

ENABLING LUNAR AND SPACE MISSIONS BY LASER POWER TRANSMISSION

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N 9 3 - 1 7 4 2 3

Applications are proposed for laser power transmission on the Moon. A solar-pumped laser in lunar orbit would beam power to the lunar surface for conversion into either electricity or propulsion needs. For example, lunar rovers could be much more flexible and lighter than rovers using other primary power sources. Also, laser power could be absorbed by lunar soil to create a hard glassy surface for dust-free roadways and launch pads. Laser power could also be used to power small lunar rockets or orbital transfer vehicles, and finally, photovoltaic laser converters could power remote excavation vehicles and human habitats. Laser power transmission is shown to be a highly flexible, enabling primary power source for lunar missions.

INTRODUCTION

Lunar bases and major space activities in the next century will substantially increase the demand for power. Present power technology such as solar photovoltaics, solar dynamics, and nuclear reactors can meet the near-term power requirements, but these technologies all have major disadvantages when scaled to high power levels with the additional demand of powering a very diverse set of remote lunar missions. One potential power scenario, not previously considered for lunar missions, is laser power transmission to multiple lunar users from a lunar orbiting solar-pumped laser (De Young et al., 1987). Such a system allows a maximum of flexibility, since the primary power source is not located on the lunar surface. The laser beam could service a variety of users at diverse locations simultaneously as long as each user was in line of sight with the orbiting power station. The lunar receiver could convert the received laser power into electricity or propulsion with potentially greater than 50% efficiency in either case (Walker and Heinbockel, 1987a,b; Jones, 1981). This power concept would use relatively inexpensive and lightweight photovoltaics as the laser-to-electricity converter. The goal of laser power transmission is to make the receiver primary power system a minor component with respect to mass and complexity, and thus more emphasis can be placed on the science, materials processing, or other mission requirements at the lunar receiver.

This paper outlines in broad perspective a solar-pumped laser power system and several potential missions that such a power system would enable. The intent here is to stimulate further technical discussion of such a concept and to define both its advantages and disadvantages. We believe that this concept has potential for radical new missions not thought possible using more conventional primary power sources.

SOLAR LASER POWER STATION

A schematic diagram of a 1-MW solar-pumped laser is shown in Fig. 1. This is one of several potential solar-pumped laser concepts that could produce a laser beam of sufficient continuous wave (CW) power to meet the power needs of future space missions. In this specific design (De Young et al., 1987), a 395-m-diameter solar collector focuses sunlight onto a laser cavity

containing $t\text{-C}_4\text{F}_9\text{I}$. This molecule photodissociates and creates excited I, which lases at $1.315\ \mu\text{m}$. The laser beam is sent to a 28-m-diameter transmission mirror where the laser energy is beamed to the receiver of a lunar mission.

The power station would orbit the Moon at an altitude of approximately three lunar radii (5200 km). Since the lunar synchronous orbit is too high to be useful, multiple laser stations are necessary to cover the entire lunar surface. Also, it is not possible to avoid going into the Moon's shadow, as is possible in sun synchronous Earth orbits; thus, again, multiple stations are necessary. A receiver on the lunar surface could receive 6 hours of continuous power transmission before the laser station went below the horizon. A single laser station would then return

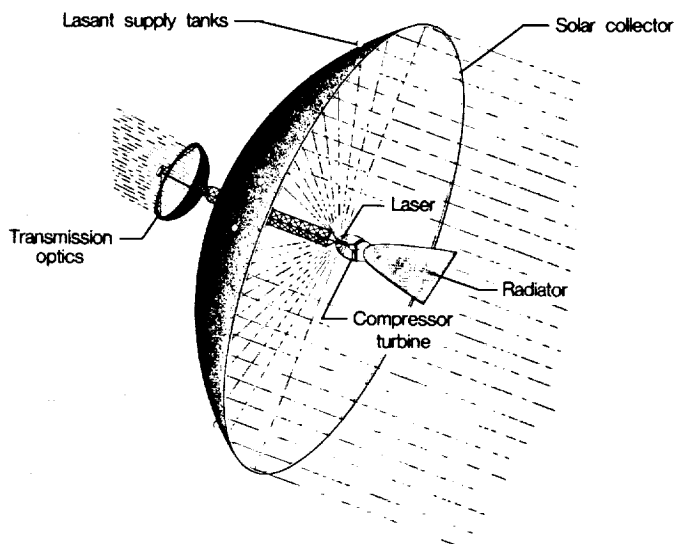


Fig. 1. An iodine solar pumped laser using $t\text{-C}_4\text{F}_9\text{I}$. From one to five of these laser stations would orbit the Moon and transmit power to the surface.

14 hours later. With multiple stations, this dead time (8 hours) could be substantially reduced, and with 5 stations, every lunar spot could be continuously covered with laser power.

The above description of the laser-power station is only an example. The exact nature of the power station will depend on the number of missions, the power requirement per mission, mission location, and mission duty cycle. The major advantages to such a system are that the prime power source (laser) is not taken to the lunar surface, thus saving mass, and, as a result of orbiting the surface, can supply power to diverse locations.

LUNAR APPLICATIONS OF LASER POWER

Research is continuing to define potentially more efficient solar laser systems. High-efficiency solar lasers would convert a significant fraction of the absorbed solar spectrum into laser light. Laser wavelengths should be shorter, i.e., nearer the visible spectrum, to minimize the size of the laser transmission optics. Pointing and tracking, as well as safety issues, also need to be addressed in a lunar laser power station.

A variety of missions are now proposed that give an indication of the diversity and flexibility inherent in laser power transmission. Each mission uses a simple photovoltaic laser-to-electric converter to power electric motors, storage batteries when necessary, and science or industrial mission requirements. Also, laser power could be used for direct lunar launch and orbit raising requirements.

Lunar Rover Power

Figure 2 shows a remote rover involved in lunar regolith science missions being powered by a laser beam. The rover uses a simple lightweight photovoltaic laser-to-electric converter of approximately 1-m diameter. Calculations have indicated that the laser-to-electric converter would have a mass of 20 kg for a 74 KW_e system. The radiator for this system is the dominant mass component at 240 kg for the 48% efficient converter. With such a system, more emphasis could be placed on mission require-

ments and less on the primary power system. The rover could be lightweight and very maneuverable and could maintain its mission for a considerably longer time than if powered by battery or fuel cells. It also does not have the radiation hazards associated with nuclear reactor power sources. The laser beam power level could be varied depending on real time power requirements, whereas with totally onboard power systems, the rover primary power system must be designed to the maximum power requirements, adding unnecessary weight to the rover for some missions.

Rover missions could be designed that demand power significantly greater than that available from radioisotope thermoelectric generators (RTGs), fuel cells, or batteries for enabling new mission scenarios.

Lunar Laser Propulsion

As materials processing, manufacturing, and habitats expand, transportation from the lunar surface to orbit will become a key activity and potentially a constraint on further lunar base expansion. Laser power transmission could have a dramatic impact on lunar transportation. In Fig. 3, a laser-powered rocket or orbital transfer vehicle (OTV) is shown. A laser beam is intercepted and used to heat hydrogen to approximately 15,000 K, producing a specific impulse (I_{sp}) of 1500 to 3000 sec (*Jones and Keeker, 1981; Krier and Glumb, 1986*). Such a rocket would not need to carry oxidizer, thus substantially reducing weight.

The thrust, F_T , of a laser propulsion engine is given by

$$F_T = 2 P_{\text{jet}}/g I_{sp} \quad (1)$$

where P_{jet} is the engine efficiency times the incident laser power, g , the acceleration due to gravity, is 9.8 m/sec², and I_{sp} is typically 1500 sec. For direct launch from the lunar surface, the thrust must be greater than the vehicle weight times $g/6$ where $g/6$ is the Earth acceleration of gravity divided by 6 for lunar environment. A calculation of the payload, m , that can be delivered to a very

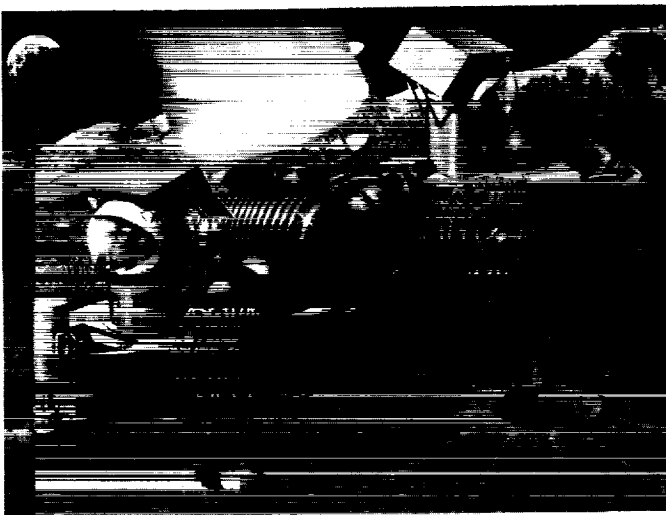


Fig. 2. A laser photovoltaic-powered lunar rover.



Fig. 3. A laser propulsion vehicle lifting high-value cargo from the lunar surface.

low lunar orbit (just above the surface, assuming that the engine mass in kilograms is equal to the engine thrust in N divided by 8, gives (Frisbee, 1984)

$$\frac{m(\text{payload})}{p(\text{laser})} = 25 \frac{\text{kg}}{\text{MW}} \quad (2)$$

when 50% of the laser power, p , is converted into jet exhaust power by an engine with a I_{sp} of 1500 sec. If a 10-MW laser is available, then 250 kg of payload could be launched to low lunar orbit. From there, laser power would be used to change the orbit and inclination as required.

Figure 4 shows the relationship between the ratio of payload mass to laser power (kg/MW) and laser power (MW) for launching payloads from the lunar surface to low lunar orbit. The laser propulsion engine is assumed to be 50% efficient, that is, 50% of the incoming laser power is converted into kinetic energy of the H_2 propellant. Propulsion is shown for engine mass equal to $(F_T)^{1.15}/8$, $F_T/8$, and zero (Frisbee et al., 1984).

Also shown is the time required to go from the lunar surface to lunar orbit for the zero engine mass case. Looking at the ideal case of engine mass equal to zero, we see the relationship between I_{sp} , launch time to low lunar orbit, and the amount of H_2 fuel per kilogram of payload expended. Going from an I_{sp} of 2000 sec to an I_{sp} of 1000 sec increases the engine thrust but also expends more H_2 fuel per kilogram of payload. Note that the launch time to low lunar orbit is nearly the same for all three cases. Thus, higher I_{sp} laser propulsion engines are desirable, since they more efficiently use the valuable H_2 fuel.

Lunar Surface Modification

Another laser application would use the beam directly to modify the lunar landscape. In the previous 1984 NASA/NAS Lunar Base Symposium, the desirability and potential applications, of molten regolith were addressed in several presentations (Rowley and Neudecker, 1985; Khalili, 1985). Large numbers of rocket launches from the lunar surface can create dust clouds that can travel considerable distances, deposit material on solar panels, radiators, and other structures, and degrade their performance. Thus, some method for hardening the lunar surface is needed. In Fig. 5, a beam from the orbiting lunar power station is absorbed

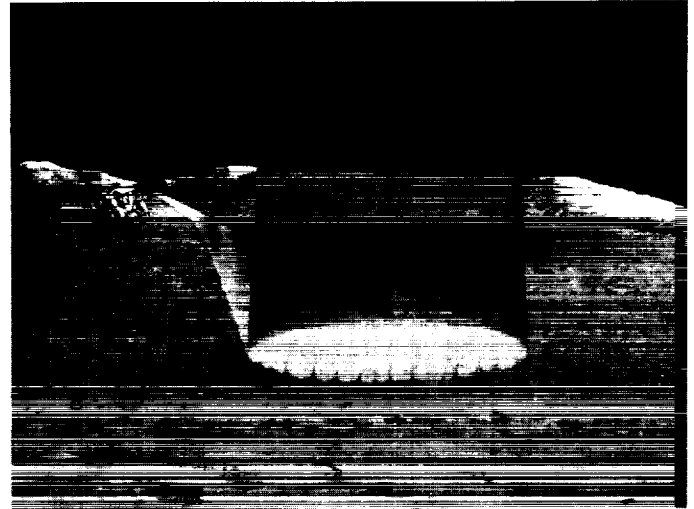


Fig. 5. A high-intensity laser beam heating the lunar surface to the melting point. After cooling, a hard glassy surface is created for roadways and launch pads.

by the lunar surface. The surface is heated to the melting temperature and then cooled, resulting in a thin, solid glassy surface. Such surfaces are dust free and thus could be used as "paved" surfaces for launch pads, roadways, and building sites. Also, glassmaking for construction and containers could be additional benefits.

A first-order analysis was made of lunar surfaces heated by laser beam absorption in order to indicate the thickness of the glass surface, assuming a laser input power of 1 MW. To characterize the time rate of change of surface temperature (T) as a function of depth (z), the following equation was used

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C_p} \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) \quad (3)$$

where ρ is the regolith density (2 g/cm^3), C_p is the specific heat (1.26 J/g-K), and k is the thermal conductivity (0.021 W/sec-cm-K). Nominal values of the thermal parameters k and C_p have been chosen based on lunar sample studies (Stimpson and Lucas, 1972), and for these preliminary calculations they are held constant. The initial condition is $T(z,0) = 350 \text{ K}$, which is representative of lunar surface daylight temperatures. The boundary conditions are

$$k \left(\frac{\partial T}{\partial z} \right)_{z=0} = -q + \epsilon \sigma [T(0,t)]^4 \quad (4)$$

and

$$T_{z \rightarrow \infty} - T(z,0) = 350 \text{ K} \quad (5)$$

where

$$q = 0.8P/\pi R^2 \quad (6)$$

It is assumed that 80% of the incident laser power, P (assumed to be 1-MW), is absorbed by the lunar soil in a circular area of radius R . The symbol ϵ is the emissivity (0.8), and σ is the Stefan-

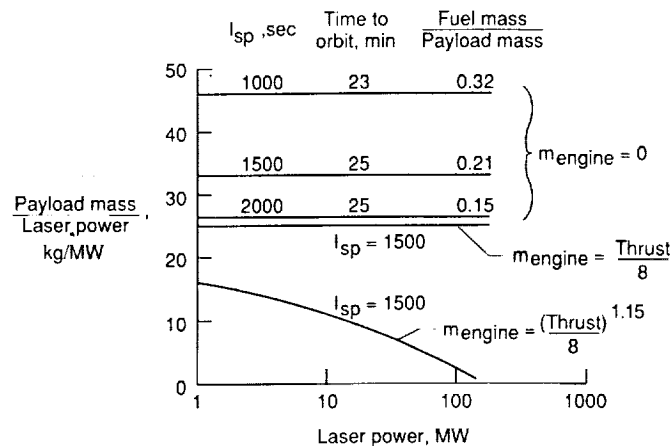


Fig. 4. Surface-to-low lunar orbit laser propulsion. Conversion efficiency = 50%.

Boltzmann constant. The maximum surface temperature is defined when the absorbed surface energy is equal to the reradiation energy or

$$T_{lim} = (q/\epsilon\sigma)^{1/4} \quad (7)$$

Figure 6 shows the results of calculations of surface temperature as a function of surface depth for absorbed energy of 800 kW in either a 1- or 0.75-m-diameter spot. Laser irradiation times extend from 10 to 40 min. T_{melt} is the typical melting temperature of the lunar soil (Lin, 1985); thus, temperatures above T_{melt} result in a hard glassy surface. For a 1-m spot size in Fig. 6 and a 10-min irradiation time, a glassy surface of approximately 2-cm depth can be achieved. This may be sufficient depth for roadways and launch pads, depending on vehicle mass. By increasing the energy density with a 0.75-m spot diameter, the irradiation time can be reduced for a given depth z . For larger lunar surface areas and greater depths, much higher laser powers are required.

Power for Lunar Base

Significant electrical power will be needed at the lunar base, on the order of 1 MW_e, to accomplish a variety of missions, including an oxygen production plant, mining and refining lunar materials, habitat life support systems, and transportation. Nuclear reactors with Sterling engines have been proposed to meet the power need. Such technology requires a fixed permanent lunar location with significant radiation protection problems. An alternative approach would be to put the solar- or reactor-driven laser in lunar orbit and beam the power to a variety of lunar locations.

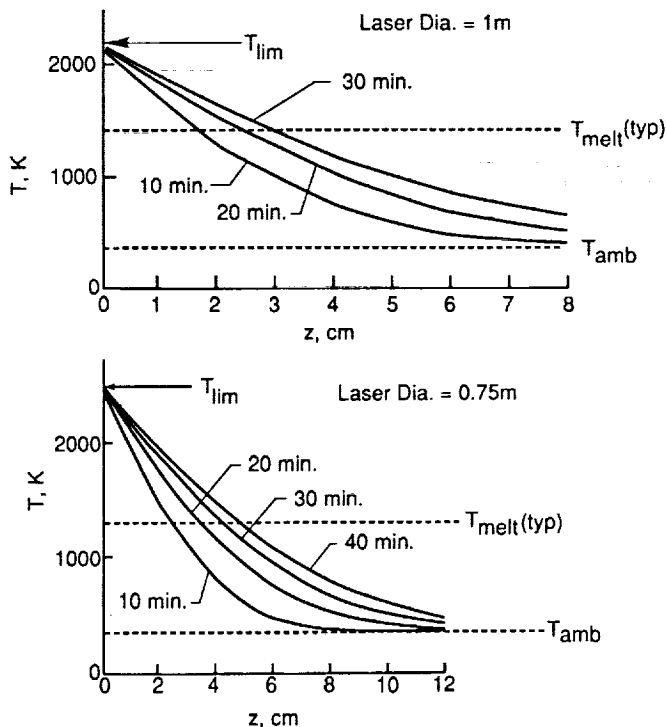


Fig. 6. Surface temperature as a function of surface depth.

In Fig. 7 a remote lunar site is being excavated by equipment powered by a laser beam. Since the vehicle power system is compact and lightweight, the excavation equipment could be highly mobile and remotely controlled. Temporary human habitats could also receive their power through laser transmission. The figure also shows a glass-brick-fabrication vehicle producing construction materials for future buildings.

A long term presence on the lunar surface will require extensive power for human habitats. Figure 8 shows such a major habitat, which houses approximately 100 people and is powered by a laser photovoltaic converter. The converter is a flat plate design mounted to track the lunar orbiting laser station. Two photovoltaic converters are needed to have continuous power as one laser station goes below the horizon and another comes above the opposite horizon. If multiple laser stations are not available, then energy storage must be added to the habitat.

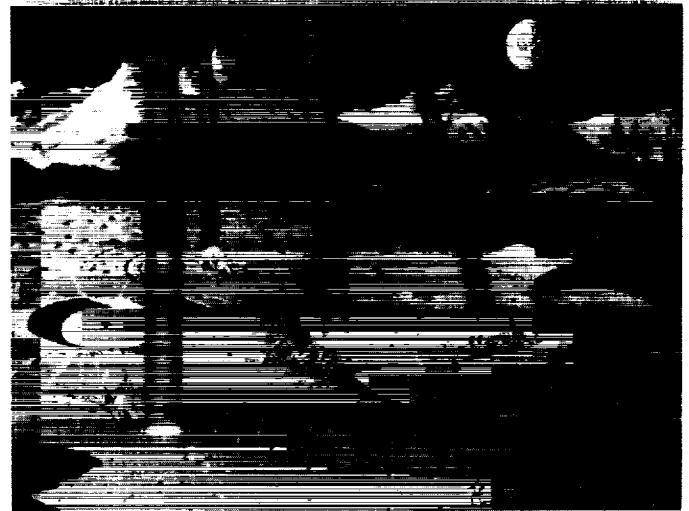


Fig. 7. Multiple laser beams powering excavation vehicles at a remote lunar site.

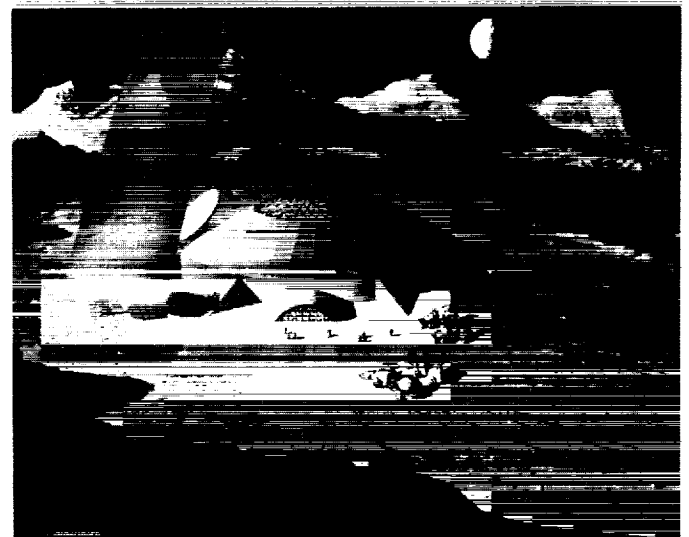


Fig. 8. A lunar human habitat powered by laser photovoltaics.

CONCLUSION

Laser power transmission to the lunar surface could power a wide variety of missions including prospecting rovers, surface-to-orbit propulsion, lunar surface hardening, excavation equipment, and human habitats. Using simple high power photovoltaic converters would permit more emphasis to be placed on the mission rather than its primary power requirements. Future studies may reveal other missions enabled by laser power transmission.

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