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ANALYSIS OF A MARS-STATIONARY ORBITING MICROWAVE POWER TRANSMISSION SYSTEM

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SUMMARY

An efficient Mars-stationary orbiting microwave power transmission system can fulfill planetary exploration power requirements. Both nuclear power generation and photovoltaic energy conversion have been proposed for the orbiting power source. This power is to be converted to RF energy and transmitted to the surface of the planet, where it is then to be converted to dc power.

An analysis was performed for example systems at 2.45 GHz, where rectenna technology is currently well developed, and at several higher frequencies in the 2.45- to 300-GHz range, where small antenna requirements make the system more viable.

This analysis demonstrates that while component efficiencies are high at 2.45 GHz, antenna dimensions required to deliver a desired power level to the planetary surface are unachievably large at that frequency. Conversely, as the operating frequency is raised, component efficiencies fall, requiring an increase in source power to achieve the desired rectified power level at the surface. Efficiencies of free electron lasers operating in the 30- to 200-GHz range are currently low enough to offset any advantage derived from the highly directional laser output beam.

State-of-the-art power transmitters at 20 to 30 GHz have moderate component efficiencies and provide fairly high output power levels. In this frequency range, the antenna dimension requirement is approximately one-tenth that of a 2.45-GHz system. These factors, along with current rectenna development efforts at 20/30 GHz, make the 20- to 30-GHz range most desirable for initial microwave power transmission system development.

Both parabolic and phased-array transmitting antennas were investigated. The number of phased-array elements required to prevent grating lobe interference at these high frequencies may present significant phase control problems unless an appropriately dimensioned phased-array-fed reflector system can be designed.

Development of rectenna technology at 20 GHz and above is of prime importance in achieving realistic transmitting antenna dimensions. Large, high-gain transmitting antennas are necessary to provide a power flux density high enough to meet the threshold power density criteria of the rectenna dipole elements.

INTRODUCTION

To determine the feasibility of providing efficient RF power transmission from a Mars-stationary (areosynchronous) orbit to the surface of the planet, an assessment was made focusing on RF propagation in the 2.45- to 300-GHz range. In order to provide a rectified load power of 10 to 100 kW at the surface, generated power of approximately 10 MW to 1.5 GW was considered.

The proposed orbiting system configuration, described in the first section, provides for power generation by either photovoltaic array or nuclear reactor, the conversion of the dc output to RF, and the subsequent propagation of RF energy from the orbiting array to the Martian surface. On the planet, a rectenna array will convert RF to dc power to be distributed for planetary power needs.

The state-of-the-art of component technologies applicable to the orbiting microwave power transmission system is presented in the second section. Continuous-wave power transmitters within the desired frequency range were assessed with regard to operating efficiency, peak power output, and magnetic field requirements.

The third section derives the total efficiency of the energy conversion chain from dc to RF in orbit through RF to dc on the planetary surface for a 2.45-GHz system, which is the sole frequency for which dipole-element rectenna technology has been developed to date. Because it would not be possible to accurately project rectenna efficiencies for higher frequencies, the efficiency of the energy conversion chain is calculated only up through the incident RF power at the surface of the rectenna. Tradeoffs between component efficiency and transmitting antenna requirements were considered for each of several representative frequencies within the 2.45- to 300-GHz frequency range. Receiving antenna criteria were determined from desired received power levels and rectenna element power density threshold at 2.45 GHz.

Recommendations are presented for research into developing technologies which may afford enhanced viability of the proposed microwave power transmission system.

MARS-STATIONARY ORBITING MICROWAVE POWER TRANSMISSION SYSTEM

System Design

Figure 1 illustrates the proposed design of the Mars-stationary orbiting microwave power transmission system. A nuclear reactor or photovoltaic array will be placed in orbit about 17 000 km above the surface of the planet. A power distribution array will then transfer the dc power from the source to a power transmitting device, or to an array of devices, for conversion from dc to RF energy. A transmitting antenna array will then propagate the RF energy through the Martian atmosphere down to an array of rectennas on the surface of the planet. This rectenna array will convert the received energy from RF to dc, where it will be distributed as dc power for planetary use.

For simplification, in this analysis the receiving antenna array is taken to be centered at the subsatellite point (i.e., at a point on the Martian equator). Transmission to surface points other than this would increase the transmission path length and atmospheric attenuation.

Radio Frequency Energy Attenuation in Martian Atmosphere

The physical and chemical properties of the Martian atmosphere were assessed to determine extinction effects on RF transmissions from Mars-stationary orbit down to the surface of the planet. These properties include atmospheric composition, absorption characteristics, and scattering effects due to windborne dust particles.

The composition of the atmosphere is approximately 95 percent carbon dioxide (CO_2), 2.7 percent nitrogen (N), 1.6 percent argon (Ar), and trace gases of oxygen (O_2), carbon monoxide (CO), neon (Ne), krypton (Kr), xenon (Xe), and ozone (O_3).

Relative concentrations of these molecules are

$$[CO]:[CO_2] = 10^{-3}$$

$$[O_2]:[CO_2] = 1.3\times10^{-3}$$

$$[O_3]:[CO_2] = 2\times10^{-6}$$

Atmospheric pressure on Mars ranges from 5 to 8 mbar as compared with the 1.013 bar Earth value.

Water vapor appears to be a highly variable component of the Martian atmosphere. The north polar cap is believed to be water ice, which partially sublimates in the summer to release water vapor into the atmosphere. Although water vapor has been detected in the Martian atmosphere, the concentrations of other species of hydrogen and oxygen (H, H_2, OH, and H_2O_2) are apparently below the detection threshold of the Viking lander instruments. Since the concentration of water vapor varies widely both seasonally and geographically, it is not possible at this time to assess the degree of attenuation due to that molecule. However, since the overall concentration appears to be quite low, attenuation at the two H_2O absorption lines within this band (22 and 180 GHz) should be minimal.

Although molecular oxygen, O_2, has absorption lines extending from 53.5 to 65.2 GHz and at 118 GHz, this molecule exists only in trace quantities. Attenuation at these frequencies should therefore be negligible.

The majority of the absorption lines for CO_2, the predominant atmospheric constituent, fall within the infrared region between 20 and 150 THz (15 and 2 μm). This is well above the 1- to 300-GHz (3×10^{-1} to 1×10^{-3} m) range of investigation. It should be noted, however, that complete absorption data for the Martian atmosphere are not currently available because the Viking lander data have not been completely analyzed to date.

Estimates of Martian windborne dust particles range in diameter from 0.1 to 30 μm (ref. 1). Scattering of transmissions in the 1- to 300-GHz range is not expected to be of concern because the wavelengths corresponding to these frequencies (3×10^{-1} to 1×10^{-3} m) are much larger than the dust particle diameters. However, heavy accumulation of dust on surface-based rectenna elements is expected to cause scattering of incident RF radiation.

Orbiting Power Source

To meet the power requirements of Mars planetary exploration by the proposed microwave power transmission system, it has been estimated that the orbiting power source must be able to generate between 1 MW and 1 GW of dc power.

Nuclear generators and photovoltaic arrays have been proposed as power sources. While each has its respective merits and disadvantages, it is not within the scope of this initial study to assess these power sources for use in the power transmission system.

TECHNOLOGY APPLICABLE TO ORBITING MICROWAVE POWER TRANSMISSION SYSTEM

Direct Current to Radio Frequency Conversion and Transmission

For efficient transmission to the surface of Mars, the dc power generated at the orbiting source must be converted to RF. This dc to RF conversion and transmission may be achieved by any one of several devices which, according to the associated phase velocity, are categorized as slow-wave or fast-wave devices. Selection of the appropriate power transmitter is a function of operating frequency, gain requirements, noise limitations, and efficiency.

Slow-wave devices[1] (phase velocity $< c$). - Slow-wave devices include magnetrons, amplitrons, klystrons, and traveling-wave tubes.

Magnetrons can provide up to 1 kW of peak power at 2.45 GHz with an efficiency of 0.7 percent. They are relatively low in weight, but have a low degree of frequency stability.

Although amplitrons offer high efficiency (~80 percent) and need no active cooling, they have a low-gain, low-power output with a high degree of noise. These devices are constrained to frequencies less than 10 GHz.

Klystrons, by comparison, offer high gain, a high degree of phase control, and low noise. If depressed collectors are incorporated into the klystron tube design, efficiencies of 80 to 85 percent can be obtained. However, for high-power tubes (peak power > 50 kW for continuous-wave (cw) operation), an active

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[1] Kosmahl, H.G.: Microwave Power Tubes for Martian Power Station. Handout presented at the Mars Power Transmission Seminar, NASA Lewis Research Center, Cleveland, OH, August 5, 1987.

cooling system is required and the power per unit must not be too small. The frequency range of klystrons is approximately 1 to 50 GHz.

Traveling-wave tubes (TWT's), by themselves, have been deemed relatively inefficient for this application, but may enhance system efficiency when integrated into the design of other transmitting devices, such as gyro-traveling wave tubes.

Fast-wave devices (phase velocity $\geq$ c). - Power transmitting devices which have a phase velocity equal to, or greater than, the speed of light are termed fast-wave devices. These currently include gyrotrons and free electron lasers (FEL's).

Gyrotrons: The gyrotron is the most likely candidate device for power transfer in the millimeter wave range because of its high efficiency and ability to operate in the cw mode. Gyrotrons, however, have high magnetic field requirements.

Since the cyclotron frequency

$$\omega_c = \left[\frac{q}{m}\right]_{e-} B \tag{1}$$

where

ω 2πf

B magnetic field, Wb/m^2 (See note.[2])

$\left[\frac{q}{m}\right]_{e-}$ charge-to-mass ratio for the electron (1.758×10^{11} C/kg for $m = m_o$, where m_o = rest mass)

the required magnetic field for a given operating frequency f can be determined by

$$B = 2\pi f \left[\frac{m}{q}\right]_{e-} \tag{2}$$

Rest mass is used here as an approximation. In general, the velocity v of electrons within a gyrotron becomes a significant fraction of the speed of light, so that the relativistic mass applies.

$$m_{rel} = m_o\left(1 - \frac{v^2}{c^2}\right)^{-1/2} \tag{3}$$

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[2] Note that 1 Wb/m^2 = 1 V-sec/m^2 = 1 T = 10^4 G.

From equation (2), a table of magnetic field requirements as a function of fundamental cyclotron resonance frequency is obtained (table I). A graph of this function is presented in figure 2.

These high magnetic field levels require that for high frequencies (usually defined as being above 60 GHz) the gyrotron operate either with superconducting magnets, or at harmonics of the cyclotron resonance frequency ω_c. Operation at a harmonic frequency reduces the required magnetic field by a factor approximately equal to the harmonic number, thereby overcoming the need for superconducting magnets. Beyond the second harmonic, however, efficiency rapidly degrades.

A 500-GHz experimental gyrotron has been developed (Heinen, V.; and Delayen, J.: Applications of High T_c Superconductors to Electromagnetic Power Transmission. NASA Internal Memo, Mar. 1988.), but operation is currently limited to the pulsed mode, where peak output powers are generally higher than achievable by cw operation at the same frequency. Continuous-wave gyrotrons have achieved 200 kW peak power at 140 GHz, with an efficiency of approximately 28 percent. The use of high-critical-temperature superconducting materials in solenoids (Heinen, V.; and Mercereau, J.: HTS and Microwave Power Transmission. NASA Internal Memo, Nov. 1987) may be desirable to produce the large magnetic fields required above 140 GHz, without necessitating operation beyond the second or third harmonic.

<u>Free electron lasers</u>: State-of-the-art free electron lasers (FEL's) have operating frequencies ranging from 30 GHz in the microwave range up to the visible region of the spectrum. Although 30-GHz-pulsed FEL's have achieved peak powers of 1 GW (ref. 2), the pulsed nature of their output could not provide the steady supply of power necessary for the proposed power transmission configuration. Peak output power levels decline as the FEL operating frequency increases. Current pulsed FEL's have efficiencies of less than 10 percent. Continuous-wave FEL operation may be achievable; output power for the cw devices would be substantially lower than for pulsed FEL's of identical operating frequency.

Two constraints exist in the generation of high-energy electrons for FEL operation: a linear accelerator is necessary for the production of the electron beam, and the output wavelength of the FEL decreases as the square of the beam energy requirement increases.

<u>Solid state devices for power transmission</u>. - Solid state devices have been considered for power transmission applications; however, the high-frequency limit for solid state devices ranges from 150 GHz for solid state Gunn oscillators to about 300 GHz for IMPATT[3] sources. Both the power output and the efficiency of electron tube devices far exceed that of current solid state technology, as does the upper frequency limit (ref. 3).

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[3] Interaction of impact ionization avalanche and transit time of charge carriers.

Receiving Antenna Array

A receiving antenna array (rectenna) located on the surface of the planet will receive microwave radiation from the Mars-stationary orbiting power source. This array will convert the incident RF power into dc electrical power to meet planetary exploration needs.

When interception of the transmitted power is greater than 80 percent, a circular receiving array is more efficient. For interception efficiencies below that figure (as associated with microwave power transmission over long distances) a rectangular receiving array would be the more likely candidate.

Dipole-element rectenna development. - Dipole-element rectenna technology is currently well developed at 2.45 GHz, where an overall efficiency of approximately 80 percent has been achieved (ref. 4). At this frequency, however, array dimensions required for efficient energy interception are large, as demonstrated in the section Determination of Free-Space Interception Efficiency, and lead to a high degree of pointing error.

To reduce the required array dimensions and increase interception efficiency, it may prove desirable for the orbiting power transmitter to operate at a higher frequency. Investigation has been made into the design of a 20-GHz rectenna, frequency-scaled from the current 2.45-GHz rectenna design. However, the scaling factor is quite large ($\sigma = f/f_o = 8.16$). Since the number of elements per square meter is dependent upon σ^2, the resulting 20-GHz design would require approximately 13 300 elements per square meter, as opposed to the 200 per square meter required at 2.45 GHz. If this approach were extended to 300 GHz ($\sigma = 122.45$), then 200 (σ^2), or approximately 3 000 000 elements, would be required per square meter. Other approaches are being considered, including a completely monolithic design in which both the diodes and the circuitry would be built on a gallium arsenide (GaAs) or silicon (Si) substrate.

With increased operating frequency, associated dipole-element spacing decreases. This gives rise to undesirable inductive and capacitative effects which degrade efficiency. Scattering of incident radiation from the rectenna edges may present a problem at shorter wavelengths.

As discussed further in the section Power Flux Density at Receiving Array, a minimum power density must be incident upon the dipole elements in order to effect rectification.

ANALYSIS OF POWER TRANSMISSION SYSTEM EFFICIENCY

Several representative frequencies in the 2.45- to 300-GHz range were chosen for assessing overall efficiency of power transfer from the orbiting source to the output of rectified power at the receiving antenna array on the surface.

Calculations were made of required source power, incident power flux density at the surface, and antenna gain and dimension requirements. By using these parameters along with efficiencies of state-of-the-art and projected system components, interception efficiency $\eta(\tau)$ was calculated using both manual methods and an analysis program developed by Grady H. Stevens of the NASA Lewis

Research Center for use on the IBM-PC. This program was slightly modified by the author for the range of load powers in this study. Data from this study are presented in the section Analysis of System Performance.

Radio Frequency Transmitting and Receiving Components

Transmitting antenna. - Transmission of RF energy from the output of the orbiting power generator to the receiving array on the surface of Mars is to be effected by either a parabolic reflector or a phased-array-fed reflector system. An aperture field distribution of $f(r) = (1 - r^2)^2$, as produced by a feed horn array, is assumed for either type of antenna and is associated with an aperture efficiency (or gain factor) of 56 percent.

Assessment of phased array and parabolic reflector transmitting antenna. - Phased-array antennas offer the advantages of electronic beam steering and beam shaping but entail high cost due to the phase shifters required for each element in the array (a very large number at microwave frequencies). In addition, spurious radiation arises between the feed networks, and undesirable coupling occurs between the antenna elements, thereby degrading efficiency. In general, the gain achieved by a phased array is less than that of a parabolic reflector antenna of the same dimension. The phase locking necessary for phased arrays of gyrotrons and free electron laser sources has not been achieved to date.

The extreme number of antenna elements necessary to avoid grating lobe contribution to the main beam of each element make large, stand-alone planar phased arrays impractical in the 2.45- to 300-GHz range. Phased-array-fed reflector systems have been suggested as a means of reducing element requirements; the dimensions of the phased-array feed are on the order of those of the subreflector.

To avoid grating lobes, which would reduce the main beam power and consequently the antenna gain, no grating lobe may exist within a circle of radius $r = 1 + \sin\theta_m$, where θ_m is the maximum scan angle. From the Mars-stationary orbit, the maximum scanning angle from the equator toward one of the poles is approximately 9°. Under this condition, $r = 1.156$. If a square lattice is assumed, then

$$\frac{\lambda}{d_x} = \frac{\lambda}{d_y} = 1.156 \tag{4}$$

and the required element spacing becomes

$$d = 0.865\ \lambda \tag{5}$$

A 30-GHz ($\lambda = 0.01$ m) phased-array-fed reflector system with a subreflector diameter of 50 λ ($D = 0.50$ m) would require approximately 3340 elements under this grating lobe avoidance constraint. If coupled with a 56-percent efficient 4.25-m parabolic dish, a directive gain on the order of 60 dB could be achieved. By contrast, a stand-alone planar phased array would require approximately 1.4×10^5 elements to meet this gain level.

Calculation of Required Source Power

The source power required to provide a specified received (load) dc power can be ascertained by

$$\frac{P_L}{\eta_{system}} = P_{source} \tag{6}$$

The system efficiency is

$$\eta_{system} = (\eta(\tau))(\eta_{DC\rightarrow DC})(\eta_{DC\rightarrow RF})(\eta_{RF\rightarrow DC}) \tag{7}$$

where

$\eta(\tau)$	interception efficiency
$\eta_{DC\rightarrow DC}$	efficiency of transmission from power source to power transmitter
$\eta_{DC\rightarrow RF}$	power transmitter conversion efficiency
$\eta_{RF\rightarrow DC}$	rectenna efficiency

Power Flux Density at Receiving Array

A dipole-element rectenna array has a characteristic threshold level of incident power per unit area (power flux density) below which the elements cannot achieve rectification of the received RF energy. Element efficiencies have been measured for 2.45-GHz arrays (ref. 5) as illustrated in figure 3.

Incident power flux density (W/m^2) can be determined from the transmitted power and transmitting antenna gain:

$$PFD = \frac{P_T g}{4\pi L^2} \tag{8}$$

where

P_T	transmitter output power, W
g	transmitting antenna gain, numerical
L	antenna separation distance, m, 17×10^6 m for Mars-synchronous orbit

The assumption is made in equations (9) to (11) that the rectenna array is located in the far field of the transmitting antenna, so that

$$L \geq \frac{2D_T^2}{\lambda} \tag{9}$$

From figure 3, based upon data derived in a study of a proposed space-to-Earth power transmission system (ref. 6), a rectenna element efficiency of 78 percent requires a PFD of approximately 10 mW/cm^2 (100 W/m^2). To determine the transmitting antenna diameter D_T required to meet this threshold PFD, the transmitter output power P_T is used in the relationship for the area A_T of the transmitter

$$A_T = \frac{(\lambda^2 L^2)(PFD)}{\eta_T P_T} \tag{10}$$

where

η_T efficiency (gain factor) of transmitting antenna (assuming a circular antenna), so that

$$D_T = \left[\frac{4A_T}{\pi}\right]^{1/2} = 2L\lambda\left[\frac{PFD}{\pi P_T \eta_T}\right]^{1/2} \tag{11}$$

Dielectric breakdown of the air at Earth's atmospheric pressure occurs at power densities of about 10^5 to 10^6 W/cm^2. In the Martian atmosphere, which averages 0.006 that of the Earth, the breakdown power density would be on the order of 5×10^2 W/cm^2 (5×10^6 W/m^2) (ref. 6). This is well above the maximum PFD levels created by microwave transmission at or below 1.5 GW source output power at an antenna separation distance of 17 000 km, as in this study.

Minimum Receiving Array Dimension

Planetary applications of the proposed microwave power transmission system require that, as a minimum, a specified level of dc power be available at the output of the rectenna. This is referred to as the load power. The level of RF power incident upon the rectenna array must therefore be greater than the required dc load power by a factor of the reciprocal of the rectenna conversion efficiency. The received power requirement is then

$$P_R = \frac{P_L}{\eta_{RF\rightarrow DC}} \tag{12}$$

where

P_R	RF power input to the rectenna, W
P_L	dc load power at output of rectenna, W
$\eta_{RF\rightarrow DC}$	rectenna conversion efficiency

A known power flux density, along with the received power requirement, can be used to determine the receiving antenna array dimension requirement

$$A_R = \frac{P_R}{PFD} \qquad (13)$$

where

A_R minimum array area, m^2

P_R power intercepted at the receiving array, W

PFD power flux density at the surface of the receiving array, W/m^2

Since the rectenna array is assumed to be square for this application, the diameter or edge dimension of the array is

$$D_R(m) = \sqrt{A_R} \qquad (14)$$

Determination of Free-Space Interception Efficiency

Assuming a circular transmitting antenna and a rectangular receiving array, the free-space interception efficiency $\eta(\tau)$ (the fraction of transmitted energy intercepted by the receiving antenna), can be obtained by calculating the free-space transmission interception factor (refs. 7 and 8).

$$\tau = \frac{\sqrt{A_T A_R}}{\lambda L} \qquad (15)$$

where

A_T area of transmitting antenna

A_R area of receiving antenna array

L antenna separation distance = 17×10^6 m for a Mars-stationary system

The free-space interception efficiency is (refs. 7 and 8)

$$\eta(\tau) = 1 - e^{(-\tau^2)} \qquad (16)$$

which, for small τ, represents the optimal power coupling efficiency of a Gaussian main beam focused at the receiver.

A large value of τ, obtained either by means of an extremely large antenna dimension or by a comparatively short antenna separation distance, would indicate that most of the transmitted energy is collected, and therefore $\eta(\tau)$, the interception efficiency, would be on the order of unity. Small τ values correspond to the receiving antenna's intercepting only a small fraction of the main beam.

Several example microwave power transmission systems were modeled by using the relationships in equations (6) through (16) along with rectenna efficiency values from figure 3. Results for 2.45-GHz systems are presented in table II. A requirement of 10 kW dc load power on the Martian surface, with 100 W/m^2 power flux density incident upon the rectenna array, would require approximately 1.429 GW of dc source power coupled to a transmitting antenna 693 m in diameter. This system necessitates a rectenna array area of 127 m^2 (11.3 m on each side). The effects of varying load power and incident PFD are also given in table II.

As shown in table II, a greater fraction of incident RF energy can be intercepted when the criterion for incident PFD is dropped from 100 W/m^2 to 10 W/m^2. This increase in $\eta(\tau)$ outweighs the corresponding reduction in rectenna element efficiency resulting from operation at the lower PFD value. In this analysis, diode-element efficiency was used to approximate the efficiency of rectification. For a fixed PFD level, an increased load power requirement mandates enlarging the receiving array dimension, thereby increasing the interception efficiency.

From this analysis, the set of parameters yielding the highest interception efficiency (P_L = 100 kW, PFD = 10 W/m^2) was used as a guideline for computing comparative interception efficiencies and required source power for systems operating within the 2.45- to 300-GHz frequency range. These data, presented in table III, demonstrate that while (for a fixed transmitting antenna gain level) requirements drop with rising frequency, the transmitted power efficiency η_{TP}

$$\eta_{TP} = \eta(\tau) \times \eta_{DC\rightarrow DC} \times \eta_{DC\rightarrow RF} \tag{17}$$

decreases as a result of decreasing power transmitter device efficiency, $\eta_{DC\rightarrow RF}$, since $\eta(\tau)$ and $\eta_{DC\rightarrow DC}$ are constant. This device efficiency, however, is subject to improvement with the development of device technology.

Transmitted power efficiency, the fraction of dc source power which is intercepted as RF power by the rectenna, was calculated. Interception efficiency $\eta(\tau)$ is a function of the interception factor τ, as defined by equation (15), and is thus dependent upon the area of the receiving rectenna array.

The transmitting antenna diameters used in table III were based on the assumption of an approximate 100-dB antenna gain as eventually achievable for frequencies greater than or equal to 20 GHz. Below 20 GHz, such high-gain antenna dimensions may prove impracticable. A 100-dB gain transmitting antenna for a 2.45-GHz system, for example, requires a diameter of almost 3 km; therefore, an 85-dB gain antenna with a diameter of 693 m, was assumed. An analogous 30-GHz system could be achieved with a 100-dB gain antenna with a diameter of approximately 240 m, less than one-tenth the requirement for a 2.45-GHz transmitting antenna of the same gain. Additionally, power transmitters in the 30-GHz frequency range have demonstrated fairly high peak output power levels (on the order of 300 kW for cw operation). Their currently moderate component efficiencies may be raised with development. These factors, along with ongoing rectenna research at 20/30 GHz, suggest that 30 GHz may be desirable for initial microwave power transmission system development. Component technology at higher frequencies would require considerably more development to bring efficiencies up to those currently available at 2.45 GHz.

These system performance analyses demonstrate that large, high-gain transmitting antennas would be necessary to provide power flux density levels sufficient for rectification of incident RF radiation at the Mars-stationary orbiting system range. Although source power requirements are extremely high and component efficiencies range from 30 to 90 percent for frequencies below 140 GHz, the antenna separation distance severely impacts the transmitted power efficiency η_{TP}, and in turn the interception efficiency $\eta(\tau)$.

CONCLUSIONS AND RECOMMENDATIONS

The range-spreading inherent in a Mars-stationary orbiting system mandates the use of either large, very-high-gain transmitting antennas or transmitter output power levels in the multi-megawatt to gigawatt range to provide power flux density levels above the threshold necessary for the rectification of received power.

For state-of-the-art power transmitting devices, efficiency declines with rising frequency. Experimental gyrotrons operating at 140 GHz have peak efficiencies of less than 30 percent. Beyond this frequency, magnetic field requirements currently make operation at higher harmonics necessary, thereby degrading efficiency. Use of high-critical-temperature superconducting materials in gyrotron design may allow higher magnetic fields to be achieved, obviating the need for operation above the fundamental frequency. In an array of power transmitters, phase and amplitude control are necessary to achieve a uniform distribution of output power.

To enhance component efficiency, it may be desirable to integrate depressed collectors into the design of power transmitters. However, the degree of such efficiency enhancement may decline with increasing frequency.

Free electron lasers capable of producing microwave emissions are currently limited to pulsed, low-efficiency devices. Linear accelerators are necessary to produce the required electron beam.

The development of rectennas for frequencies above 2.45 GHz will allow for a reduced transmitting antenna requirement in the proposed system. The operating frequency must be low enough, however, to avoid undesirable coupling effects which would arise if the rectenna elements were very closely spaced. Efforts are ongoing in the development of 20/30-GHz rectenna technology. State-of-the-art power transmitters provide fairly high output power levels in the 20- to 30-GHz range with moderate component efficiencies, and have antenna dimension requirements on the order of one-tenth that of a comparable 2.45-GHz system. These factors make the 20- to 30-GHz range appear most desirable for initial development of a microwave power transmission system.

Developments in solid state device technology may provide enhanced rectenna efficiency. For optimum element efficiency, each dipole and associated Schottky detector must have a high degree of impedance matching. Monolithic circuitry has been suggested as a means of enhancing impedance matching. Diode sensitivity can be improved with a gallium arsenide heterostructure, thus leading to increased rectification efficiency.

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APPENDIX - SYMBOLS

A_{em}	maximum effective area
A_R	area of receiving array
A_T	area of transmitting antenna
B	magnetic field
c	speed of light
D_R	edge dimension of receiving array
D_T	transmitting antenna diameter
d	phased-array element spacing
f	frequency
fo	reference frequency for scaling
G	gain of transmitting antenna, dB
g	gain of transmitting antenna, numerical
L	antenna separation distance
m	mass
m_o	rest mass
m_{rel}	relativistic mass
N	number of elements
PFD	power flux density, W/m^2
P_L	load power
P_R	received power
P_{source}	source power
P_T	transmitter output power
$[q/m]_{e-}$	electron charge-to-mass ratio
R	radius of circular transmitting antenna
r	radius

$\eta_{DC \rightarrow DC}$	efficiency of transmission from power source to power transmitter
$\eta_{DC \rightarrow RF}$	power transmitter efficiency
$\eta_{RF \rightarrow DC}$	rectenna efficiency
η_{system}	overall system efficiency
η_T	transmitting antenna efficiency
η_{TP}	transmitted power efficiency
$\eta(\tau)$	interception efficiency
θ_m	maximum scan angle of phased array
σ	frequency scaling factor
τ	free-space transmission interception factor
ω_c	cyclotron frequency

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TABLE I. - GYROTRON MAGNETIC FIELD REQUIREMENT

Frequency, f, GHz	Magnetic field, B, Wb/m^2 (or T)
1	0.03
2.45	.088
30	1.072
100	3.57
200	7.15
300	10.72

TABLE II. - INTERCEPTION EFFICIENCY OF 2.45 GHz SYSTEMS

[Transmitting antenna: area, 3.77×10^5 m^2; diam, 692.84 m; gain, 85 dB; efficiency, 56 percent. $\eta_{DC \rightarrow DC}$ and $\eta_{DC \rightarrow RF}$, 0.9.]

Incident PFD, W/m^2	Receiving array area, m^2	Load power, kW	Interception factor, τ	Interception efficiency, $\eta(\tau)$	Rectenna efficiency, $\eta_{RF \rightarrow DC}$	System efficiency, η_{system}	Required source power, MW
10	1 786	10	1.25×10^{-2}	1.55×10^{-4}	0.56	7.0×10^{-5}	143
10	17 860	100	3.94×10^{-2}	1.55×10^{-3}	.56	7.0×10^{-4}	143
100	127.06	10	3.3×10^{-3}	1.1×10^{-5}	.787	7.0×10^{-6}	1429
100	1 270.6	100	1.05×10^{-2}	1.1×10^{-4}	.787	7.0×10^{-5}	1429

TABLE III. - SYSTEM PERFORMANCE ANALYSIS

[Load power, P_L = 100 kW; incident RF PFD = 10 W/m^2; receiving array area, A_R = 17 860 m^2; $\eta_{DC \rightarrow DC} = 0.9$; $\eta_{RF \rightarrow DC} = 0.787$ assumed for all frequencies for load power approximation; antenna efficiency = 56 percent; transmitting antenna gain = 85 dB for <20 GHz (100 dB for $\geq$ 20 GHz); interception factor, $\tau = 3.94 \times 10^{-2}$ for <20 GHz (1.66×10^{-1} for $\geq$ GHz); interception efficiency, $\eta(\tau) = 1.55 \times 10^{-3}$ for <20 GHz (2.72×10^{-2} for $\geq$ 20 GHz).]

Frequency, GHz	Transmitting antenna area, $A_T(m^2)$	Transmitting antenna diam, $D_T(m)$	Power transmitter efficiency, $\eta_{DC \rightarrow RF}$	Transmitted power efficiency, η_{TP}[a]	Required source power, MW
2.45	3.77×10^5	6.93×10^2	0.90	1.26×10^{-3}	100.85
20	1.00×10^5	3.57×10^2	.65	1.59×10^{-2}	7.99
30	4.45×10^4	2.38×10^2	.53	1.30×10^{-2}	9.77
60	1.11×10^4	1.19×10^2	.50	1.22×10^{-2}	10.42
100	4.00×10^3	7.14×10^1	.40	$.98 \times 10^{-2}$	12.97
140	2.04×10^3	5.10×10^1	.28	$.69 \times 10^{-2}$	18.42
200	1.00×10^3	3.57×10^1	.25	$.61 \times 10^{-2}$	20.83
300	4.45×10^2	2.38×10^1	.20	$.49 \times 10^{-2}$	25.93

[a] $\eta_{TP} = \eta(\tau) \times \eta_{DC \rightarrow DC} \times \eta_{DC \rightarrow RF}$.

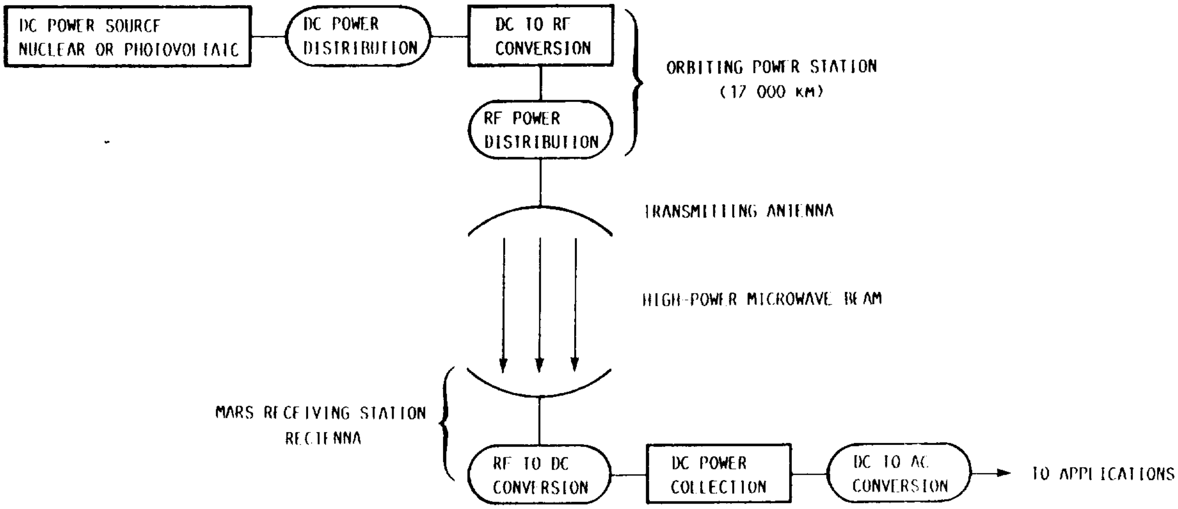

FIGURE 1. - SCENARIO OF MARS STATIONARY ORBITING MICROWAVE POWER TRANSMISSION SYSTEM.

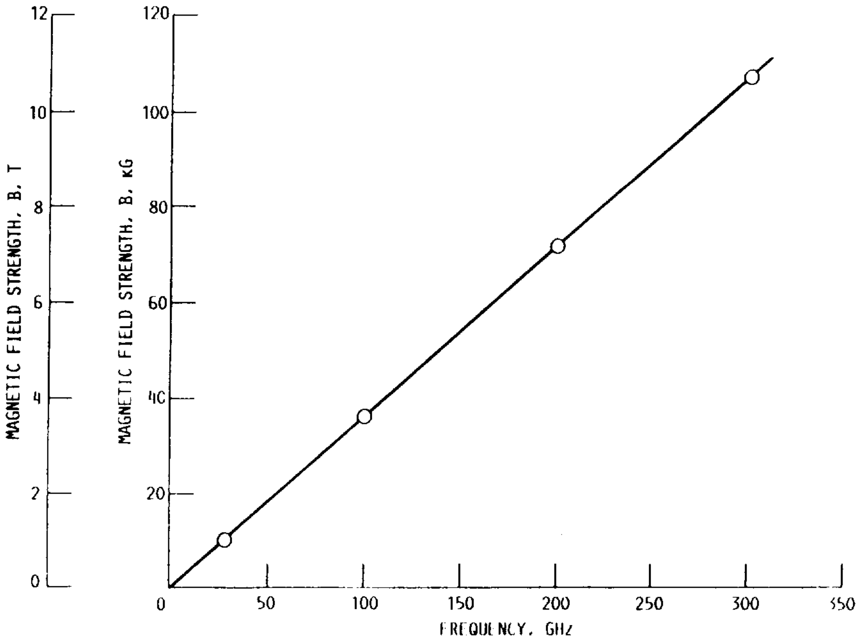

FIGURE 2. - GYROTRON MAGNETIC FIELD REQUIREMENT AS FUNCTION OF FREQUENCY.

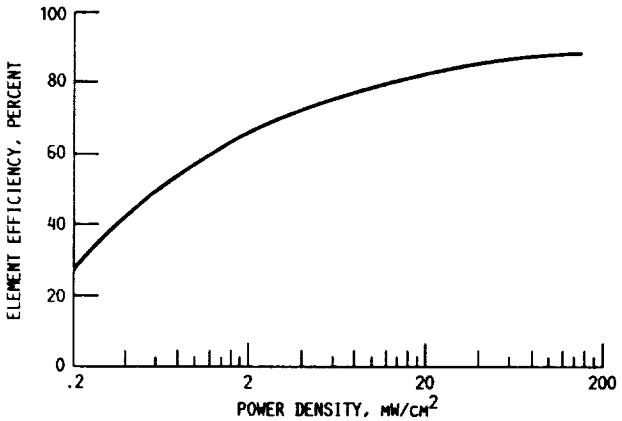

FIGURE 3. - RECTENNA ELEMENT EFFICIENCY AS FUNCTION OF LOCAL POWER DENSITY (REF. 6).

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16. Abstract

To determine the feasibility of providing efficient RF power transmission from a Mars-stationary orbit to the surface of the planet, an assessment was made focusing on RF propagation in the 2.45- to 300-GHz range. The proposed orbiting system configuration provides for power generation by either photovoltaic array or nuclear reactor, the conversion of the dc output to RF, and subsequent propagation of RF energy from the orbiting array to the Martian surface. On the planet, a rectenna array will convert RF to dc power to be distributed for planetary power needs. Total efficiency of the energy conversion chain from dc to RF in orbit through RF to dc on the planetary surface was derived for several representative frequencies in the range of study. Tradeoffs between component efficiency and transmitting antenna requirements were considered for each of these frequencies. Rectenna element power density thresholds and desired received power levels were used to determine receiving antenna criteria. Recommendations are presented for research into developing technologies which may afford enhanced viability of the proposed microwave power transmission system.

17. Key Words (Suggested by Author(s))
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