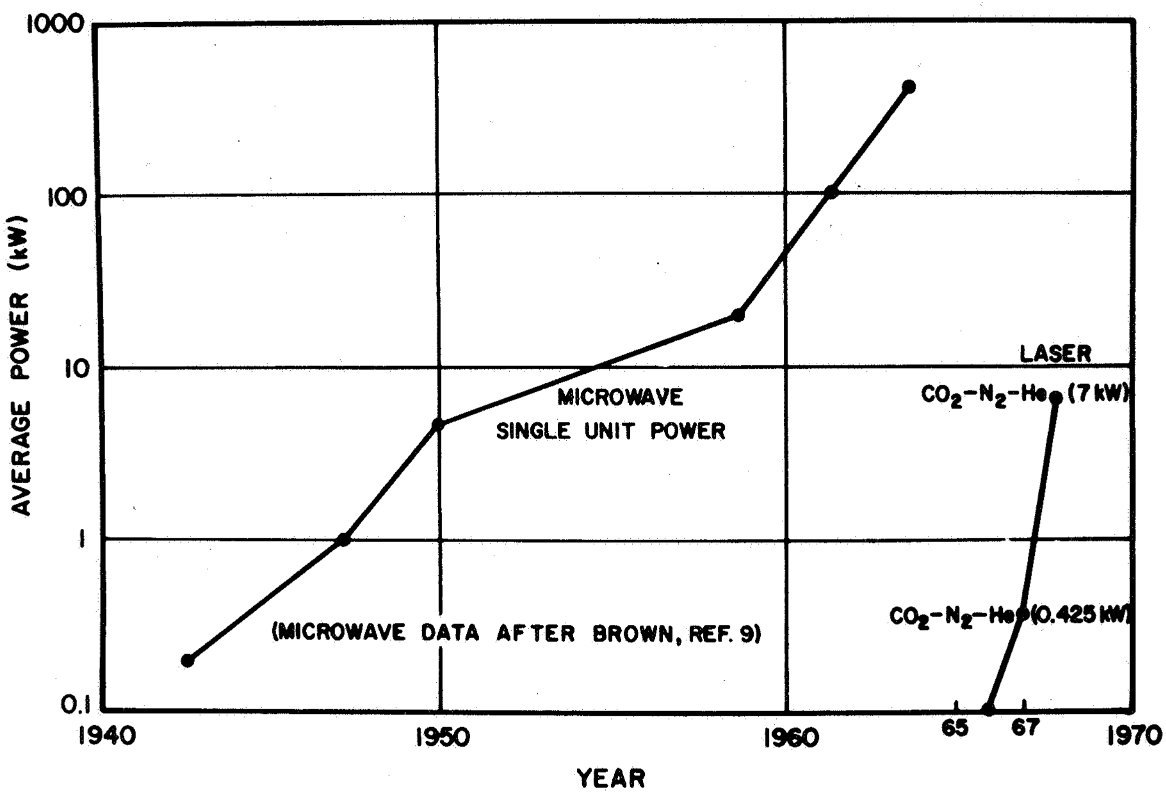

FIGURE 21. DEVELOPMENT OF POWER OUTPUT OF LASERS AND SINGLE MICROWAVE GENERATORS

Power Transmission

Transmission of power over a microwave beam has been demonstrated experimentally, and investigations of long distance transmission for control as well as power transfer are in progress.

The newer field of laser power generation has not reached this state of development. Even suitable materials and components (for example, mirror coatings and lenses) are still in the research or developmental stage.

In studies on theoretical power density distributions, particularly those following a Fraunhofer diffraction pattern, calculations indicate that a laser system would require very much smaller transmitter (and receiver) apertures than microwave systems. This potential advantage of a laser system may justify continued work toward the development of a practical laser high-power transmission system.

Power Reception and Conversion

Reception and conversion of high levels of electromagnetic energy have lagged behind power generation. This state may be attributed to the fact that the need for efficient conversion had not been emphasized until high levels of microwave energy were made possible through the development of "super-power" microwave generators.

While reception and conversion of high-energy radiation are relatively new fields of study, such study has had an earlier start in microwave application. The rectenna used in Raytheon's helicopter experiment already has demonstrated the practicality of semiconductors in microwave conversion to electricity. Still in the developmental stage, the close-spaced thermionic diode rectifier has produced up to 900 W of dc power. Electric conversion of laser energy is only in the research stage. Semiconductor diodes (doped p-n junctions of Cd_x-$Hg_{1-x}Te$ alloys) have been used experimentally as photovoltaic detectors. This is a promising development since their bandgap is very small and can be adapted for CO_2-laser operating wavelength. Moreover, the diode efficiency may be very high.

CONCLUSIONS

This study points out that wireless power transmission is not only feasible but has been demonstrated to be workable. The design and development of microwave-system components are sufficiently advanced to justify the expectation that a practical microwave high-power transmission system for use in space could be available within a few years.

One of the estimated disadvantages of a microwave power system is the antenna size, which would be large for maximum power-transfer efficiency. A laser system would eliminate this disadvantage. Moreover, its very slight beam divergence would make the laser system especially suitable for power transmission in space beyond several kilometers.

Since the laser is well behind microwaves in research, development, and available devices for system design, laser research and development programs should be strengthened now, so that a practical system will be ready in 5 to 10 years.

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TM X-53701

APPROVAL

THE FEASIBILITY OF WIRELESS POWER TRANSMISSION FOR AN ORBITING ASTRONOMICAL STATION

By

William J. Robinson, Jr.

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