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Ground-Based and Space-Based Laser Beam Power Applications

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GROUND-BASED AND SPACE-BASED LASER BEAM POWER APPLICATIONS

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INTRODUCTION

Laser beam power systems with a beam directed at a photovoltaic (PV) array far removed from the laser source can provide substantial mass benefits over conventional solar-based PV array power systems for some missions. The following mass comparisons of solar-based power systems to laser-based power systems will detail application areas where a particular power system is preferred.

A laser beam power system consists of a beam generator and a beam receiver. For a ground- (Earth-) based laser system, the beam generator is a free-electron laser with controlling adaptive optics (ref. 1). The free-electron laser receives its electrical power from the grid. For a space-based laser system (SBLS) (refs. 2 and 3), the beam generator is an array of laser diodes, e.g., GaAs, coupled to a PV array for electrical power. In both laser systems, the beam receiver is a PV array. The PV cells in these receiver arrays are specially fabricated to efficiently convert the monochromatic laser light into electricity for the user. Included are electrical and thermal management system ancillaries.

The solar-based power system consists of a PV array containing PV cells tuned to the Sun's spectrum. Again, appropriate power management subsystems are required as well as an appropriately sized energy storage subsystem.

The mass benefits of a laser system (ground- or space-based) over a competing solar-based system originate from two inherent, comparative aspects of the laser system: (1) elimination or reduction of energy storage requirements and (2) increased power from comparably sized power receivers or comparable power to decreased mass of power receivers. The magnitude of the mass advantage is dependent not only on the subsystem and component performance assumptions but also on the energy storage requirements of the solar-based power system.

The applications of interest are shown in figure 1. Here, the ground-based lasers will supply beam energy to a spacecraft's PV array in cislunar space or on the Moon. Space-based lasers will supply beam power to surface or near-surface elements such as outposts, rovers, airplanes, and orbiting or flyby spacecraft.

Discounting the mass of the laser generator in a ground-based laser system, a laser-based power system may be less massive than a solar-based system in cislunar space. However, the ground-based laser beam cannot effectively reach beyond the Earth-Moon system. Space-based laser systems may be less massive than solar-based power systems at application distances less than five astronomical units (AU) from the Sun.

GROUND-BASED LASER SYSTEMS

Ground-based laser systems can provide power to many types of users that can be reached by the laser beam. It is beyond the scope of this report to discuss all possible applications. However, electrical (lunar surface) power and electric propulsion (low-Earth orbit to geosynchronous orbit (LEO to GSO)) applications will be discussed which indicate the breadth of applications.

Lunar Surface Power

A laser beam power system can eliminate an energy storage requirement by illuminating a PV array during eclipse or shadow portion of a mission. For example, the power from a PV array on the Moon can be the same whether illuminated by the Sun or lasers. However, the laser scenario will permit continuous illumination. A PV array illuminated by the Sun will experience two weeks of darkness. The concomitant requirement of energy storage greatly increases the mass which must be landed on the surface of the Moon. Figure 2 shows the mass advantage of a ground-based laser system providing kilowatts to megawatts of power on the lunar surface (ref. 1). The mass of the laser system is less than that of the solar-based system (marked PV-RFC for photovoltaics-regenerative fuel cells) at the lower power levels (~50 kWe). Based on mass considerations, the laser system appears more attractive than a nuclear reactor system beyond the 100-kWe power level. At 1 MWe, the landed mass of a laser-based system is nominally ten times less than the solar-based system and at least two times less than a nuclear system.

LEO to GSO Tug

A ground-based laser beam power system can provide a spacecraft with increased power with concomitant increased mission capability or performance options. Photovoltaic arrays illuminated by a laser beam can produce many times more power per unit area than solar-illuminated PV arrays. For example, a PV array may provide substantially more power to an electric propulsion system if the PV array is illuminated by a laser beam. This propulsion system, whether solar or laser illuminated, can be used for orbit raising from LEO to GSO after insertion into a LEO with an appropriate chemical propulsion system.

Figure 3 (ref. 1) shows the outbound and return transit times for one solar electric propulsion system scenario and two laser electric propulsion system scenarios. All three scenarios were conceived to raise a large spacecraft from different-altitude LEO's to GSO and back down to LEO. The assumptions shown in table I (ref. 1) result in laser electric propulsion trip times shorter than solar electric propulsion trip times. These shorter trip times are a result of the higher power level achievable with a laser-illuminated PV array.

SPACE-BASED LASER SYSTEMS (SBLS's)

A ground-based laser system can provide high power and reduce the energy storage required, but only in cislunar space. As shown in figure 4, the intensity of a ground-based laser's radiation at 0.5 AU from Earth (even at the 10-MW upper limit of the ground laser) is close to five orders of magnitude lower than solar intensity; therefore, expecting a mass benefit from a ground-based laser system beyond cislunar space is unrealistic. Space-based laser systems should then be considered. Here, the laser beam is generated in space and is directed toward a receiver at the mission site, (see fig. 1). Such a scenario may allow a Mars surface rover continuous roving capability without the need of a 12-hr energy storage system. The same advantage would exist for a surface outpost or an airplane flying in the martian atmosphere. Also, an SBLS could provide power to a planet orbiter or flyby spacecraft, should it be shadowed from the Sun during portions of the mission. In an attempt to quantify the mass advantage of an SBLS, a brief analysis (discussed below) was performed.

The magnitude of the mass savings of an SBLS over a solar-based power system will depend heavily on the performance level assumed for the various technologies, the eclipse/shadow period, and the distance from the Sun. The SBLS consists of a laser generation portion (PV array, radiator, diode laser array and electrical power management) which may or may not be displaced from the laser-to-electric conversion portion (PV array and electrical power management). The solar-based system consists of a solar-to-electric conversion portion (PV array and electrical power management) and a co-located energy storage portion with its electrical power management. Both the SBLS and the solar-based systems analyzed below can provide power to a load located in space (Space-to-Space) or on the surface of a planet, a planet's satellite, or an asteroid (Space-to-Surface).

Space-to-Space

Figures 5 and 6 show the impact energy storage requirements have on the specific power of solar-based systems and the impact the energy storage has on the specific power comparisons between an SBLS and solar-based power system. Technologies designated "maximum" (fig. 5) encompass near-term, higher-mass components while "minimum" technologies (fig. 6) include the far-term, lower-mass components for SBLS and solar-based systems. Table II lists the component mass assumptions used for the maximum and minimum mass analysis. As seen in figures 5 and 6, the energy storage requirements (defined here as the length of time the energy storage subsystem must supply power to a load) dictate crossover points where laser-based technologies would have a higher specific power than solar-based technologies. The mass savings of an SBLS occurs at distances less than 5 AU for maximum and less than 3 AU for minimum mass technologies and then only for the longer eclipse periods (~100 hr of energy storage).

The mass advantage of an SBLS extends to applications ranging from Venus (0.4 AU) to Pluto (40 AU) if the important figure of merit is the mass at the user-site rather than total system mass. Figures 7 and 8 show the user-site specific power comparison of an SBLS and a solar-based power system at various energy storage requirements. Data presented in figure 7 utilizes maximum mass assumptions shown in table II while figure 8 data utilizes minimum mass assumptions. Since a solar-based power system requires the total system to be placed on or near the user while the laser-based system requires only the PV array receiver and electrical power management subsystems be placed near the user, the specific power advantage of an SBLS can be large. Figure 7 (maximum mass assumptions) shows that an SBLS is better than or equal to a solar-based system when the solar-based system requires energy storage. For the minimum mass assumption (fig. 8), the SBLS always shows an advantage over a solar-based system whether energy storage is needed.

Space-to-Surface

For surface or near-surface applications, Mars was chosen for analysis. A laser beaming down through the martian atmosphere was assumed to be attenuated in a manner similar to sunlight. The metric of intensity loss is optical density. Figures 9 and 10 show the specific power comparisons of an SBLS and solar-based power system as a function of atmospheric attenuation. Again, maximum and minimum assumptions are used as shown in table II. In both figures, the mass advantage of an SBLS occurs only when large amounts of energy storage (~100 hr) are required in the solar-based power system and the optical density is less than 1 or 2. At an energy storage requirement of 10 hr (close to the 12-hr night period of the martian surface), an SBLS cannot match the specific power of a solar-based power system.

However, the solar-based power system will require the complete system to be placed near or on the load, whereas the SBLS will only require the laser-to-electric conversion portion (plus the electrical power management subsystem) of the power system to be placed on or near the load. For example, a solar-based power system delivering continuous power (with a 12-hr eclipse) to a surface rover during a minor dust storm (optical density of 0.7) can have an on-board specific power as high as 10 W/kg. An SBLS could provide the same continuous power with an on-board rover power system at 480 W/kg. These values were calculated using assumptions for minimum technologies shown in table II. Using maximum technologies shown in table II gives a solar-based system an on-board, specific power of 1.6 W/kg while an SBLS has an on-board, specific power of 10 W/kg. Therefore, for a martian rover with a continuous roving requirement, a power system based on laser beam power could be at least six times lighter than a solar-based power system (10 W/kg versus 1.6 W/kg).

An airplane flying above the martian atmosphere could also benefit from an SBLS. In this case, the optical density will be zero and the eclipse period will remain at 12 hr. Using minimum assumptions shown in table II gives a solar-based system an on-board specific power of 12 W/kg while an SBLS has an on-board specific power of 480 W/kg. Using maximum assumptions shown in table II gives the SBLS a specific power of 10 W/kg while the solar-based power system has a specific power of 1.7 W/kg. As with the rover, there is a six-times mass advantage for the SBLS. This reduction in the rover and airplane mass with a concomitant reduction in PV array area at the user site caused by higher incident intensity will permit more science (e.g., real-time video) and will facilitate pointing and maneuvering. If the load was a spacecraft operating above the atmosphere with a PV array sized for solar-based power, application of laser beam power may facilitate orbit changes requiring power levels beyond solar-based capabilities.

APPLICATION SUMMARY

The summary of analysis results is presented in table III. As can be seen, the benefits of laser beam power over solar-based power system technologies do exist. The benefits, whether time or specific power, are very dependent upon needs that drive the mission and maturity of the technologies used in analysis.

As seen in table III, there are reductions in trip times for spacecraft traveling between LEO and GSO for ground-based laser systems for cislunar space applications. A substantial mass savings can be realized for lunar surface systems.

Space-based laser systems may have a system mass benefit as well as a mass benefit at the user-site for applications near Mercury, Venus, Earth, or Mars. Beyond Mars, the mass advantage of the SBLS occurs only when the user-site mass is a major consideration. The mass advantage of an SBLS for Mars applications is shown in table III for rovers and airplanes. However, the advantage of an SBLS is at atmospheric optical densities less than 2, i.e., small or no dust storms. At optical densities greater than 2, the mass advantage of the SBLS disappears for total system mass figure of merits and is compromised for user-site figure of merits.

CONCLUDING REMARKS

Although they cannot effectively reach beyond cislunar space, ground-based laser systems may substantially increase the power and/or propulsion performance in cislunar space. Space-based laser systems may reduce mass by providing an eclipse period and provide power without the need for energy storage. This may cause a reduction in user-site mass or an increase in payload capabilities by providing for a high specific power receiver on a spacecraft or on surface elements. Once the "giggle" factor is overcome, the advantages of laser beam power comes into focus. Wireless power transmission via laser beam power can provide power to remote sites shaded from the Sun or sites where the size and mass of conventional solar-based systems are limited. Wireless transmission may find applications where continuous high power is desired without resorting to nuclear technology.

REFERENCES

1. Bozek, J.M., et.al.: Comparison of Selected Laser Beam Power Missions to Conventionally Power Missions, NASA TM–106110, 1993.

2. Lee, J.H.: Solar-Pumped Laser for Free Space Power Transmission. Free-Space Transmission, NASA CP–10016, 1989, pp. 137-152.

3. Lee, J.H.: Earth Orbit Laser Systems. Second Beamed Space-Power Workshop. R.J. Deyoung, ed., NASA CP–3037, 1989, pp. 377–381.

TABLE I.—SPECIFIC MASSES OF LASER AND SOLAR ELECTRIC PROPULSION ORBIT TRANSFER VEHICLES (EPOTV's)

[Support systems (e.g., structures and thermal) modeled after Mariner Mk II bus; advanced thrusters: Isp = 5000 sec, efficiency = 50 percent, NH_3 tankage = 0.12; 2500-kg payload to geostationary orbit.]

Subsystem	EPOTV, kg/kWe	
	Laser[a,b]	Solar[b]
Advanced thruster and power processing unit	0.5	0.5
Photovoltaic (PV) array	.7	9.6
PMAD and TCS	1.8	1.8
Total power and propulsion specific mass	3.0	11.9

[a]Self-annealing laser PV cells ten times more power per kilogram than normal solar cells.

[b]GaAs solar cell shielding of 20 mil front and 12 mil back.

TABLE II.—LASER-BASED AND SOLAR-BASED POWER SYSTEM ANALYSIS ASSUMPTIONS

Assumption parameters	Units	Mass assumption	
		Maximum	Minimum
Laser diode wavelength	μm	0.8	0.8
Laser diode intrinsic efficiency		30 percent	30 percent
Single laser diode	Power, W Height, cm Width, cm Depth, cm Mass, g	1 0.091 0.055 0.3 0.272	1 0.091 0.055 0.3 0.272
Insolation at 1 AU at 1 Sun at AMO	kW/M^2	1.35	1.35
PV array for solar conversion	Conversion efficiency Specific power at AMO, We/kg	14 percent at 0.4 AU to 20.5 percent at >2 AU 125	20 percent 300
Batteries for solar-based system	Turn-around efficiency Specific energy, W-hr/kg Discharge and charge time, hr each Depth of discharge	80 percent 40 0, 1, 10, and 100 60 percent	80 percent 200 0, 1, 10, and 100 100 percent
Power management for solar conversion	kg/kWe	20	1.76
Laser diode radiator	Radiator temperature, K Sink temperature, K Specific mass, kg/M^2 View factor Emissivity	250 200 2.7 2 0.85	250 5 2.7 2 0.85
Atmospheric absorption	Optical density	0.0 for space: up to 7 for surface	0.0 for space: up to 7 for surface
Location	Distance from Sun, AU Location, near planet	0.4 to 40 AU Mercury to Pluto	0.4 to 40 AU Mercury to Pluto
Laser-to-electric conversion subsystem	PV array conversion efficiency PV array specific power at 1 sun, We/kg Laser incident intensity, sun Power management specific mass, kg/kWe	20 percent 125 0.1 20	20 percent 300 10 1.76

TABLE III.—FIGURE-OF-MERIT PERFORMANCE SUMMARY OF LASER-BASED VERSUS SOLAR-BASED POWER SYSTEMS[a]

(a) Comparison of power system spacecraft trip time

Mission	Spacecraft trip time, day		Assumptions			
	Ground-based laser power system	Solar power system	IMLEO,[b] kg	GSO payload, kg	LEO orbit, km	Return mass to LEO, kg
LEO to GSO EPOTV tug	88	125	7000	2500	500	----
GSO to LEO EPOTV tug	44	80	----	----	500	4500
LEO to GSO EPOTV tug	32	89	7000	2500	4000	----
GSO to LEO EPOTV tug	17	55	----	----	4000	4500

(b) Comparison of space system specific power

User site	Specific power, W/kg			Assumption
	Space-based laser power system[c]		Total solar power system	Duration of eclipse, hr
	Total system	Subsystem at user site only		
Lunar surface	---------	[d]60	3.0	336
Near-Mercury	1.7 to 8.0	10 to 480	0.24 to 2.0	100
Near-Venus	1.5 to 7.0	10 to 480	0.24 to 2.0	100
Near-Earth	1.4 to 5.8	10 to 480	0.24 to 2.0	100
Near-Mars	1.2 to 4.1	10 to 480	0.24 to 1.9	100
Near-Jupiter	0.27 to 0.66	10 to 480	0.22 to 1.4	100
Near-Saturn	0.077 to 0.18	10 to 480	0.17 to 0.80	100
Near-Uranus	0.020 to 0.045	10 to 480	0.092 to 0.285	100
Near-Neptune	0.0089 to 0.020	10 to 480	0.052 to 0.138	100
Near-Pluto	0.0050 to 0.011	10 to 480	0.032 to 0.080	100
Mars surface (rover)[e]	0.62 to 2.1	10 to 480	1.6 to 10	12
Near-Mars (airplane)[f]	1.2 to 4.1	10 to 480	1.7 to 12	12

[a]Shaded areas are judged as best architecture when total system mass or subsystem mass are critical.
[b]Initial mass in low-Earth orbit.
[c]Subsystems at user site plus laser generator subsystem.
[d]Ground-based laser system.
[e]Optical density is 0.7.
[f]Optical density is 0.0.

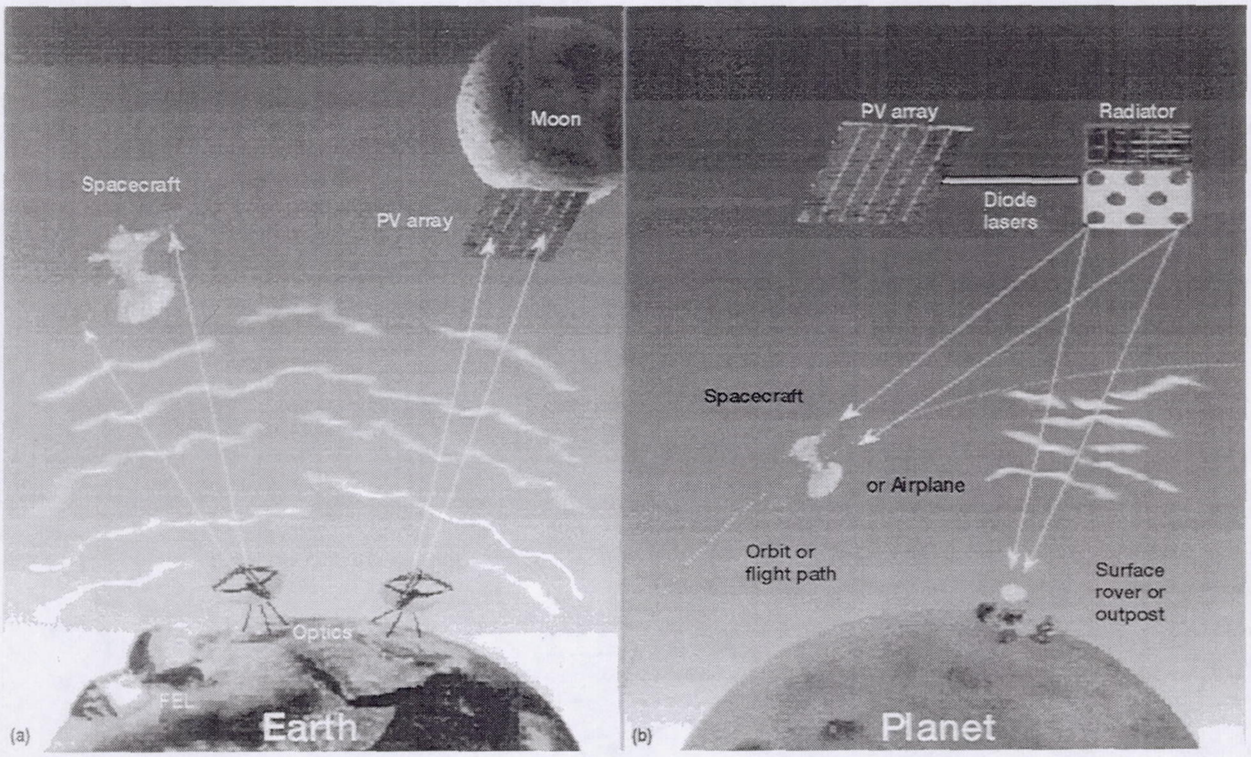

Figure 1.—Laser systems. (a) Ground based. (b) Space based.

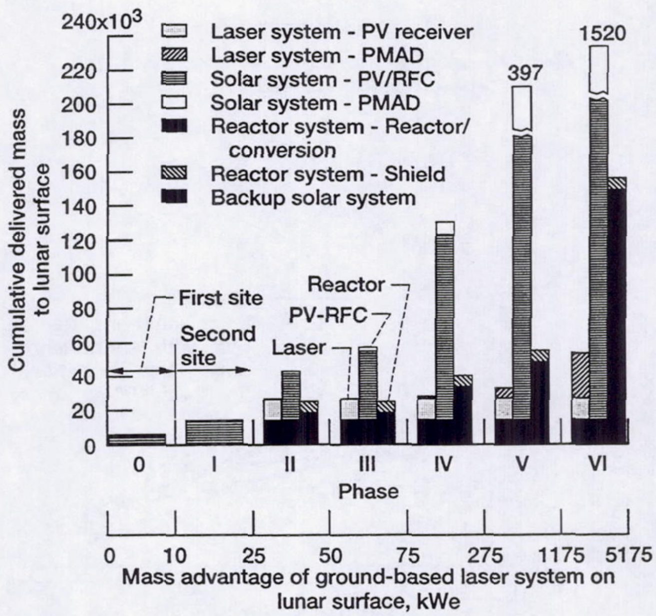

Figure 2.—Lunar surface power system options (one central power station for habitat and ISRU area).

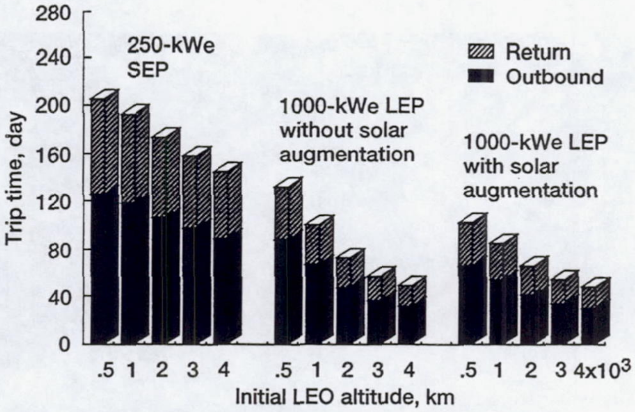

Figure 3.—LEO to GSO trip times for OTV tug (7000-kg-class OTV).

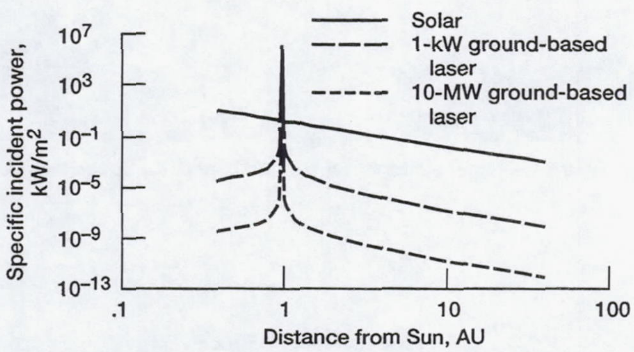

Figure 4.—Incident power (0.85-μ laser: 12-m-diam ground-based laser transmitter).

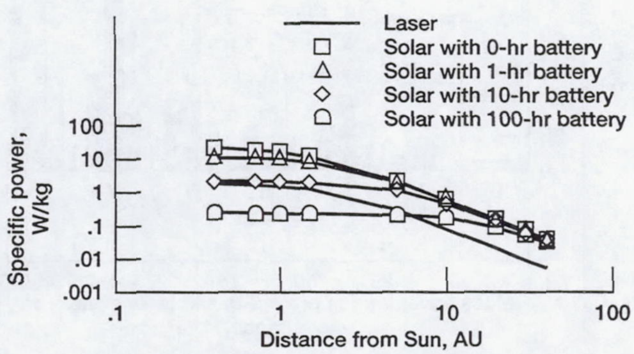

Figure 5.—Space power systems at maximum mass assumptions.

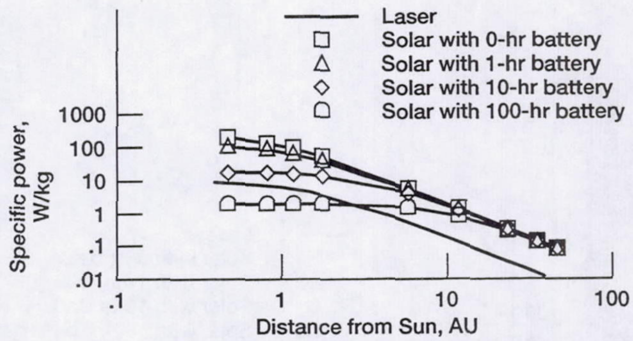

Figure 6.—Space power systems at minimum mass assumptions.

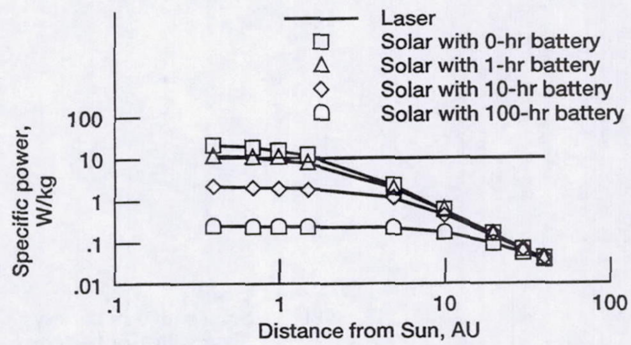

Figure 7.—Space power systems at maximum mass assumptions for user-site subsystem.

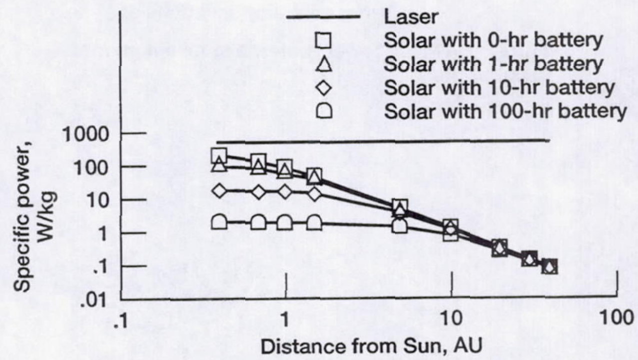

Figure 8.—Space power systems at minimum mass assumptions for user-site subsystem.

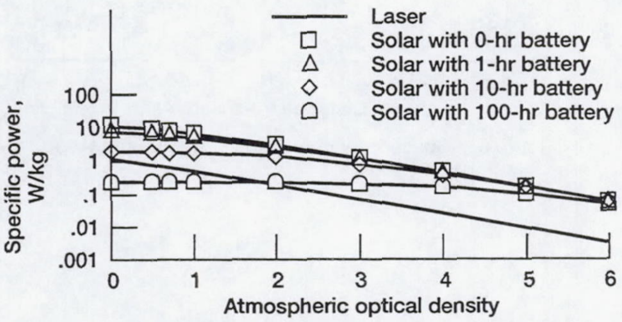

Figure 9.—Mars power systems at maximum mass assumptions.

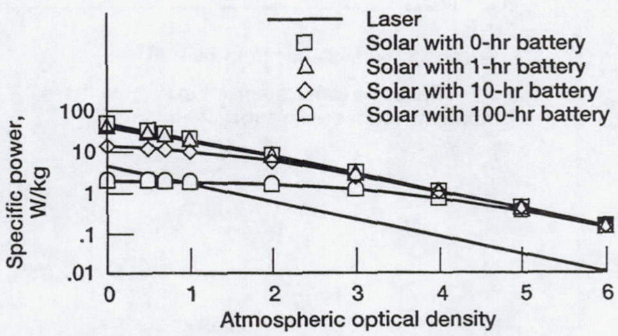

Figure 10.—Mars power systems at minimum mass assumptions.

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A space power system based on laser beam power is sized to reduce mass, increase operational capabilities, and reduce complexity. The advantages of laser systems over solar-based systems are compared as a function of application. Power produced from the conversion of a laser beam that has been generated on the Earth's surface and beamed into cislunar space resulted in decreased round-trip time for Earth satellite electric propulsion tugs and a substantial landed mass savings for a lunar surface mission. The mass of a space-based laser system (generator in space and receiver near user) that beams down to an extraterrestrial airplane, orbiting spacecraft, surface outpost, or rover is calculated and compared to a solar-based system. In general, the advantage of low mass for these space-based laser systems is limited to high solar eclipse time missions at distances inside Jupiter. The power system mass is less in a continuously moving Mars rover or surface outpost using space-based laser technology than in a comparable solar-based power system, but only during dust storm conditions. Even at large distances for the Sun, the user-site portion of a space-based laser power system (e.g., the laser receiver component) is substantially less massive than a solar-based system with requisite on-board electrochemical energy storage.

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