PNL-SA-19713

PNL-SA--19713

DE92 006727

POWER BEAMING-MISSION ENABLING
FOR LUNAR EXPLORATIONS

JAN 24 1992

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January 1992

Presented at the
9th Symposium on Space Nuclear
Power Systems
January 12-16, 1992
Albuquerque, New Mexico

Work supported by
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

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POWER BEAMING: MISSION ENABLING FOR LUNAR EXPLORATION

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Abstract

This paper explores several beam power concepts proposed for powering either lunar base or rover vehicles. At present, power requirements to support lunar exploration activity are met by integral self-contained power system designs. To provide requisite energy flexibility for human expansion into space, an innovative approach to replace on-board self-contained power systems is needed. Power beaming provides an alternative approach to supplying power that would ensure increased mission flexibility while reducing total mass launched into space. Providing power to the moon presents significant design challenges because of the duration of the lunar night. Power beaming provides an alternative to solar photovoltaic systems coupled with battery storage, radioisotope thermoelectric generation, and surface nuclear power. The Synthesis Group describes power beaming as a technology supporting lunar exploration. In this analysis beam power designs are compared to conventional power generation methods.

INTRODUCTION

Providing continuous power to support exploration and manned activities on the moon for one full lunar-day stay (28 Earth days) presents significant design challenges because of the length of the lunar night. Continuous power to activities on the lunar surface can be supplied using electrochemical energy storage devices, photovoltaic energy, radioisotope decay, or nuclear fission reactors (Synthesis Group 1991). To enhance exploration flexibility on the moon, the ability to distribute power to remote sites is critical. Power beaming is a technology to distribute power to remote sites from the generator source. In the Synthesis Report (1991) power beaming is described as a technology supporting extended lunar exploration. The Synthesis Group (1991) reports "Power beaming for surface-to-surface power distribution may greatly reduce the mass of rovers and other mobile surface systems, assuming line of sight constraints can be met. If nuclear electric propulsion is developed for use in the lunar or Mars cargo vehicle, the orbiting transfer vehicle may be a convenient power source for surface operations. If power beaming can be demonstrated at a reasonable cost, long term development could provide attractive benefits." Several power beaming concepts have been proposed for providing surface base power and remote power for lunar missions. This paper explores several beam power concepts proposed for powering either lunar base or rover vehicles.

EARTH-BASED LASER POWER BEAMING CONCEPT

Energy storage comprises a significant fraction of the mass of a lunar power system such as a solar photovoltaic array. The energy storage requirements associated with the photovoltaic system can be significantly reduced or eliminated by illuminating the arrays by an earth-based laser system. Landis (1991) describes an earth-based system designed to provide power to the lunar photovoltaic system during the lunar night. Rather (1991) also describes an earth-based system for providing continuous lunar power.

The system involves locating large lasers on high-elevation cloud-free sites at multiple ground locations to beam power to the moon. Large lenses or mirrors with adaptive optics would reduce beam spread due to diffraction or atmospheric turbulence. System components are detailed in Table 1. In this application, lasers must operate in or near the visible spectrum in which the atmosphere is nearly transparent.

TABLE 1. Components of a Ground-Based Laser Beamed Power System

<u>Power Requirements on Earth</u>	<u>Power Requirements on Moon</u>
2.5 MW laser power required	50 kW power required at night
options	
• one 2.5 MW free electron laser	
• 50-50 kW conventional lasers	
0.53 μm wavelength	
<u>Earth-Based Transmitter</u>	<u>Lunar-Based Receiver</u>
10 m diameter lens or mirror with adaptive optics	750 m ² GaAs photocells at 20% efficiency

Significant mass savings are derived by reducing the amount of energy storage on the moon. Additional benefits derived from this concept center around the location of the laser power system on earth. This location permits considerable design simplification for the laser power beaming system; terrestrial systems can be easily repaired; therefore, highly redundant systems are not required. Disadvantages include the large transmission distance and the need for adaptive optics to compensate for atmospheric turbulence.

SPACE-BASED LASER POWER BEAMING CONCEPT

Power needs projected for lunar exploration missions on the lunar surface range from a few kilowatts for initial manned outposts and rovers to hundreds of kilowatts for permanent bases and in-situ resource utilization. Operation during the lunar night presents a formidable energy storage challenge for non-nuclear power systems because of the length of

those nights. The most massive components of the non-nuclear power systems are those used for energy storage. This excessive mass limits non-nuclear technologies that require energy storage to low power missions. By eliminating or reducing the need for energy storage the competitiveness of non-nuclear power systems with nuclear power systems would be enhanced. Gill et al. (1991) investigates two types of space-based beam powered systems and compares these systems with conventional lunar-based technologies requiring energy storage.

The reference concept for providing lunar surface power is a photovoltaic array (PV) coupled with a regenerative fuel cell (RFC). To supply 100 kW of power during the lunar night, the system mass associated with the regenerative fuel cell is estimated to be 50,000 kg. The photovoltaic array mass is estimated to be 5,000 kg, less than 10% of the total system mass. An alternative to the regenerative fuel cell that involves power beaming includes locating a beam power system at the lunar libration point (L1), a distance of 56,000 km from the moon. Two types of laser systems are analyzed for this application: a solar pumped iodine laser and a free electron laser.

In comparing the lunar surface power system mass for the three systems at surface power levels above 25 kW, both laser systems require less mass on the lunar surface than the photovoltaic/regenerative fuel cell system. At a nighttime surface power level of 100 kW, the PV/RFC system requires 55,000 kg, the PV/FEL system requires 30,000 kg, and the PV/solar-iodine system requires 25,000 kg. When considering the results of this analysis, power beaming offers a lower mass option than fuel cell technologies. This mass advantage may diminish when a beam power system is compared to a nuclear power system sited on the lunar surface; however, other issues such as safety and transmission flexibility may dominate.

Nuclear electric propulsion (NEP) offers synergism with beaming power to the lunar surface. Initially, NEP systems can be used to transport cargo to the lunar surface; after completing this mission, the NEP is stationed at a libration point and power is beamed to the lunar surface. This alternative has been investigated by Pacific Northwest Laboratory (Bamberger and Segna 1991 and Coomes et al. 1991). The laser system design is an AlGaAs laser diode beaming power to a GaAs photovoltaic energy conversion system (Coomes et al. 1990). At L1, a 10 MW nuclear electric power system could provide 5 MW of electrical power for use on the lunar surface.

LUNAR ROVER POWER SYSTEMS

The power system constitutes a significant fraction of the mass of a lunar rover vehicle. Replacing the on-board power system with a receiver and beaming the power to the rover vehicle would significantly reduce the vehicle mass. De Young et al. (1991) presents a conceptual design of a high-power long-duration lunar rover powered by a laser beam power system.

The concept involves three lunar-orbiting, laser diode array power systems, each powered by an SP-100 reactor beaming power to a lunar rover located on the lunar surface. The

laser diode array is phase locked to produce a single, coherent beam with a 0.62-m^2 spot size at the rover vehicle at the maximum transmission distance with a pointing accuracy of $0.2\ \mu$ radians. System components are detailed in Table 2.

TABLE 2. Components of a Lunar-Orbit Based Laser Beamed Power System to Power a Lunar Rover Vehicle

<u>Power Requirements on Orbit</u>	<u>Power Requirements on Moon</u>
50 kW laser power required	22.5 kW power required for rover vehicle
<ul style="list-style-type: none"> • 3 SP-100 reactors • 1815 km orbit 	
<u>Lunar Orbit-Based Transmitter</u>	<u>Lunar-Based Receiver</u>
0.8 μm wavelength	GaAlAs photovoltaic converter
8 m^2 aperture with gas lens	0.62 m^2 maximum spot size
0.2 μ radians pointing accuracy	23 kg/kW specific mass

Benefits derived from this concept center around the reduced mass and increased mobility of the rover vehicle. The laser power transmission concept provides a lunar power infrastructure that is highly flexible in its ability to provide power to any point on the lunar surface. Disadvantages include the need for the rover to continuously track the beam, even while the rover vehicle is in transit. System enhancements may be obtained by providing some energy storage capacity on the rover vehicle.

Meador (1991) has investigated several power beaming systems that could be used to power lunar surface exploration vehicles (SEV). These vehicles are pressurized, serve a crew of four, and provide a mobile habitat/laboratory with a range of more than 1000 km for lunar exploration. In the analysis, Meador (1991) designs several beam power systems capable of providing 25 kW to the SEV. The lunar orbiting laser beam power stations would be either pumped by the sun or powered by SP-100 nuclear reactors. In comparison to other on-board power systems, the beam power system requires only a photovoltaic energy conversion system which is very light. Competing on-board power technologies and their disadvantages include

- photovoltaic arrays with battery storage - very large for high power
- nuclear systems radioisotope thermoelectric generation (RTG) and dynamic isotope power system (DIPS) - intrinsically low power; plutonium fuel shortage
- regenerative fuel cell coupled with photovoltaic arrays with battery storage - massive energy storage capacity required for operation during the lunar night
- SP-100 on-board (design would be considered a two vehicle SEV, one for exploration, one for the power system) - mobility, maneuverability, mass, and safety problems.

Meador (1991) concludes that laser power beaming is mission enabling for lunar exploration. Two laser technologies are proposed. Photodissociation iodine systems, with $\text{C}_4\text{F}_9\text{I}$ as the gaseous iodine lasant are close to being technologically ready for lunar applications. Longer term laser alternatives include electrically pumped laser-diode arrays and laser-diode-pumped neodymium slabs. Optical focusing, pointing, and tracking technologies have been partially developed and tested, and photovoltaic conversion systems are being developed. Research programs to develop these concepts are underway; laboratory databases are being generated, and full-scale system design may be complete by 1997.

CONCLUSIONS

A variety of power beaming concepts have been proposed for providing power to the lunar surface to support extended lunar base operations and surface exploration. The concepts center around laser energy transmission from a remote power system located either on Earth or in lunar orbit. Several laser technologies are under consideration. Each of these concepts provides significant mass savings when compared to power system alternatives sited on the lunar surface because the latter require significant mass for energy storage during the lunar night.

Acknowledgments

This work was performed at the Pacific Northwest Laboratory operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

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