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Lunar Orbiting Microwave Beam Power System

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LUNAR ORBITING MICROWAVE BEAM POWER SYSTEM

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ABSTRACT

A microwave beam power system using lunar orbiting solar powered satellite(s) and surface rectenna(s) was investigated as a possible energy source for the moon's surface. The concept has the potential of reduced system mass by placing the power source in orbit. This can greatly reduce and/or eliminate the 14 day energy storage requirement of a lunar surface solar system. Also propellants required to de-orbit to the surface are greatly reduced.

To determine the practicality of the concept and the most important factors, a "zero-th order" feasibility analysis was performed. Three different operational scenarios employing state of the art technology and forecasts for two different sets of advanced technologies were investigated. To reduce the complexity of the problem, satellite(s) were assumed in circular equatorial orbits around the moon, supplying continuous power to a single equatorial base through a fixed horizontal rectenna on the surface.

State of the art technology yielded specific masses greater than 2500 kg/kw, well above projections for surface systems. Using advanced technologies the specific masses are on the order of 100 kg/kw which is within the range of projections for surface nuclear (20 kg/kw) and solar systems (500 kg/kw). Further studies examining optimization of the scenarios, other technologies such as lasers transmitters and nuclear sources, and operational issues such as logistics, maintenance and support are being carried out to support the Space Exploration Initiative (SEI) to the moon and Mars.

INTRODUCTION

Operations on the surface of the moon will depend on a reliable electrical energy source. Providing low cost electrical power on the surface presents a significant challenge. Energy storage requirements for the 14 day eclipse period make surface solar power systems heavy. Proposed nuclear power sources have masses highly dependent on power level and may have political and safety concerns. An alternative is to place the the power source in orbit and beam the energy to the surface. The concept has the potential of lowered system mass by greatly reducing and/or eliminating energy storage and also reducing propellents required to de-orbit to the surface.

Specific masses for surface power plants are projected to range from a low of approximately 20 kg/kw for high powered nuclear up to approximately 500 kg/kw for continuous solar power [1]. The objective of this study was to determine, with reasonable technology projections, if a beam power system was competitive with surface power sources.

Multiple approaches including systems using nuclear sources and/or laser beaming can be conceived and will be addressed in future work. For this study, a simple system where energy is beamed at microwave frequencies from a solar powered satellite(s) to a fixed non-tracking rectenna (an antenna that receives and converts the RF energy to useful dc electrical energy) is investigated. To further reduce the complexity, a single equatorial base and satellite(s) in circular equatorial orbit were assumed.

It is recognized that more optimum designs are possible and will be explored in future work. Likewise, operational issues such as logistics, installation, maintenance, etc. must be addressed. (See Future Work and Conclusions Section). This first assessment with limited scenarios and technology is thus presented as an initial scoping document.

APPROACH

Three different scenarios of beaming power from orbit to the lunar surface were investigated. Figure 1 shows the block diagrams for each scenario.

The first scenario, Case 1, consists of a single satellite in orbit that transmits power to the surface when in the field of view of the receiver (rectenna). Energy storage is needed on the satellite as well as the ground. Batteries on the satellite provide power for transmission when the satellite is in the eclipse while within the beaming field of view (see figure 2) The energy storage on the surface provides power to the user while the satellite is out of view.

Case 2 is a constellation of satellites providing continuous coverage of the rectenna (see figure 2). Energy storage on the surface is therefore not necessary. Batteries are provided on each satellite as the energy source for transmission to the surface when that satellite is in the eclipse.

Case 3 is also a constellation of satellites providing continuous coverage, but with the energy storage located only on the surface to provide power to the user when the satellites are in the eclipse.

Figure 1. System Block Diagrams

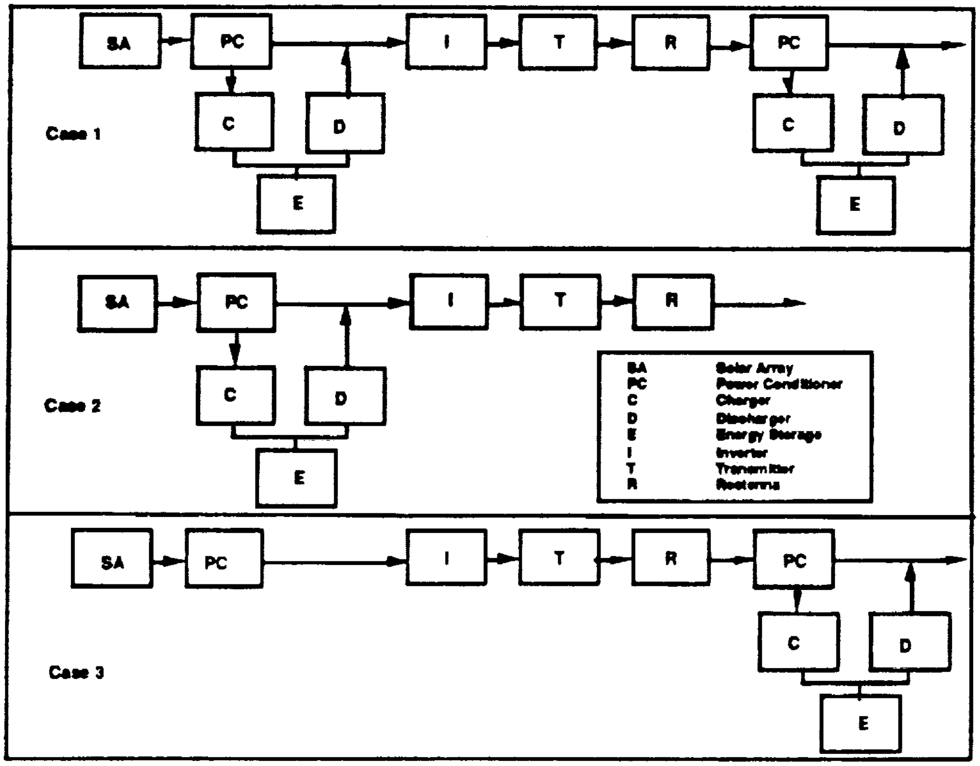


Figure 2. Lunar Orbiting Satellites

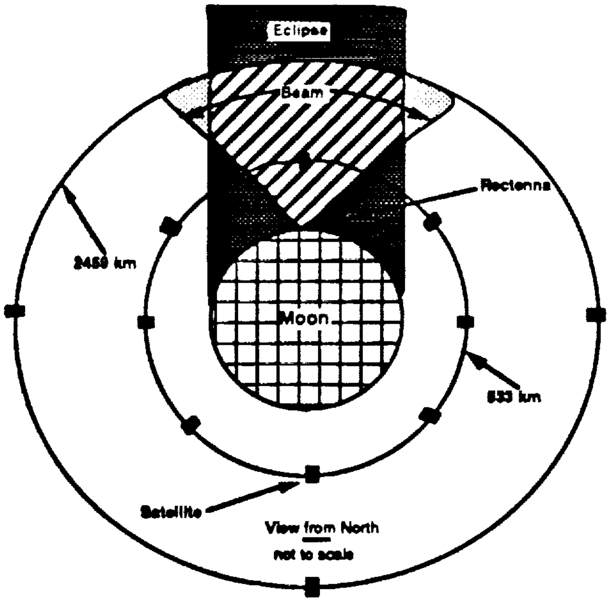


Table 1 indicates the specific masses and efficiencies assumptions for the technologies used in this study. Three levels of technologies were considered:

1. State of Art (SOA) : This design is similar to the Solar Power Satellite (SPS) studied considerably in the 1970's, but uses SOA components available in the 1990's (see figure 3). The structure uses Space Station Freedom (SSF) trusses. (An "average" specific mass is shown in Table 1, but structure mass is not a linear function of area). The solar array employs single crystal silicon cells, and nickel hydrogen batteries are chosen for energy storage (SSF designs). The nickel hydrogen batteries are sized assuming a depth of discharge (DOD) of 50%. Power Management and Distribution (PMAD) uses components developed for SSF. The thermal management radiators' specific masses assume a rejection temperature of 25° C. Six percent of the masses for solar array drives, batteries, transmitter, and PMAD is added to account for integration masses.

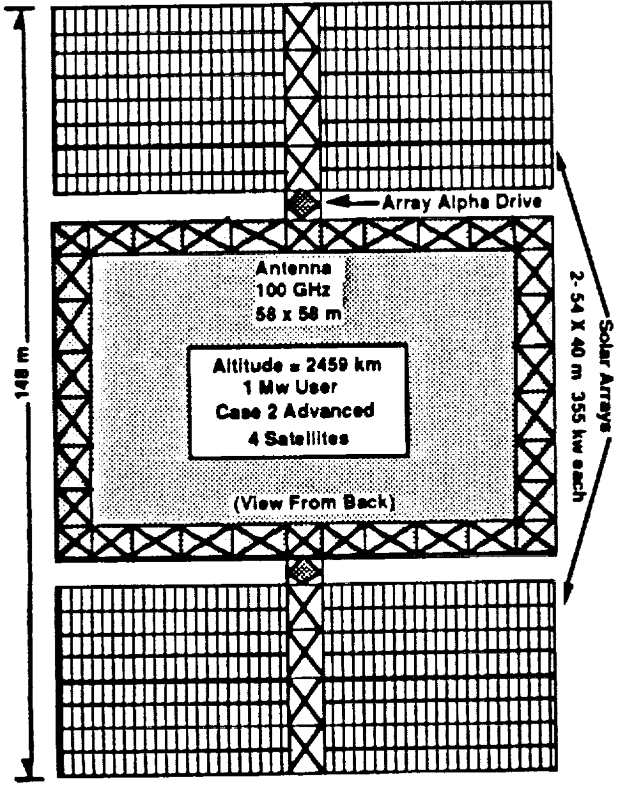
The aluminum slotted waveguide antenna array uses parameters from the SPS [2]. No space qualified microwave tubes of the power level required were known, therefore parameters for 35 GHz terrestrial gyrotron were assumed for the transmitter. (As for all technology levels, the transmitter efficiencies were assumed constant for all frequencies. Efficiency is expected to decrease with higher frequency, and this effect will need to be factored in later analyses, but it is expected that the efficiency at higher frequency will be more a function of time and technology evolution than basic physics.)

2. Advanced: Advanced technology represents the evolution of state of the art technologies to levels believed to be possible by the year 2000. Advanced lightweight solar cells and batteries are used for the power source. Satellite batteries in this case are sodium sulfur operating at

a temperature of 350° C which leads to a correspondingly lower specific mass for the radiators. The sodium sulfur batteries are sized assuming 50% DOD. PMAD components are improved and their operating temperature is also raised, lowering the thermal specific mass. Regenerative Fuel Cells (RFC's) were chosen for surface energy storage since the charge and discharge cycles are of relatively long durations. The RFC's are sized assuming an 80% DOD. The transmitter is an improved efficiency tube.

Figure 3 shows schematically a beam power satellite using advanced technology. Four of these Case 2 satellites beaming power at a frequency of 100 GHz from an altitude of 2459 km provide 1 Mw of continuous power to a user(s) on the surface of the moon. It is of the same general size as SSF. The SSF transverse boom length is 145 m and its solar array "tip-to-tip" length is 72 m. The beam power satellite's overall dimensions are 148 x 58 m. As will be discussed later, lower power levels or altitudes would reduce each satellite's size.

Figure 3. Beam Power Satellite Concept (sized using advanced technology)



3. Thin Film: Thin film solar cells and solid state MMIC (Microwave Monolithic Integrated Circuit) devices are presently available for terrestrial applications and projections were made if space versions of these products could be developed around 2000. This technology assumes an inflatable structure to support an integrated solar array and antenna , see figure 4 [4]. Amorphous silicon solar cells and RFC's are chosen for power components. The transmitters are solid state MMIC devices in a phased array. This technology level is used only for Case 3 since no thin film storage technology was known to exist for the satellites.

Figure 4. Thin Film Technology Beam Power Satellite Concept [4]

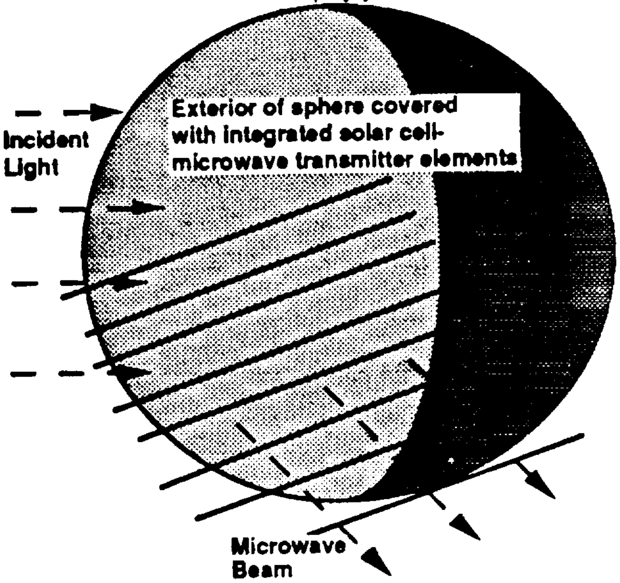


Table 1. Technology Performance Parameters [1,2,3,4]

	SOA		Advanced		Thin Film	
System	(kg/kw) -or- (kg/kwh)	%	(kg/kw) -or- (kg/kwh)	%	(kg/kw) -or- (kg/kwh)	%
Solar Array System						
Solar Array	20	14	3	25	.7	5
Drives	1		1		0	
Structure	3		3		0	
Energy Store System (Satellite)						
Cells	21		10			
Packaging	6		3			
Thermal	70		15			
Charge Eff.		95		95		
Discharge Eff @ DOD		84		84		
Energy Store System (Surface)						
Cells	21		.5		.5	
Packaging	6		.5		.5	
Thermal	70		5		5	
Charge Eff.		95		80		80
Discharge Eff @ DOD		84		80		80
PMAD System						
Power Conditioner	5	97	3	97	1	98
Inverter	10	95	2	98	1	98
Charger	14	95	7	95	1	95
Discharger	14	96	7	96	1	96
Thermal	70		15		5	
Integration	6 %		6 %		6 %	
Transmitter System						
Transmitter	3	40	3	80	.1	50
Thermal	5		5		5	
Antenna System						
Antenna (kg/m²)	4.6	100	4.6	100	.1	100
Structure (kg/m²)	3		3		0	
Rectenna (kg/m²)	1	85	1	85	1	85

A spreadsheet was developed to perform energy balances and calculate the beam power system mass for each scenario and technology level. Power components are sized as a function of user power. End-to-end system masses are calculated including all support such as thermal management and structural subsystems. By using three different technology levels under three scenarios, the sensitivity of system specific mass to various subsystem and component performances was obtained. Also, the effect of technology on achieving a specific mass competitive with surface options was determined. The modular nature of the spreadsheet can accommodate different power sources (such as a nuclear reactor) and transmission types (such as laser) for future studies.

ASSUMPTIONS

Transmission frequencies of 2.45, 35, 100, and 300 GHz were investigated in this study. The receivers were taken to be placed flat horizontally on the surface with an assumed field of view of 135°.

A near field approximation equation was used to size the antenna and rectenna:

$$P_r/P_t = 1-\exp\{-A_tA_r/(LR)^2\} \qquad \text{Equation 1.}$$

Where:

R = Separation Distance (m)
L = Wavelength (m)
A_t = Antenna Area (m^2)
A_r = Rectenna Area (m^2)
P_t = Transmitted Power (w)
P_r = Received Power (w)

When the satellite is directly overhead (i.e.. normal to the rectenna), a 15% space transmission loss was assumed in the calculations (i.e. P_r/P_t is set equal to 0.85). The overall transmitter to rectenna link efficiency will be reduced from the 85% space transmission efficiency due to off-normal pointing losses which are a complex function of many parameters such as antenna/rectenna design, orbit parameters, antenna pointing, etc. A simple numerical integration for an ideal tracking antenna at variable distance yielded a 54% link efficiency, which was used for all cases. (See Discussion of Results and Future Work sections for further discussion of this assumption.)

The propulsion requirements to land a surface power system from a low lunar orbit will require propellent at least equal to the mass of the power system, effectively doubling the entire system mass. The orbiting portions of the beam power system, of course, requires no de-orbiting capability. To provide a common scale for comparisons with surface-only systems, masses presented are surface equivalent masses (ie orbiting masses are added as half of what they would weigh on the surface).

Orbit parameters calculated for the three cases are presented in Table 2. The beam times, battery discharge and recharge times, and the number of satellites required for continuous coverage assume a 135° rectenna field of view.

For altitudes less than 1336 km, the eclipse time is greater than the beam time (see Fig. 2). Thus, for periods of the lunar night, the satellite will be entirely in eclipse while within the rectenna field of view. For Case 1 and 2, this means that the satellite batteries' must be sized to provide the entire energy for transmission since the solar arrays will be unable to produce power. The satellite batteries discharge time thus equals beam time. For altitudes at or above 1336 km, the solar array can supply some power directly for transmission even in the middle of the lunar night. The discharge time thus transitions from beam time to eclipse time above 1336 km. Recharge time in both cases is when the satellite is in the sun but not transmitting. The solar array is thus sized to charge the batteries during this recharge time.

For Case 1, the surface batteries provide power when the satellite is out of the rectenna's view. The surface batteries are recharged during the beam time and discharged during the remainder of the orbit. For Case 3, the surface storage is charged when the satellite is in the sun and transmitting power. During periods of the lunar night when the satellite is eclipsed, the storage provides power for the surface. In all cases, the energy storage requirements are much less than a surface solar power system.

DISCUSSION OF RESULTS

Table 3 shows the Cases 1, 2 and 3 specific masses for a 1 Mw system at 2.45, 35, 100 and 300 GHz, using state of the art, advanced and thin film technologies. All specific masses are shown at their optimum altitude, but no system optimization was performed except trades of antenna and rectenna sizes. The specific masses range from 2920 kg/kw using state of the art technology at 2.45 GHz to 84 kg/kw using thin film technology at 300 GHz. For any of the three cases using state of the art technologies, and Case 1 advanced, the resulting specific masses are greater than the surface solar option. Therefore, they will not be discussed further.

Table 2. Orbit Parameters
all times in hours

Altitude (km)	Orbit Period	Eclipse Time	No. Sat's	Beam Time	Case 1 & 2 Orbiter Storage		Case 3 Surface Storage	
					Discharge Time	Recharge Time	Discharge Time	Recharge Time
90	1.95	.78	30	.07	.07	1.17	268	403
146	2.04	.76	20	.10	.10	1.28	251	420
211	2.14	.75	15	.14	.14	1.39	235	436
374	2.42	.74	10	.24	.24	1.68	206	465
533	2.70	.75	8	.34	.34	1.95	186	485
900	3.38	.77	6	.56	.56	2.61	153	518
1336	4.31	.82	5	.86	.82	3.45	128	543
2459	6.78	.92	4	1.7	.92	5.08	91	580
10566	34	1.53	3	11.3	1.53	22.7	30	641

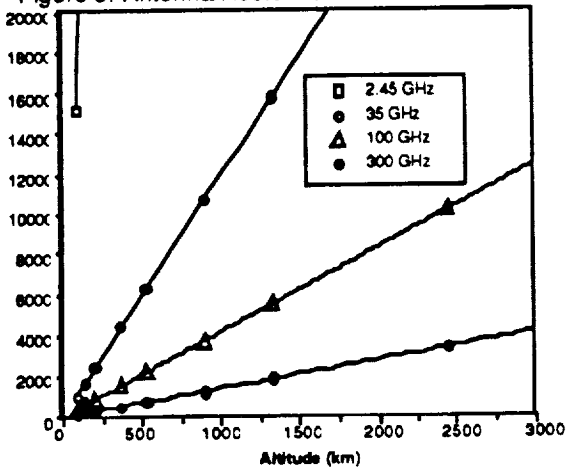
Table 3. Specific Mass Results

Frequency (GHz)	Case 1 (kg/kw)		Case 2 (kg/kw)		Case 3 (kg/kw)		
	SOA	Adv	SOA	Adv	SOA	Adv	Thin Film
2.45	2920	887	2474	901	8863	1286	367
35	2482	611	1448	387	3043	415	170
100	2460	589	1328	327	2606	295	107
300	2452	582	1269	282	2447	200	84

For Case 3, the efficiencies assumed for the thin film devices represent todays terrestrial versions (and should go higher with time) but specific masses for the components quoted and structures designed with them have a large error band since there are still many unknowns. There is a higher confidence value placed on the performance of the advanced technologies since it is an extension of large space structure design such as SSF and a more established space qualified technology database exists.

One of the first parameters of interest is transmission frequency. Figure 5 shows the antenna/rectenna areas, calculated using equation 1., versus altitude for 2.45, 35, 100 and 300 GHz. Altitude and frequency have a large effect on antenna/rectenna areas and tend to drive the satellites to a lower orbit to minimize the antenna/rectenna size and mass.

Figure 5. Antenna/Rectenna Area vs Altitude



This effect of frequency can be seen in figure 6 which shows the specific mass of the beam power system versus frequency using advanced and thin film technologies. The beam power system is sized to deliver 1 Mw of continuous power at the surface. The points plotted here relate to the altitude yielding the lowest system mass. At 2.45 GHz the antenna and rectenna masses are so large that they dominate the total system mass. Overall though, the transmission system does not contribute significantly to the system mass at greater than 35 GHz and little is gained at frequencies above 100 GHz for the cases investigated.

The small dependence on transmission system above 100 GHz reduces the importance of the 54% efficiency assumption used for the transmission link. If the actual link efficiency is less, the antenna/rectenna sizes can be increased without major effect on total mass (assuming larger sizes can be built).

The system mass is composed of power dependent components (which scale linearly with power level), and the antenna/rectenna which are not a function of power, but of altitude and frequency. The antenna/rectenna will contribute most of the mass to very small power systems.

As power level is increased, the antenna/rectenna sizes remain constant and further mass increases come only from the power system. The total system specific mass thus will decrease with increasing power.

One Mw continuous supplied power at 100 GHz transmission frequency will be used in further discussions of Case 2 Advanced, Case 3 Advanced and Case 3 Thin Film. The specific mass results can be scaled (to a first order) to other power levels and frequencies by proportional increases (decrease) of the plotted antenna/rectenna specific mass for decreased (increased) power and/or frequency.

Figure 6. Specific Mass Advanced & Thin Film Technology

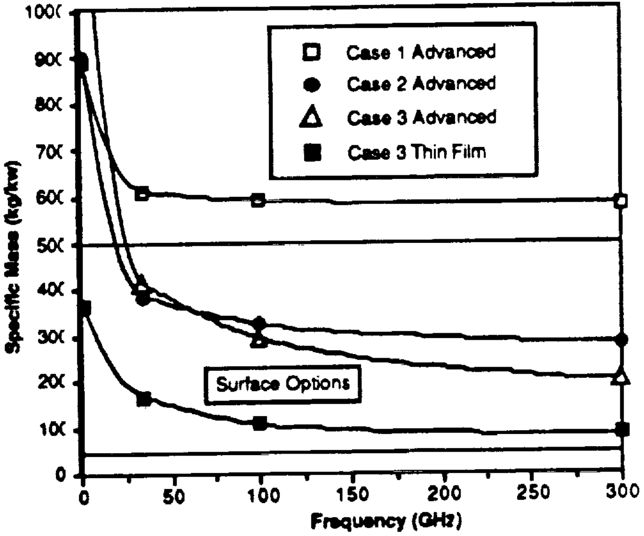
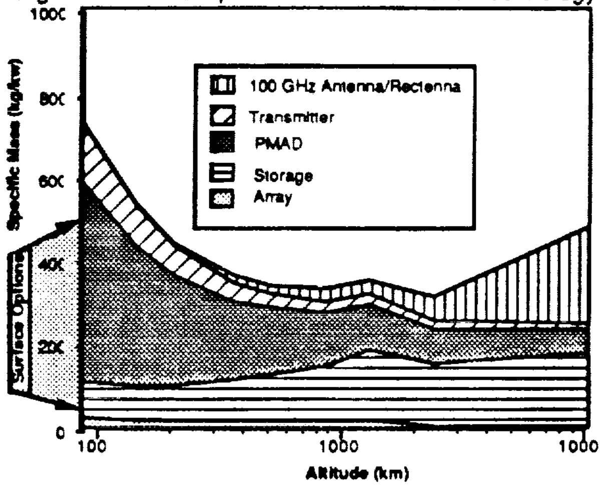


Figure 7 shows the specific mass of the beam power system under Case 2 scenario using advanced technology. The PMAD and transmitter on each satellite are sized to provide the total continuous power to the user. As seen previously from Table 2, the beam time increases with altitude which leads to a lower number of satellites required. Thus, as the altitude increases, the reduction in satellites, in turn, decreases the total satellite PMAD and transmitter mass.

The energy storage mass increases due to an increase in discharge time. Notice that the storage mass is increasing up to 1336 km, decreases up to 2459 km, then continues to increase as the altitude increases. At 1336 km, the discharge time changes from the beam time to the eclipse time which causes the storage mass trend to become discontinuous and decrease due to the array being able to provide some power during transmission. Above 2459 km, the storage mass continues to increase from an increase in eclipse time. (If the total discharge time from the constellation is plotted versus altitude, the trends will be the same as the storage mass shown in figure 7).

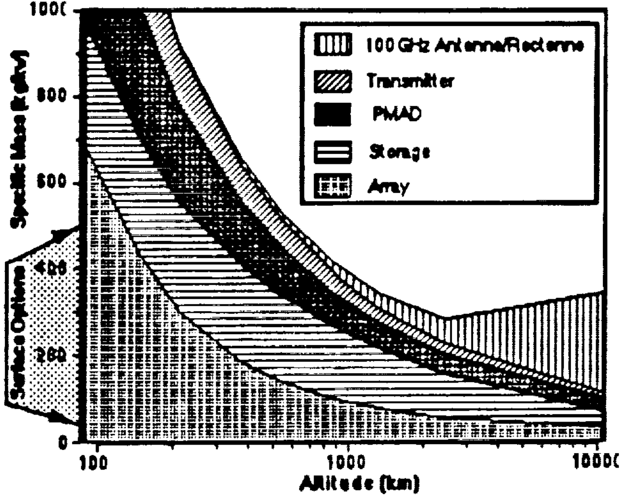
The arrays and storage are not a function of the number of satellites but rather the total energy needed from the entire constellation. On the other hand, the antenna needs to be replicated on each satellite. Even so, the antenna (and rectenna) are not significant mass drivers until altitudes above 1000 km.

Figure 7. Case 2 Specific Mass Advanced Technology



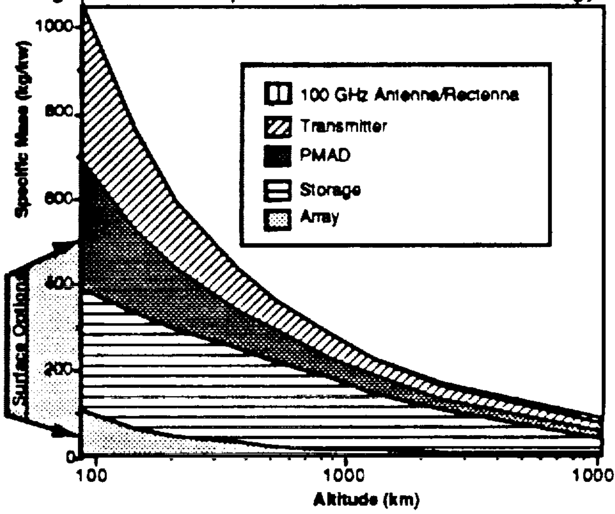
The specific mass is plotted for Case 3 advanced technology in figure 8. All elements except the antenna/rectenna decrease with altitude due to the increasing view time with the satellite in the sun. The RFC's mass is decreasing with altitude because of the corresponding decreasing discharge time. The satellite and surface PMAD and the transmitter masses decrease as the altitude increases due to a lower peak power resulting from increasing transmission times. The antenna/rectenna do not contribute significantly below 2500 km.

Figure 8. Case 3 Specific Mass Advanced Technology



Plotted in figure 9 is the specific mass using the thin film technologies at 100 GHz. The mass trends of the thin film technologies are the same as in the advanced technology case. However, the array has become much less of a mass driver than the energy storage by virtue of its lower specific mass. The energy storage total mass has not decreased since it assumes the same RFC's as in the advanced technology. The transmitter mass is larger than in the advanced technology due to the thermal support arising from the assumed 50% efficiency. Finally, by using inflatable structures for the integrated thin film antenna and solar array, the significance of antenna weight has been further reduced.

Figure 9. Case 3 Specific Mass Thin Film Technology



FUTURE WORK

In all scenarios of interest, storage and PMAD are the dominate mass. To reduce the system specific mass without using very optimistic projections for energy storage, means must be developed to further reduce or eliminate the energy storage. One method of reducing the energy storage requirements is to place the satellites into inclined elliptical orbits such that they experience shorter eclipses. High enough inclination could eliminate the need for surface or orbiting energy storage except for periods of earth eclipse (possibly twice a year) and for emergency back-up.

The antenna and/or rectenna could be articulated with a large gimballed mechanism to point directly at the satellite, capturing more incident RF energy and allowing inclined orbits. The increased transmission efficiency would result in lower power dependent masses. Additionally, the field of view would be greatly increased resulting in fewer satellites at a given altitude. Further, the beam time to eclipse ratio would be greatly increased resulting in reduced storage requirements. More analysis needs to be performed to understand the issues involved and to determine the ultimate payback.

The antenna and rectenna masses dominate the total system at 2.45 GHz, leading to the conclusion that higher frequencies are necessary to lower the system mass. For the cases investigated other considerations such as structural needs or the ability to articulate the antenna/rectenna may also justify the higher frequencies.

Conversely, transmitter efficiency versus frequency must be determined. The transmitter can become a major mass driver if the actual efficiencies are considerably less than assumed for this study. The mass could increase due to the larger thermal management needed to reject the increased waste energy. Also, lower efficiency would have a ripple effect through the entire system by increasing the size of the power dependent masses.

High magnetic fields are needed to operate gyrotron tube microwave transmitters. These high magnetic field levels require that for high frequencies, the gyrotron operates either with superconducting magnets, or at harmonics of the resonant frequency. 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, the efficiency rapidly degrades [5]. Further analysis needs to be done to determine the mass of the thermal rejection system needed to cool the superconducting magnet to cryo-level temperatures.

In this study several assumptions were made that will need to be addressed in future studies. The actual transmitter/rectenna link efficiency should be calculated, although it was seen that the antenna/rectenna size was not the mass driver in the scenarios investigated. Parameters such as antenna size and array/storage size though should be traded to optimize system performance. Operations issues such as installation, maintenance, station keeping and reliability must be considered. Also, the assumption of a single base,located on the equator, may not be realistic and inclined orbits may need be investigated to accommodate high latitude base locations. The only figure of merit truly considered in this study was specific mass. Other criteria such as volume, cost and operation issues must be addressed.

CONCLUSIONS

The energy storage for the 14 day "lunar night" is the major mass driver for a lunar surface power system with a solar source. Using an orbiting beam power system, the eclipse times are greatly reduced, and therefore, the energy storage mass is greatly reduced.

To realize this gain though, requires the additional elements of a beam power transmission link consisting of satellite(s), structure, PMAD, transmitter, antenna, microwave link and rectenna. These add not only mass but also efficiency losses to the power train that must be made up with additional solar array size. The net mass change will depend on many factors.

The study has demonstrated that the specific mass of a beam power under certain technology and scenario assumptions falls between surface solar and nuclear power options (ie 20 to 500 kg/kw). More favorable system scenarios then those examined and system optimization could bring down the specific mass further. However, more work needs to be accomplished to understand the actual feasibility of microwave beam transmission.

In order to consider a beam power system as a lunar power option, advanced and/or thin film technologies are required. The costs and risks involved in developing these technologies needs to be examined. Likewise, operational issues such as satellite control, station keeping, installation and maintenance need to be addressed.

Presently we are commencing a study to determine the feasibility of beam power transmission concepts for the moon and mars as part of the Space Exploration Initiative (SEI). The system level studies described here will be expanded to include other options such as laser transmission and nuclear power sources. Also, more intensive investigations into the performances, costs, risks and developments of the technologies needed in a beam power transmission system will be accomplished with particular attention paid to system integration issues.

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16. Abstract

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