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APPLICABILITY OF THE BEAMED POWER CONCEPT TO LUNAR ROVERS, CONSTRUCTION, MINING, EXPLORERS AND OTHER MOBILE EQUIPMENT

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INTRODUCTION:

~~This paper will address~~ some of the technical issues dealing with the feasibility of high power (10 Kw - 100 Kw) mobile manned equipment for settlement, exploration and exploitation of Lunar resources

This study ~~has d~~ivided this problem into ~~three~~ categories:

* Short range mining/construction equipment
* Moderate range (50 Km) exploration vehicle
* Unlimited range explorer

The following are some general assumptions made through the analysis:

PV array systems (including structure)	22 kg/kw
Advanced PV concepts (including structures)	3 kg/kw
Multimegawatt Nuclear	12 kg/kw or 80 w/kg
Regenerative Fuel Cells (includes cooling)	100 W-hr/kg 65% efficiency

CASE STUDY I: SHORT RANGE MINING/CONSTRUCTION EQUIPMENT

It is supposed that :

* All vehicles should have enough stored energy to make the trip back home. In this example we are going to assume that the trip is 5 km on a 15° slope, with roughness (friction coefficient) of 0.32.

* It is supposed that 25% of the power capability of the vehicle is for housekeeping and life support. For the beamed powered vehicles, enough of this power should be stored for emergencies. If the beam goes down, the vehicle should be able to return home with the crew.

* This trip should be made in 15 min., which is equivalent to 20 Km/hr.

* For these design specifications we will consider three vehicles: 25 Kw (4,000 Kg), 50 Kw (8,000 Kg) and 100 Kw (16,000 Kg).

MINING VEHICLES OPERATED WITH REGENERATIVE FUEL CELLS

	Vehicle Power		
	25 Kw	50 Kw	100 KW
5 Km trip storage	127 Kg	253 Kg	486 Kg
Pmad	500 Kg	1,000 Kg	2,000 Kg
work storage			
1 hr	385 Kg	770 Kg	1,540 Kg
2 hr	769 Kg	1,538 Kg	3,076 Kg
3 hr	1,154 Kg	2,308 Kg	4,615 Kg

MINING VEHICLES OPERATED WITH REGENERATIVE FUEL CELLS

		Vehicle Power		
		25 Kw	50 Kw	100 KW
total masses				
1 hr	24.7 w/kg 25%	1,011 Kg	2,023 Kg	3,419 Kg
2 hr	17.9 w/kg 35%	1,395 Kg	2,791 Kg	4,958 Kg
3 hr	14 w/kg 45%	1,780 Kg	3,561 Kg	6,494 Kg

Beam Power System Description:

RF source: Gyrotron 5 Kg/kw
50 % efficiency
collector temperature 800 K
no window used
cryo-cooling for magnets included
radiator mass for collector based on 450 K ambient temp.
operation frequency 289 GHz
suport structure 1/4 of the mass of the tube

Optics: Monolithic parabolic reflector
2 m in diameter
1.4 kg/m^2
losses less 2%
surface temperature 800 K

Rectenna: 60% efficiency
› 770 K operating temperature (vacuum microelectronics)

REQUIRED INFRA-STRUCTURE TO SUPPORT BEAMED POWER VEHICLES

	Vehicle Power		
	25 Kw	50 Kw	100 KW
TRANSMITTER:	84 Kw	167 Kw	334 Kw
antenna	4.5 Kg	4.5 Kg	4.5 Kg
gyrotron	540 Kg	1,080 Kg	2,160 Kg
Pmad *	1680 Kg	3,360 Kg	6,720 Kg
structure	130 Kg	260 Kg	520 Kg
totals:	2,354 Kg	4,704 Kg	9,404 Kg

* This might or might not be included in the beam power infra-structure, since it might be part of the base/outpost power system.

BEAMED POWER SYSTEM AT THE VEHICLE END

	Vehicle Power		
	25 Kw	50 Kw	100 KW
RECEIVER:			
rectenna	22 Kg	22 Kg	22 Kg
Pmad	500 Kg	1000 Kg	2000 Kg
energy storage	96 Kg	192 Kg	384 Kg
totals:	618 Kg	1192 Kg	2384 Kg
40 w/kg	15% power system mass		

This architecture provides an almost unlimited amount of power to the user.

CONCLUDING REMARKS ABOUT MINING/CONSTRUCTION VEHICLES

Mining/construction operation:	Effective time utilization:	
8 hrs. working day	1 hr. 45%	7 hr. 83% power system mass
1 hr. lunch	2 hr. 51%	7.5 w/kg
two 15 min. breaks	3 hr. 53%	100% time utilization
effective time 7 hrs.		

beamed power vehicle = 100% time utilization
40 w/kg
15 % power system mass

This time utilization efficiency takes into account the time invested by the worker on traveling back and forth (5 Km) to recharge his batteries and the time invested on charging the batteries. The power supply utilized to do this is the same power supply for the beam power example.

CASE 2: MODERATE RANGE (50 Km) EXPLORATION VEHICLE

* 100 Kw continuous power vehicle
* 25% of total power capacity dedicated to housekeeping and life support
* The system should have enough power storage for return trip if beam is down. Also should have an extra hour storage in case of beam blockage due to geological features.
* Two types of vehicles will be analyzed. A 29 tonne (10 Km/hr) and a 14.5 tonne (20 Km/hr).
* The analysis considers also two possible frequencies. One is 140 GHz for which an optics of 8.86m is used and 280 GHz for which an optics of 6.27 m is used. If an optics at the receiver is to be 4m, then the minimum interception efficiencies are 20% for 140 GHz and 41% for 280 GHz, assuming that the maximum distance between receiver and transmitter is 50 Km.

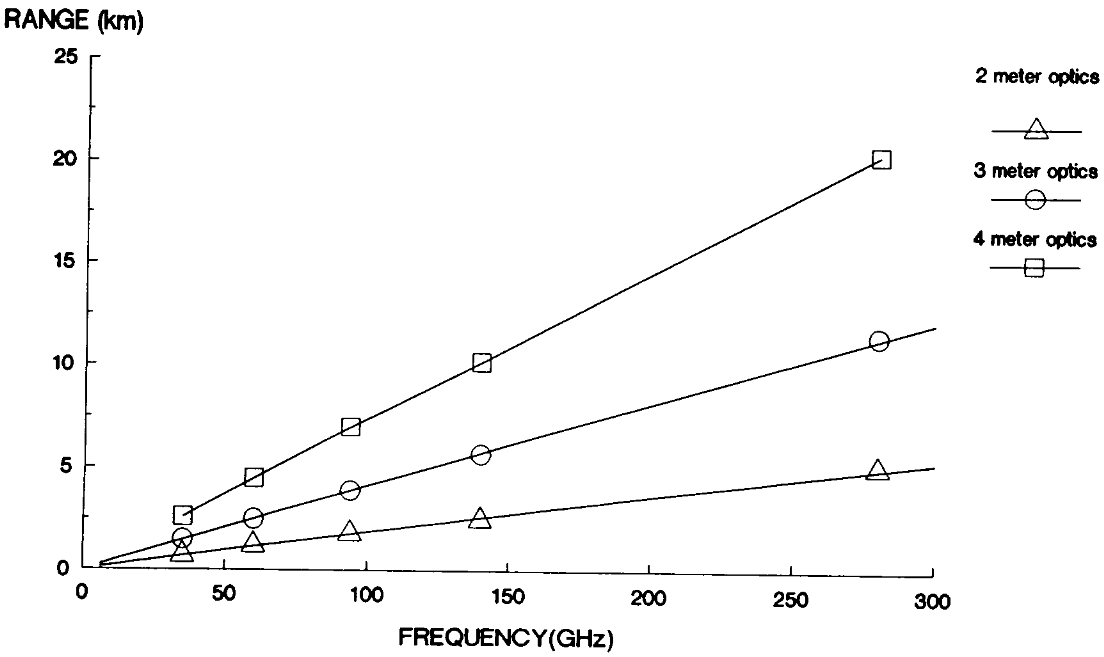
SOLAR/RFC LUNAR EXPLORER FOR DAYTIME OPERATION ONLY

		10 Km/hr	20 Km/hr
mobility (round trip)		11,334 Kg	5,666 Kg
Pmad		2,000 Kg	2,000 Kg
PV system			
(conventional)		2,200 Kg	2,000 Kg
(advanced)		300 Kg	300 Kg
	totals:		
	(conventional)	15,484 Kg	9,866 Kg
	sp	6.5 w/kg	10 w/kg
	%	53%	68%
	(advanced)	13,634 Kg	7,966 Kg
	sp	7.3 w/kg	13 W/kg
	%	47%	55%

RFC EXPLORER FOR NIGHTTIME OPERATIONS

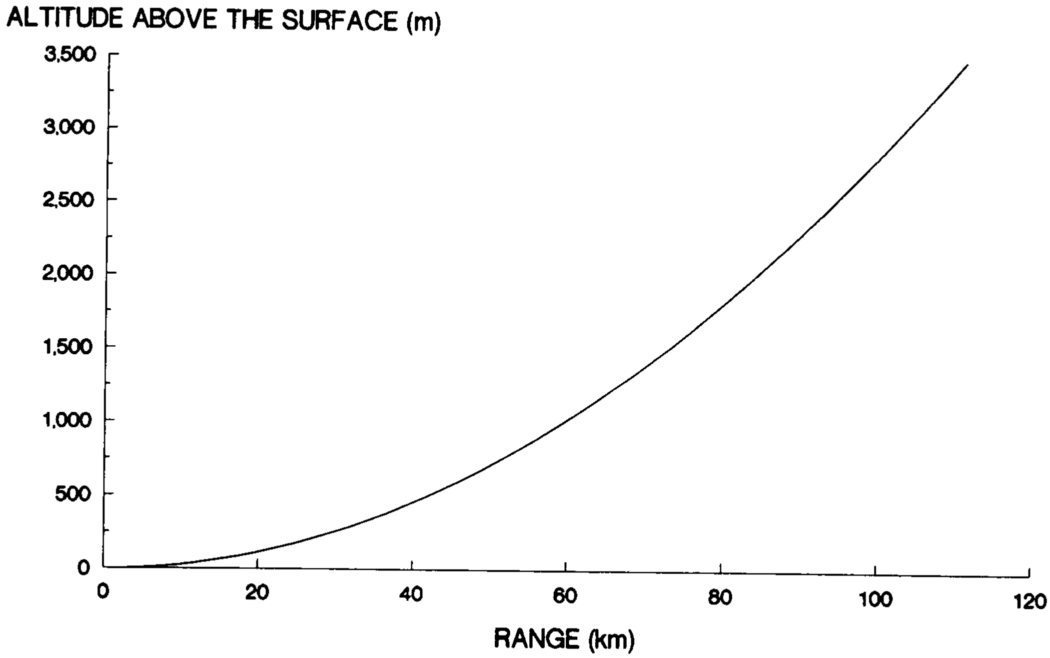
		10 Km/hr	20 Km/hr
mobility (round trip)		11,334 Kg	5,666 Kg
Pmad		2,000 Kg	2,000 Kg
Life support and operations			
	1 hr.	1,538 Kg	1,538 Kg
	3 hr.	4,615 Kg	4,615 Kg
	5 hr.	7,690 Kg	7,690 Kg
	1 hr.	51% 7 w/kg	63% 11 w/kg
	3 hr.	61% 6 w/kg	84% 8 w/kg
	5 hr.	72% 5 w/kg	106% 6.5 w/kg

RANGE ACHIEVED BY A COLLIMATED BEAM



VISUAL RANGE ABOVE THE HORIZON ON LUNAR SURFACE

ASSUMING NO GEOLOGICAL OBSTACLES



SUPPORT INFRA-STRUCTURE TO BEAMED POWER EXPLORER

		140 GHz	280 GHz
Transmitter characteristics		1,865 Kw	900 Kw
gyrotron (50 % eff.) (1 kg/kw)		2,390 Kg	1,114 Kg
antenna (1.4 kg/m^2)		86.3 Kg	43 Kg
Pmad (95% eff) (20 Kg/kw)		37,000 Kg	18,000 Kg
structure (1/4 tube)		466 Kg	225 Kg
	totals	39,861 Kg	19,382 Kg
	RF system	2,861 Kg	1,382 Kg

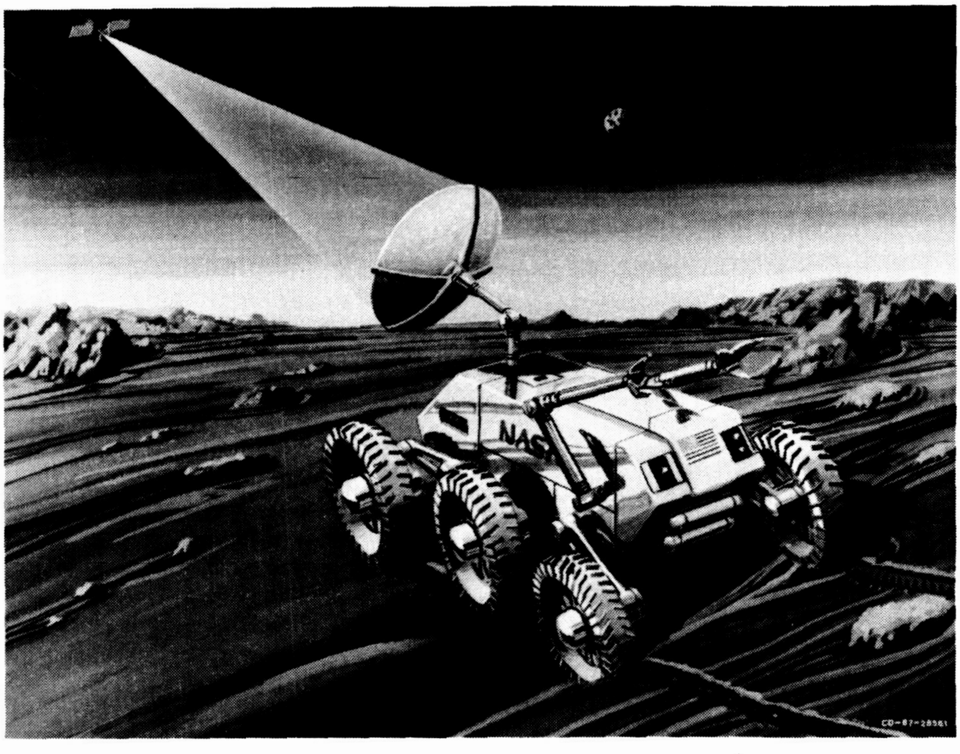
ANALYSIS OF THE WORST PERFORMANCE OF EXPLORER VEHICLE OBTAINED WITH A BEAMED POWER SYSTEM.

Receiver:	10 Km/hr	20 Km/hr
rectenna	62.8 Kg	62.8 Kg
Pmad	2,000 Kg	2,000 Kg
"shadowing" 1 hr. supply	1,538 Kg	1,538 Kg
return emergency storage	5,667 Kg	2,833 Kg
totals:	9,267 Kg	6,434 Kg
power plant fraction	32%	44%
specific power	11 w/kg	15 w/kg

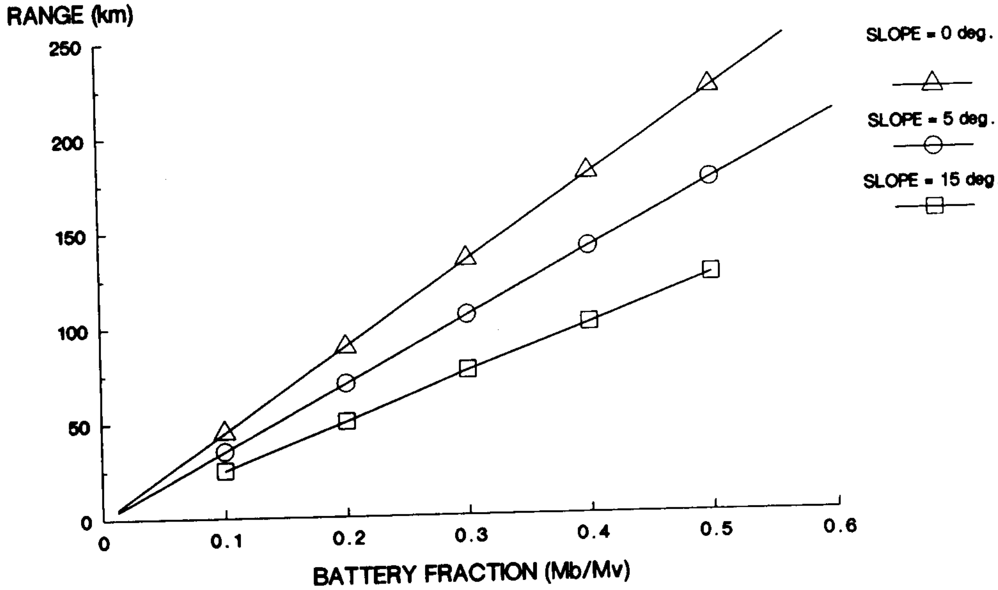
CASE 3: UNLIMITED RANGE EXPLORER

This vehicle has the capability of sustaining missions of very long duration (several days) with journeys up to hundreds of kilometers. This differs from the previous case since there is not any mountaintop on the surface of the Moon that could meet this kind of requirements.

This case assumes the existence of an orbiting beam power infra structure, capable of providing power to any ground mobile vehicle (or any surface facility) virtually any where on the planet.



RANGE OF RFC ON LUNAR SURFACE
FOR ROVER APPLICATION



The system used is a RFC
100 W-hr/kg and 65% efficiency

NOMENCLATURE

n_{depth} = Depth of discharge

n_a = interception efficiency

n_e = overall electronics efficiency

n_{ch} = charge efficiency

n_{dis} = discharge efficiency

SSC = specific storage capacity (W-hr/kg)

P = period of the orbit

DC = duty cycle (fraction of the time that the orbiter is visible)

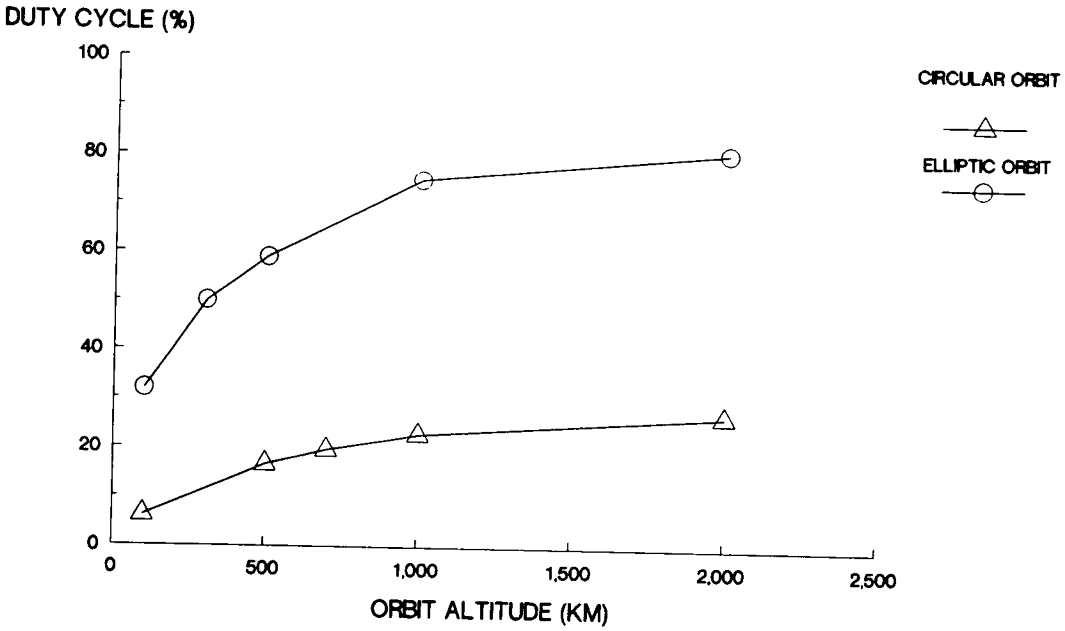
The following expression relates the power required at the transmitter with the power demanded by the receiver as a function of the duty cycle and system's efficiencies.

$$P_d = n_a n_e \left\{ \frac{1-DC}{n_{depth}\, n_{ch}\, n_{dis}\, DC} + 1 \right\}^{-1} P_t$$

The mass of the battery at the receiving end is also determined by the demanded power at the receiver Pd (watts) and the period of the orbit P (seconds).

$$M_b = \frac{P_d \ (1-DC)P}{\{ n_{depth}\, n_{ch}\, n_{dis}\, SSC\ (3600) \}} \qquad (kG)$$

LUNAR BEAM POWER ORBITING STATION DUTY CYLES
FOR DIFFERENT ORBITAL TRAJECTORIES



PERFORMANCE OF A HYPOTHETICAL VEHICLE POWERED BY AN ORBIT BEAMED POWER STATION

rectenna

- 10.6 μm rectenna
- 60% efficiency
- MOM structure
- 4 m optics
- mass...... 15.7 Kg (5 kg/m^2)
- passive cooling (617 K)

storage

20% of the cycle	1,101 Kg
1 hr shadow	1,538 Kg

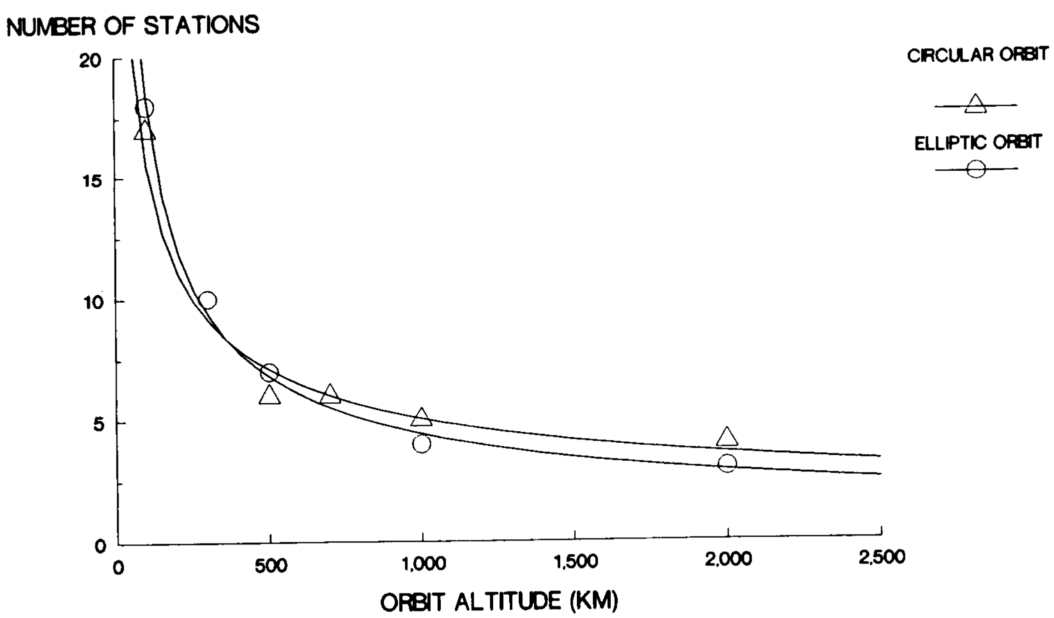
Pmad 2,000 Kg

power level = 100 Kw
speed = 20 Km/hr
total mass = 14,500 Kg

Orbiter:
elliptic orbit
80% duty cycle
2,000 Km apog.
3hr. 34min. 45sec.
(period)

18% mass power fraction
37 w/kg

LUNAR BEAM POWER ORBITING STATIONS FOR COMPLETE COVERAGE



ORBITER'S POWER REQUIREMENTS

The major concern at this point is to conceive an efficient way to generate and beam the power such that the power requirements on the orbiter are not unrealistic.

$$P_d = n_a n_e \left\{ \frac{1-DC}{n_{depth}\, n_{ch}\, n_{dis}\, DC} + 1 \right\}^{-1} P_t$$

$n_a = .8$

$n_e = .1$

$DC = 80\%$

For these assumptions, the power requirements at the transmitter are about 31 times higher than at the user. This is due to the inefficiencies of the system.

A 3.1 Mw orbit transmitter might be reasonable if its existence could be justified in relation to other activities. A stand alone infra-structure of this magnitude might reduce all the benefits of a beamed power very long range explorer vehicle.

CONCLUSIONS:

Based on the assumptions made in this preliminary analysis, the beamed power concept might not be a too unreasonable alternative.

A more in depth analysis should follow, addressing some technology feasibility issues in regard to antenna, RF generation and rectenna concepts. An objective assessment is appropriate at this point in order to evaluate the merits of state-of-the-art technology, and its predicted evolution in the future in regard to its applicability to beamed power.