ORBIT TO SURFACE BEAMED POWER
FOR
MARS BASES EXPANSION

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ABSTRACT:

A scenario is presented wherein the interplanetary supply vehicles for the expansion of the Mars bases are nuclear powered-electrically propelled. For the initial build-up phase every supply vehicle need not return to earth but could be utilized as a one-way transport to Mars synchronous orbit. Upon arriving at Mars, they would land their cargos with one-way descent vehicles. Base personnel will arrive at Mars in separate "fast trip" vehicles.

Once in the Mars synchronous orbits, the nuclear power system is will longer be needed for propulsion. Thus, this power system - megawatt power range - can be used as an orbital power station beaming its power to locations on the surface of the planet. Placing a number of such power systems at strategically located synchronous orbit positions will permit coverage of the major portion of the Martian surface. The megawatt size power system for one interplanetary electric propulsion vehicle will be capable of supplying a number of surface bases or installations.

INTRODUCTION:

The report of the Sally Ride Committee [1], the Committee on Advanced Space Technologies and the NASA Initiatives for Future Space Endeavors [2-3] present viable scenarios for NASA's future directions in space. The proposed thrusts of NASA's future activities are: The Advancement of Scientific Knowledge of the Planet Earth, To Explore the Solar System and the Universe Beyond and To Expand Human Presence Beyond the Earth Into the Solar system.

In keeping with the last of these stated goals, it may not be too long before man himself will visit Mars. Possibly the initial visit will be a fly-by of the planet, but humans will explore the planet surface in following missions.

An aggressive Mars exploration/colonization program will require a supporting transportation infrastructure between the earth and Mars. In establishing the initial bases on the surface, the primary transport need will be that of delivering supplies and cargo to the Martian surface. Return trips to carry supplies and cargo back to earth

will be required but not with the same frequency of the trips to Mars during the expansion phase.

A scenario wherein the interplanetary transit supply vehicles for the support of the Mars bases are nuclear-powered, electrically propelled vehicles is postulated. For the initial phase of the Mars surface base-outpost expansion it is assumed that every other supply vehicle will not return to earth but will be utilized as a one-way transport. Upon arriving at Mars in synchronous orbit, these vehicles will land their cargos from attached one-way descent vehicles. The vehicle will remain in synchronous orbit and since it no longer requires electrical power for propulsion, the vehicle and its multi megawatt power system can be used as an orbital power station. The electrical power will be "delivered" to the surface by means of microwave beams.

When the landing party arrives (by separate manned vehicles) they will deploy lightweight flexible rectennas [4] on the surface. Because of the multi-megawatt capability of the orbiting power station, exact alignment of the rectennas is not required and its light weight will make large area rectenna deployment possible. Power levels to meet 100's of kW's of usable electrical power can be beamed down from the power station to meet the power and energy needs of a surface installation. A large area on the planet can be covered from a single station in Mars synchronous orbit. Because of the low mass of the microwave power equipment, a number of outposts removed from the initial landing site can easily be set up and accommodated. As additional freighters deliver supplies to the Martian surface, they can be placed in predetermined synchronous locations to permit wide coverage of the planet to support exploration activities without dependence on massive surface power systems. The microwave power systems, both airborne and surface, their present state of technology and the benefits attainable from their use are the subject of this paper.

THE MARS TRANSIT VEHICLE:

Figure 1 shows a nuclear powered Mars Transit Vehicle (MTV). This vehicle as initially conceived was for an Earth-Mars and return mission [5]. It is nuclear-powered, electrically propelled; the total electrical capability being 10 megawatts. The characteristics of this vehicle are given in Table I:

TABLE I. The Mars Transit Vehicle.

Mass of MTV in GEO (Earth)	619,000 kg.
Mercury ion electrical propulsion;	
Specific impulse;	4260 seconds.
Nuclear heat source - Brayton energy conversion	
- 10 mW; 30 degree shadow shield for radiation protection.	
Length of spacecraft - approximately 200 meters.	
Mars surface operations:	
Detachable Mars descent and ascent vehicle;	
Mass 57,500 kg.	
H ₂ -O ₂ propulsion - 460 seconds Isp.	
Mars aerobreak reentry.	
Mission profile;	
Earth GEO to Mars GEO orbit - 196 days.	
Mars GEO to Earth GEO (Return) - 294 days.	

The vehicle design and its trajectory characteristics, Figures II and II, were taken from [5] and they are described in detail in that report. For that study [5] an electric propulsion system was used which utilized mercury ion engines. A more current technology for the propulsion system would be that of xenon ion engines. For the purposes of this paper the difference is minimal between these two systems.

The MTV will be adapted to a one-way freighter configuration. By not carrying return trip propellant, the payload mass fraction of the transit vehicle is increased. Some of this gain must be used for the microwave transmitting antennas, power management and other power system support equipment. The transit vehicle and its power system now becomes a usable resource at the planet.

The descent vehicle, also being a one way vehicle, need not carry propellant for the ascent and rendezvous with the Mars-Earth return vehicle. This vehicle can now carry additional payload to the surface in addition to the surface microwave reception equipment.

The propellant inventory for the various stages of the Earth-Mars transit vehicle is given in Table II:

TABLE II. Propellant Inventory For MTV.

Mass of Earth-Mars and return vehicle in GEO -	619,000 kg.
Propellant inventory	
Earth spiral to escape	35,700 kg.
Earth-Mars transfer phase	133,900 kg.
Mars capture spiral	11,500 kg.
Mars spiral to escape	97,000 kg.
Mars-Earth transit phase	77,500 kg.
Earth spiral capture	16,300 kg.
Total Propellants	371,900 kg.

The Mars excursion module has a propellant inventory as follows;

Propellant inventory;	
Mars deorbit and descent	11,750 kg.
Mars ascent/rendezvous in GEO	15,750 kg.

Thus for the one-way vehicle approximately 190,800 kg is available for microwave power equipment and additional payload. The Mars descent vehicle also has an additional capability since it does not ascend and rendezvous with the Mars transit vehicle for the earth return. As will be shown this is more than is needed to accommodate the airborne microwave power system and the surface microwave power receiving station. In addition we have an orbiting power station with capacity to supply future base expansions, Mars surface rovers and possibly Mars airplanes and other satellites in Mars orbits. Base power supply from orbit is depicted in Figure V. Rover operations are shown in Figure V.

THE AIRBORNE POWER SYSTEM:

The MTV in its Mars GEO configuration with the airborne microwave power transmitting system is shown on Figure VI. Up to the present time, relatively low frequency microwave power systems (2.45 GHz.) have been demonstrated [7,8,9]. High frequency microwave power is assumed (300 GHz) for the Martian application since the higher frequency system will require smaller airborne transmitting antennas and ground receiving rectennas. A schematic of such a microwave system is shown on Figure VII. A 10 megawatt airborne system will have the characteristics shown in Table III:

TABLE III. Airborne Power System Characteristics.

Airborne antenna	10,000 kg
Structure, misc. support equipment	5,000 kg
Power management & distribution system	5,000 kg
Airborne antenna size	10,000 m ²
Beam power density	1 kW/m ²

Some of the additional payload that is gained from this being a one-way vehicle must go towards providing orbit attitude maintenance propellant. If the space power system is to service more than one receiving station the primary transmitting antenna must be segmented and each segment must be capable of being individually directed. Additional on-board propellant for station keeping for a 10 year lifetime is assumed to be 10,000 kg. The station keeping function, while in orbit as a power station, can be accomplished by the electrical propulsion system which was used for the interplanetary transit portion of the mission. However, only a fraction of the power - compared to the Earth-Mars transit phase - is required for the station keeping function.

THE GROUND POWER SYSTEM:

The ground power receiving system can be incorporated into the descent vehicle which also could be integrated with the crew habitat on the surface. When the descent vehicle lands, the crew who arrived by a separate manned transport vehicle, will deploy a lightweight receiving rectenna. At the early stages where the orbiting power station will have an excess of power the receiving efficiency is of not too great importance. Thus the rectenna can be deployed directly on the surface without too much attention being paid to precise

orientation. The light weight of this rectenna (a 0.2 kg per m² rectenna was developed for the 2.45 GHz frequency [4]) will allow a large area to be deployed to overcome the possible low transmission efficiency. A detailed description of this rectenna and its construction is given in Reference 4. In the later stages of base development more elaborate equipment can be used to increase operational efficiency.

The initial base will be assumed to require amounts of usable electric power in the range of 100's of kilowatts. To receive 250 kW of usable electrical power, the ground receiving station will have the characteristics shown in Table IV:

TABLE IV. Receiving Station Characteristics.

Rectenna	750 kg.
Power management & distribution system	250 kg.
Miscellaneous support equipment	250 kg.
Receiving rectenna size	500 m ²

Power at additional outposts or bases can be obtained by providing the correct rectenna area along with its required power management and distribution equipment. The orbital system must, however, be capable of beaming to a number of surface locations under these circumstances. An estimate of additional mass on the orbiting power station to support four surface locations would be on the order of an additional 1000 kg. in orbit.

STATUS OF MICROWAVE TECHNOLOGY IN 1989:

Many studies of microwave beamed power have been made in the past. The best known of these is for the Space Power System which converts solar energy in GEO and transmits it to earth by means of microwave beams [6]. In this system a micro-wave frequency of 2.45 GHz is used since this frequency represents the present state of the art for transmission through the atmosphere. The performance of this system has been demonstrated [7]. Rectennas and supporting components have been developed at this frequency and are available off-the-shelf. Demonstrations of actual systems have also been carried out. A model helicopter has been flown powered by beam power [8] and a prototype model of a high altitude airplane has been successfully demonstrated by the Canadians [9]. Other applications of microwave beamed power technology have also been studied [10].

However, 2.45 GHz is a relatively low frequency and as such is relatively inefficient at long ranges and requires large receiving and transmitting antenna and rectenna areas. Thus equipment and components for higher frequencies must be developed and demonstrated. Figure VII gives a schematic showing the various components of a microwave beamed power system. The present status of such microwave equipment and the various components are shown on Tables V. and VI.

TABLE V. Status of Microwave Technology in 1989 (Systems Demonstrations).

MICROWAVE POWER TRANSMISSION OVER SHORT DISTANCES HAS BEEN DEMONSTRATED

- o 1-2 Kilometers transmission at 2.45 GHz (30 kW in atmosphere - JPL).
- o Model helicopter powered by microwaves has been flown (Raytheon 1969).
- o Small airplane powered by microwaves has been flown (Canada 1987).
- Specific power of approx. 1 kW/kg with an RF to DC conversion efficiency of 85%.
- Used a modified version of light thin-film rectenna developed for LeRC by the Raytheon Corporation.

TABLE VI. Status of Microwave Technology In 1989 (Component Technology).

MICROWAVE COMPONENT DEVELOPMENT STATUS

- o 2.45 GHz (12 cm.) technology reasonably well developed.
- o Power sources available at 30, 100, and 300 GHz.
- o IR rectenna being studied by University of Cincinnati.
- o 1 - 28 THz rectenna under study by University of Cincinnati
- o 90 - 300 GHz rectenna being developed by Georgia Tech.
- o Multi million dollar national (DOE) effort under way to develop gyrotrons.

At the 2nd Beamed Space Power Workshop [11] applications of microwave and laser beam power were extensively addressed. The workshop concluded that space beamed power is an enabling technology for specific NASA missions and should be developed. Support of planet surface operations from orbital power systems was one of the applications addressed by this workshop. The workshop specifically addressed the lunar application but the concept is viable for Mars operations. In addition, a number of applications studies analyzing the viability of microwave technology for Martian operations have been published [12].

RESULTS/SUMMARY:

Employing the electrically propelled nuclear power cargo transit vehicle as a one-way freighter and an orbiting microwave beam power station at its destination (Mars) results in an appreciable increase in payload mass fraction for the MTV. By not carrying the propellants for the return to earth an additional 190,800 kg. of payload can be delivered to Mars synchronous orbit. In addition, the Mars descent vehicle need not carry propellant to ascend and rendezvous with the freighter for the return to earth. This frees up another 15,750 kg. which becomes usable.

This additional capability may be utilized as follows to support the beam power station in Mars synchronous orbit as shown in Table VII:

TABLE VII.

Mass of airborne microwave equipment (10 kW):	25,000 kg.
Station keeping propellant (10 year requirement):	10,000 kg.
Ground receiving station equipment (per site-1250 kg.):	5,000 kg.
Miscellaneous support equipment (four sites/vehicle)	5,000 kg.

However, with the increased payload capability, the mass of the descent vehicle must also be increased. Also, since this vehicle is now landing more mass on the surface, its descent propellant inventory must also be increased. A rough estimate is that the dead weight of the descent vehicle must be increased by another 10,000 kg. (unmanned vehicle) and that 40,000 kg of H₂-O₂ propellants are required to land the vehicle and payload.

Thus we are led to the following mass balance for the new MTV version as given in Table VIII:

TABLE VIII. MVT Mass Balance.

Ion engine propellants saved:	90,800 kg.
Ascent vehicle propellants saved:	15,750 kg.
Total mass saved:	206,550 kg.
Mass of airborne microwave equipment:	30,000 kg.
Station keeping propellant:	10,000 kg.
Increased mass of descent vehicle:	10,000 kg.
Increased descent propellants:	28,250 kg.
Total mass debit:	90,000 kg.
Net increase in payload:	116,550 kg.

This represents a sizable increase in payload mass fraction for the original MTV. There are, however, options available for using this increased capability.

The one-way transit vehicle remaining in Mars synchronous orbit as a microwave beamed power station could also be reconfigured with less mass in GEO before earth departure. This would result in reduced mission costs. Alternatively in the later stages of the Mars expansion, the increased capability could be used as additional payload to supply the Mars bases. In either case it would result in a lower cost per unit of delivered mass to Mars.

In addition the orbiting power station(s) would represent a usable resource at the planet thereby reducing mass which must be delivered to the surface as the bases and outposts expand. In addition, one (or more) of the stations could be configured to include a habitable module or laboratory. In this manner it could serve as a Mars GEO base. In this capacity it could also be used as a transportation node (rendezvous point) for delivery of payload to

the Mars bases/outposts.

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FIGURE IV.

FIGURE V. MARS LONG RANGE SURFACE ROVER

FIGURE VI. MARS ORBITING MICROWAVE POWER STATION