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TO CONVENTIONALLY POWERED MISSIONS

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SUMMARY

Earth-based laser sites beaming laser power to space assets have shown benefits over competing power system concepts for specific missions. Missions analyzed in this report that show benefits of laser beam power are low-Earth-orbit (LEO) to geosynchronous-Earth-orbit (GEO) transfer, LEO to low-lunar-orbit (LLO) cargo missions, and lunar-base power.

Both laser- and solar-powered orbit transfer vehicles (OTV's) make a "tug" concept viable, which substantially reduces cumulative initial mass to LEO in comparison to chemical propulsion concepts. In addition, electric propulsion OTV's powered by a laser beam have shorter trip times to and from GEO than do competing OTV's powered solely by the Sun. A round-trip savings of 3 months was calculated for the use of a laser OTV tug instead of a solar OTV tug. Lunar cargo missions utilizing laser electric propulsion from Earth-orbit to LLO show substantial mass saving to LEO over chemical propulsion systems.

Lunar-base power system options were compared on a landed-mass basis. Photovoltaics with regenerative fuel cells, reactor-based systems, and laser-based systems were sized to meet a generic lunar-base power profile. A laser-based system begins to show landed-mass benefits over reactor-based systems when proposed production facilities on the Moon require power levels greater than ~300 kWe.

The performance of conventional solar cells, when illuminated by laser light, shows a potential efficiency improvement of a factor of 2. The greatest challenge to achieving this improvement is increasing the cell's low response to pulsed free-electron laser illumination at very high intensity levels.

Benefit/cost ratios of laser power systems for an OTV, both to GEO and LLO, and for a lunar base were calculated to be greater than 1. Here benefit was defined as the transportation cost savings, and cost was defined as the cost of installing and operating four Earth laser sites.

INTRODUCTION

The laser beam power concept presently undergoing extensive analyses and technology demonstration is called SELENE (Space Laser Energy). This concept envisions numerous Earth-based laser sites propagating, in a controlled manner, approximately 10 MW of laser power through the atmosphere to space assets. Controlled propagation of the free-electron laser (FEL) beam is accomplished by an adaptive optics system that compensates for real-time measurement of atmospheric distortions. Four laser sites will adequately cover the Earth-Moon space.

The laser sites on Earth will illuminate special photovoltaic (PV) cells in an array that converts laser power into usable electric power. This resultant electric power will be available for low-Earth-orbit (LEO) to geosynchronous-Earth-orbit (GEO) electric propulsion, electric propulsion to low-lunar-orbit (LLO), lunar surface power, and Earth orbit power. However, all four missions could be accomplished by other more conventional technologies such as chemical propulsion, reactor-based power, and solar-based power. This paper compares laser beam power to conventional technologies for only LEO to GEO transfer, LEO to LLO transfer, and lunar-base power missions. Left for future analysis are the GEO and LEO power missions. (A list of acronyms and initialisms is given in appendix A to aid the reader.)

ELECTRIC PROPULSION MISSIONS

There are two generic propulsion missions that may benefit from laser electric propulsion (LEP). One is an orbit transfer vehicle (OTV) tug that will deliver a payload (e.g., a communications satellite) from LEO to GEO and then return to LEO for a repeat mission to GEO. The other is an electric propulsion cargo stage that will deliver a payload from LEO to LLO. The ultimate objective of this latter mission is to deliver cargo from Earth to the lunar surface via chemical propulsion to LEO, electric propulsion to LLO, and chemical propulsion from LLO to the lunar surface.

LEO to GEO to LEO Electrical Propulsion

Three OTV power system concepts, all based on electric propulsion, were modeled and compared: solar electric propulsion (SEP), LEP, and LEP with SEP augmentation. Nuclear electric propulsion was not analyzed because of the OTV tug's requirement of returning to LEO. The figures-of-merit chosen for comparison were trip times, both to GEO and back to LEO, as well as the initial and resupply mass to LEO.

Table I shows the specific masses input to quantify the performance of the SEP and LEP power systems. The laser-based electric propulsion OTV (EPOTV) has a specific mass of 3 kg/kWe, whereas the solar-based EPOTV has a specific mass of 11.9 kg/kWe, almost four times higher. This difference favoring the LEP systems is due primarily to the mass of the PV array: 0.7 kg/kWe for laser-based EPOTV systems and 9.6 kg/kWe for solar-based EPOTV systems. The laser-illuminated PV array is substantially lower in mass because of the increased efficiency of PV cells at laser wavelength, the higher incident intensity expected on the PV array, and the elimination of protective cover glass. None of these concepts use energy storage to reduce the effect of limited view angles.

The electric propulsion technology that was chosen is an advanced, electrodeless thruster with a nominal specific impulse of 5000 sec at 0.5 kg/kWe and 50-percent efficiency. The power management and distribution and thermal control system (PMAD/TCS) specific mass is 1.8 kg/We (1.4 kg/kWe for PMAD, 0.4 kg/kWe for TCS), assuming near-term electronics and advanced radiator technology. A more detailed discussion of these assumptions is presented in appendix B.

Figure 1 shows the resultant trip times for three EPOTV tug power system concepts—SEP, LEP, and LEP with SEP augmentation. Four Earth-laser sites were chosen to illuminate the LEP OTV tug:

White Sands Proving Grounds (U.S.A.), Morocco (N. Africa), Alice Springs (Central Australia), and Johnston Island (N. Micronesia). For this analysis, the allowable laser zenith angle was assumed to be ±60°, and the laser view factor was calculated to include an OTV plane-change from the 28.5° initial orbit inclination to the 0° inclination required in GEO. The OTV tug, whether SEP or LEP, was assumed to initially transport 7000 kg to LEO, including a 2500-kg satellite payload. The remaining 4500-kg tug would be sufficient for either a 250-kWe SEP system, a 1000-kWe LEP system, or a 1000-kWe LEP augmented with 100 kWe of solar electric power when the PV array is not in view of the Earth-based laser.

The LEP OTV tug takes 88 days to reach GEO from a 500-km LEO altitude and another 44 days to return to LEO, for a total round-trip time of 132 days. The SEP OTV tug takes 125 days to reach GEO and 80 days to return, for a total of 205 days. Augmenting the LEP system with SEP capability reduces trip times to 65 days outbound and 37 days to return, for a total of 102 days. Therefore, there is a maximum 103-day advantage for the LEP OTV system: it traverses the LEO-GEO-LEO distance in half the time as does an SEP OTV system. Starting altitudes greater than 500 km have reduced trip times (fig. 1) primarily because of the increased viewing time to the Sun or the Earth laser site per orbit. At starting LEO altitudes of 4000 km, trip times are drastically reduced for the LEP system: 32 days outbound with 17 days to return, for a total trip time of 49 days. The SEP OTV tug outbound trip time becomes 89 days with 55 days to return, for a total of 144 days. The outbound trip times of an LEP OTV tug augmented by SEP becomes 30 days, with a return time of 18 days, for a total of 48 days for a round trip. Here the LEP OTV maximum round-trip advantage over an SEP OTV system is 96 days; that is, the LEP OTV system traverses the LEO-GEO-LEO distance three times faster than an SEP OTV system.

Figure 2 shows results of the mass analysis. All three EPOTV concepts (SEP, LEP, and LEP with SEP) were calculated to be about 7000-kg initial mass in LEO (IMLEO). At low starting altitudes, all three OTV tug power concepts (SEP, LEP, and LEP with SEP) are compatible with an Atlas II AS expendable launch vehicle (ELV). At higher starting altitudes, the ELV may have to be a higher performance vehicle such as a Titan III. The resupply mass for subsequent LEO to GEO trips is sufficiently small (3500 to 4000 kg) that a Delta 7920 vehicle could be used to attain low initial orbit or an Atlas II AS class vehicle to attain higher initial orbits.

Earth to Lunar Surface Mission

Transportation requirements were estimated during the First Lunar Outpost (FLO) study performed early in 1992 by NASA. Though the requirements are not firm and an in-depth analysis is beyond the scope of this report, viable estimates are possible. Table II shows the stage masses needed to deliver about 35 000 kg to the lunar surface via an all-chemical propulsion system. The mass placed in LLO is 96 000 kg (61 000 kg for a lunar orbit insertion and descent stage plus 35 000 kg of payload). The IMLEO to put 96 000 kg in LLO is 242 000 kg, which includes the 96 000 kg needed to attain LLO plus 146 000 kg for the translunar injection (TLI) stage.

Table III shows the stage masses for a comparable mission using an LEP stage that replaces the chemical TLI stage and the need for a lunar orbit insertion burn. The LEP TLI stage is at 43 500 kg, and the absence of a lunar orbit insertion burn reduces the descent stage to only 42 000 kg. This translates to an IMLEO of 118 500 kg for an electric propulsion/chemical propulsion system compared with a similar all-chemical propulsion system at an IMLEO of 242 000 kg. Therefore, the calculated IMLEO savings realized by using a laser-powered electric propulsion TLI stage is over 123 000 kg for each mission to the lunar surface.

LUNAR SURFACE MISSION

A generic power profile was chosen as a basis for lunar power system technology comparisons. Figure 3 shows the cumulative power requirements as a function of lunar-base maturity. Phase 0 will be a small manned campsite preparing for a mature, productive base. After a permanent site is chosen from data obtained in phase 0, the base will grow through man-tended phases (phases I and II) into a permanent-presence phase (phase III) and on to productive phases (phases IV, V, and VI) where the resources of the Moon will be utilized. The campsite power level (phase 0) will be a mere 10 kWe, whereas permanent human presence will require 75 kWe. The in situ resource utilization (ISRU) phases will ultimately require an additional 5100 kWe.

Figure 4 compares the landed mass for the three power technologies analyzed: photovoltaics with regenerative fuel cell energy storage (PV/RFC), reactor systems, and laser-based systems. For the campsite (phase 0), which is assumed to have an anticipated launch at the turn of the century, PV/RFC's were chosen to be the power source. For phase I, a PV/RFC system was chosen again because we envision a need for reliable backup power as the lunar base grows at this new site. Starting with phase II, the three competing technologies were compared. Here, the PV/RFC option compares poorly with the alternatives because of its mass, 16 000 to 17 000 kg heavier than the laser and reactor systems. The laser system shows a distinct advantage of 12 000 kg less than the reactor option at 275 kWe, that is, when the ISRU phases begin in phase IV. At phase VI the mass of the laser option is ~100 000 kg less than the 141 000-kg reactor system.

The sites for the Earth-based lasers (which will beam power to the lunar base) were chosen to be four equally spaced, equatorial locations. If the four Earth laser sites are the same as those chosen for the OTV tug analysis discussed earlier, there will be times when no Earth site will be able to illuminate the lunar base. Therefore, a PV/RFC will be needed as backup. Initial estimates show that maximum outages of 92 min are expected, which translates to a maximum energy requirement of ~8000 kWe-hr for phase VI. With appropriate PMAD, the backup PV/RFC installed in phase I may satisfy this need. Other outages may be expected. However, the negative effects of cloud cover over an Earth site or malfunctioning equipment could be ameliorated by activating the 8900 kW-hr PV/RFC backup system. Up to 1.5 hr of emergency power would be available at maximum load. Thus, the choice of Earth laser sites will not unduly affect data shown in figure 4.

The lunar-base laser option assumes an 80-m-diameter circular photovoltaic array whose power output is directly related to the laser power transferred through the Earth's atmosphere. About 300 kW of laser power at each Earth site will be required for phase II. The power will grow to ~600 kW during phase III, to 1.6 MW at phase IV, and must be 7 MW at phase V. However, during phase VI each Earth site must be capable of ~30 MW of laser power or three times higher than the baseline 10-MW Earth sites. The lunar-base power technology comparison is discussed further in appendix C.

PHOTOVOLTAIC CONVERSION

Table IV presents results of an analysis on conversion efficiency obtained during tests of PV cells illuminated by several types of lasers. These data are based on experimental tests of state-of-the-art PV cells with corrections made to adjust the wavelength and incident intensity to 840 nm and 0.137 W/cm^2 respectively. The conversion efficiency of state-of-the-art PV cells, when illuminated by monochromatic light, has been demonstrated to be about a factor of 2 higher than that of sunlight illumination. However, this is for monochromatic, continuous laser insolation. If the laser insolation has characteristics of an FEL (i.e., pulsed format instead of continuous), the efficiency drops drastically because of the extremely high peak currents (1000 to 3000 peak-to-average ratio) and the concomitant response capability of PV cells. Inspection of table IV shows extremely low efficiencies for GaAs cells (<1 to 3 percent) illuminated by simulated FEL light, with Si cells much higher (13- to 21-percent range). Modifying the circuitry to smooth-out pulsed effects, via a capacitor, raises the efficiency of a GaAs cell a factor of 20 to 44 percent but only for the closely spaced pulses typical of a radiofrequency FEL. Negligible effects of this circuitry modification are seen for an induction FEL simulation, which characteristically has widely spread pulses.

The lower efficiencies for FEL laser illuminations can be overcome by proper PV cell design. As shown in figure 5, theoretical efficiencies of 60 to 70 percent may be achievable. Table IV shows the realistic efficiency goals for PV cell development. Here 45 percent for silicon is possible as is 60 percent for GaAs. Silicon cells have the advantage of operating at a long laser wavelength (1.06 nm), whereas GaAs cells can only operate at lower wavelengths but have a higher efficiency potential and lower temperature sensitivity.

COST

The quantified laser beam power benefits must be based on cost. Though a complete cost analysis is beyond the scope of this report, a short analysis is given in appendix D. For the three missions analyzed earlier (LEO to GEO to LEO electric propulsion, Earth to lunar surface, and lunar surface power) a desirable benefit/cost ratio has been calculated for laser beam power.

The benefit is defined as transportation cost savings between utilization of purely chemical propulsion stages and stages that use LEP in part or total. The cost, which excludes cost-of-money effects, is defined as the amortized capital cost of each Earth laser site plus the operating cost of each site. The operating cost includes maintenance as well as energy costs. The transportation cost savings are based on mass analysis of each mission and the concomitant cost to put a payload either in GEO or on the lunar surface. The Earth-based laser site cost, the transportation costs, and benefit/cost ratio analysis are given in detail in appendix D and summarized below.

For four Earth sites with a 10-year life, a \$500 million capital cost of the first Earth laser site with appropriate "learning curve" cost reductions for subsequent sites, and 100 payloads placed in GEO from a 500-km LEO at 10 payloads/year, the benefit/cost ratio is 2.7 in comparison to a purely chemical ELV mission to GEO. The benefit/cost ratio is 1.7 if the GEO mission begins from a 4000-km altitude instead of 500 km.

The lunar-base mission described earlier could realize a savings of \$9.1 billion over 10 years by relying on laser beam power instead of reactor-based power systems to provide over 5.0 MWe of power (see appendix D). The resultant benefit/cost ratio is 2.8, if the same Earth-site laser cost given earlier is assumed.

Replacing a chemical TLI stage with an LEP LEO to LLO to LEO OTV tug as part of an Earth-to-lunar-surface transportation system will save \$12 billion over 10 years (see appendix D). Therefore, the benefit/cost ratio for this mission alone (1 traverse per year for 10 years) is 3.9.

However, as discussed in appendix D, a \$500 million cost for the first Earth laser site may be optimistic. At \$500 million for the first site, the 10-year amortized cost of four Earth laser sites is \$3.3 billion, at \$1000 million it is \$5.1 billion, and at \$2000 million it is \$8.6 billion.

These potential increases in Earth site costs reduce the benefit/cost ratio significantly. The benefit/cost ratio for the LEO to GEO to LEO OTV mission drops from 1.7 to 1.1 for the \$1000 million scenario and to 0.7 for the $2000 million scenario given a 4000-km LEO start. For a 500-km LEO start the benefit/cost ratio drops from 2.7 to 1.7 for the $1000 million scenario and to 1.0 for the $2000 million scenario. The benefit/cost ratio for the lunar-base mission drops from 2.8 to 1.8 for the $1000 million scenario and to 1.1 for the $2000 million scenario. The benefit/cost ratio for the Earth to lunar surface mission drops from 3.9 to 2.5 and 1.5 for the $1000 million and $2000 million scenarios, respectively.

However, the total benefit/cost ratio remains above 1 for Earth site costs ranging from $500 million to $2000 million (table V). At the higher Earth-site cost, the efficacy of laser beam power may rely on quantifying the benefits of multiple missions sharing costs and definitive point designs.

As shown in table V the total benefit/cost ratio will always be greater than 1, given the performance assumptions and mission frequencies defined so far. However, in an effort to define the sensitivity of the benefit/cost ratios to mission frequencies, we varied the number of LEO to GEO to LEO missions, the number of Earth to lunar surface missions, and the lunar-base power requirement.

The results of this analysis are summarized in table VI. Here the point at which the benefit/cost ratio drops to 1 for each of the three missions is presented. For the LEO to GEO to LEO mission there must be at least 40 LEO to GEO to LEO transits over a 10-year period for the benefit/cost ratio to be greater than 1 given a first Earth laser site cost of $500 million. There must be at least two cargo missions to the Moon in the 10-year period, and the lunar power requirement must be greater than 2 MWe given the same Earth laser site cost. If all these conditions are met, each mission will have a benefit/cost ratio greater than 1. Of course, at a cost of $2000 million for the first Earth laser site, the performance and frequency requirements are much more challenging (table VI).

Yet to be factored into the benefit/cost ratio totals are the effects of the two remaining missions: GEO power and LEO power. We expect significant benefits from the laser beam power for the LEO power missions (because of the number of LEO spacecraft launched per year) and less significant benefits for the GEO power missions. Also, yet to be factored into the benefit/cost analysis are the cost differentials between laser-based and conventional flight hardware.

CONCLUSIONS

The cost benefits of Earth-based lasers beaming power to certain space assets have been quantified. The performance increase of these space assets has been documented as increases in measurable figures-of-merit.

LEP OTV tugs periodically moving 2500-kg payloads from LEO to GEO can substantially reduce the trip times from those for SEP systems. At a low starting LEO altitude (500 km), the LEP OTV tugs, with or without SEP augmentation, have round-trip times of 3.5 to 4.5 months. Comparable SEP OTV tugs have trip times close to 7 months. At higher starting LEO altitudes (4000 km), the LEP systems have round-trip times on the order of 1.5 months, whereas the SEP systems have round-trip times on the order of 5 months. In summary, an OTV tug weighing 7000 kg (4500-kg platform plus 2500-kg payload) and based on LEP can traverse the LEO to GEO to LEO space in one-third to one-half the time (a 2.5- to 3.5-month savings) that it takes a comparable SEP OTV tug.

Utilizing a LEO to LLO electric propulsion stage for Earth-to-lunar-surface missions has shown benefits over conventional propulsion systems. This analysis shows about a 100 000-kg IMLEO savings utilizing an LEP LEO to LLO stage instead of a conventional all-chemical transportation system when ~30 000 kg is placed on the lunar surface.

The comparison of a lunar surface power system based on conventional solar (PV/RFC), reactor, and laser (PV array) technologies shows a large landed mass benefit for laser technology at power levels beyond ~300 kWe. A specific lunar-base power profile shows the laser technology has a landed mass of 14 000 kg at the 275-kWe level, whereas a PV/RFC has a 115 000-kg mass and the reactor-based system has a 26 000-kg mass. At higher power levels (~1 MWe), the laser system's mass is only ~20 000 kg, whereas the reactor system is 40 000 kg and the PV/RFC is beyond consideration at 400 000 kg.

The effectiveness of laser power for space assets depends heavily on cost amortization of the Earth-based laser sites over several mission scenarios in comparison to the cost of discrete "onboard" power systems for these same missions. The cost of each 10-MW Earth laser site includes fabrication, maintenance, staffing, and electrical power for each site that will beam power to space via a 10- to 12-m adaptive optical system. Preliminary calculations show the amortized cost to be between \$330 and \$860 million/year for a 10-year life expectancy of four Earth sites.

For a comparison of transportation savings (benefits) with Earth laser site costs, the benefit/cost ratio varies between 4.5 and 5.5 for the LEP OTV tug (100 missions) and lunar-base power (10-year mission) taken together. Factoring in the benefit of an LEP LEO to LLO stage of an Earth to lunar surface cargo mission replicated 10 times, may increase the benefit/cost ratio to the 8.4 to 9.4 range. Increasing the Earth site capital cost from \$500 million to \$2000 million for the first site reduces the benefit/cost ratio for all three missions from the 8.4 to 9.4 range to the 3.3 to 3.6 range. These lower benefits may require point-designs to confirm them.

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APPENDIX A

ACRONYMS AND INITIALISMS

ELV	expendable launch vehicle
EPOTV	electric propulsion OTV
ETO	Earth to orbit
FEL	free-electron laser
FLO	First Lunar Outpost
GEO	geosynchronous Earth orbit
IMLEO	initial mass in low Earth orbit
ISRU	in situ resource utilization
LEO	low Earth orbit
LEP	laser electric propulsion
LLO	low lunar orbit
OTV	orbit transfer vehicle
PMAD	power management and distribution
PPU	power processing unit
PV	photovoltaic
PV/RFC	photovoltaics with regenerative fuel cell energy storage
SELENE	Space Laser Energy
SEP	solar electric propulsion
TCS	thermal control system
TLI	translunar injection

APPENDIX B

SPECIFIC MASS OF POWER SYSTEM FOR OTV TUG

The specific mass of the OTV tug power system, whether laser-based or solar-based, was derived from technology forecasts. Top level delineation of specific mass is shown in table I.

The electric propulsion thruster and associated power processing unit (PPU) performance values shown in table I for the SEP and LEP missions are for an advanced system based on an electrodeless concept being developed. Table VII shows the figures-of-merit of several competing electric propulsion concepts. The advanced concept chosen as the baseline has the highest specific impulse, the lowest specific mass, one of the highest thrust ranges, and the longest life.

The PV array technology chosen for both the SEP and LEP concepts is based on GaAs photovoltaic cells. These cells are assumed to be ~20-percent efficient at air mass zero (AM0) insolation (140 W/m^2). For laser illumination the efficiency of a tuned GaAs cell is assumed to increase to 50 to 60 percent at an intensity 10 times that of AM0. A redesigned PV cell that performs at this high intensity and efficiency under pulsed FEL illumination was assumed. However, the PV cell temperature is expected to be high because of the high intensity, thereby reducing the efficiency to 20 percent. Over the cell's lifetime, this reduction in efficiency is more than compensated for by anticipated advantages discussed later. For SEP missions, the PV cells must be protected from degrading radiation. Therefore, significant radiation shields, in the form of cover glass, are attached to each cell. The cover glass limits damage to about 15 percent for the first round-trip through the radiation belts at the expense of added PV array mass. The LEP system, for a similar Van-Allen Belt traverse, is assumed to require no cover glass because the high operating temperature of the PV cell is expected to anneal out any radiation damage. Taking into account the efficiency, insolation difference, and cover glass requirements, the power/unit area or power/unit mass of the PV cell array is 13 times higher for the LEP system.

As shown in table I, the specific mass of the PMAD and TCS is estimated at 1.8 kg/kWe for both SEP and LEP OTV tugs. The PMAD alone was estimated at 1.4 kg/kWe with the distribution among components shown in table VIII. The major contributor is the switching unit at 0.9 kg/kWe. Should a concept emerge requiring minimal or no switching of 1 MW of power from the PV array, the switching unit mass may be reduced. As a lower limit, the PMAD system may not be needed at all if one assumes a direct coupling of PV array power to the thruster's PPU. The effect on LEO to GEO to LEO OTV tug missions is discussed next with the effect on Earth to lunar surface missions deferred.

A major contributor to the specific mass of an electric propulsion system resides in the PMAD and TCS subsystems. These subsystems assume the need for heavy switching components in the PV array (see table VIII). However, if one assumes direct input of power from the PV array into the electric propulsion thruster as a lower limit (i.e., no PMAD necessary), the specific mass of the LEP system drops from 3.0 to 1.6 kg/kWe (0.4 kg/kWe for the TCS, 0.7 kg/kWe for the PV array, 0.5 kg/kWe for the thruster/ PPU, and 0.0 kg/kWe for the PMAD). At this lower specific mass level, the outbound trip times for an LEP system without solar augmentation drops to 65 from 88 days for a starting LEO altitude of 500-km and to 24 from 32 days for starting LEO altitude of 4000-km. This represents an outbound trip savings of 23 days for 500-km LEO starts and an 8-day savings for 4000-km LEO starts. Utilizing 1.6-kg/kWe specific mass instead of 3.0 kg/kWe will result in comparable savings for an LEP system augmented by an SEP system. However, the savings in outbound trip times due to the elimination of PMAD requirements is not as great for the SEP concept since the specific mass will only drop to 10.5 from 11.9 kg/kWe. Also, a reduced specific mass will reduce the IMLEO. Yet to be determined is the practicality of directly coupling the PV array to a thruster's PPU. A point-design may be necessary.

The TCS at 0.4 kg/kWe (see table VIII) includes a radiator and associated fluids and controls. The rejected thermal power assumed for radiator sizing was based on energy efficiency quotations supplied by the thruster/PPU manufacturer and was assumed to mirror power efficiencies (fig. 6). An advanced pulsed inductive thruster was assumed. The energy efficiency is ~70 percent for electrical components of the thruster (99.9 percent for silicon control rectifiers (SCR's), 80 percent for inductors, and 86.9 percent for field coils). However, additional thermal rejection is required to accommodate the exit beam's thermal component. It is assumed that 25 percent of the beam's thermal energy will be reflected back into the thruster. The overall efficiency of the thruster/PPU system, calculated as the ratio of directed-beam energy to input energy, is at the 35-percent level. Additional components of the exit beam's energy, if added to the directed-beam energy, result in an overall efficiency of 70 percent. For electric propulsion performance calculations, an efficiency of 50 percent was chosen midway between 36 and 70 percent. For thermal calculations, however, the efficiencies of electrical energy and reflected thruster thermal energy were used. This resulted in a rejection requirement for the thruster/PPU subsystem of 1.0 kWt at 350 K and 371 kWt at 500 K for a 1-MWe electric propulsion system. The radiator performance at these levels assumed advanced graphite composite structures at 4 kg/m^2 of sail area. For comparison one must realize that state-of-the-art radiators are at the 12-kg/m^2 level, three times heavier than the advanced technology assumed. Typical performance values for these two types of radiators are shown in table IX. The mass of the radiator's fluids and pumps is assumed to be 25 percent of radiator mass as in a typical pumped loop system, and it is assumed that the heat pipe system used in this analysis will require equivalent mass penalties.

Therefore, the total specific mass of the electric propulsion OTV tug is 3.0 kg/kWe (PV = 0.7 kg/kWe, PMAD = 1.4 kg/kWe, TCS = 0.40 kg/kWe, and thruster/PPU = 0.5 kg/kWe) for a laser-based power system and 11.9 kg/kWe (PV = 9.6 kg/kWe, PMAD = 1.4 kg/kWe, TCS = 0.40 kg/kWe, and thruster/ PPU = 0.5 kg/kWe) for solar-based power systems.

APPENDIX C

LUNAR-BASE SURFACE POWER TECHNOLOGY OPTIONS

Before lunar power system technologies can be compared, a power requirement must be established. To date, two major studies have established very diverse power requirements for a lunar base. The "90 Day Study" performed by NASA in the late 1980's showed a gentle, time-dependent, power profile starting at the 12- to 25-kWe level and increasing to the 400 to 500-kWe level. The FLO study, a NASA study that began in early 1992 as a somewhat conservative lunar mission, requires a lunar power system with a steady power level of 10 kWe with, as yet, undefined growth requirements. Figure 2 shows the assumed power profile for a generic lunar base. The generic base starts with low-level campsite power similar to FLO. The growth scenario chosen includes aspects of the "90 Day Study," but goes beyond this with a very aggressive ISRU infrastructure. The time frame for the various phases is left open; it will depend on NASA's vision and its aggressiveness in pursuing its vision.

Figure 3 shows a 10-kWe campsite as phase 0 where activity is limited. Phases I to III represent increased human presence and activity at a new site until phases IV, V, and VI where ISRU plants are deployed. The production of H_2 and He^3 goes beyond the "90 Day Study" architecture and is used here to evaluate the effect of megawatts of lunar power.

The three power system technologies sized to meet the power profile are PV/RFC, reactor, and laser-based systems. For phase 0, the mass of the PV/RFC system is 5700 kg. At phase I, which is a new site, the power requirement of 25 kWe can be met with a 14 300-kg PV/RFC system. This system is intended to be a backup system for subsequent phases, anticipating some outages in the primary power system. The 14 300-kg backup PV/RFC can accommodate up to a 2-week (terrestrial weeks) outage (~8 MWe-hr) if the lunar-base loads are restricted to life support only. Two weeks is judged sufficient to either repair the power system or evacuate the lunar base.

The reactor-based power system mass is based on advanced space reactor technology coupled to static conversion for lower power needs (~100 kWe). For high power needs (550- to 825-kWe), dynamic conversion systems are envisioned. Figure 7 shows the mass breakdown of the two reactor-based power systems: a 100-kWe reactor-thermoelectric system and a 550-kWe reactor-dynamic conversion system. Figure 8 shows the 825-kWe reactor power system.

One 4700-kg 100-kWe reactor power system is deployed during phase II, satisfying phase II and III requirements. The reactor system is deployed on the lunar surface (above grade) with an expected life of 15 years. Because it is above grade, a human-rated shield is needed at an estimated mass of 6700 kg for a total mass of 11 400 kg. To meet the requirements of phase IV and V, two 14 700-kg, 550-kWe dynamic systems are constructed below the lunar surface (below grade). Because they are below grade, the systems need no human-rated shield. The total reactor system mass at the end of phase V is 40 800 kg, delivering the required 1175 kWe during day and night periods. For phase VI the power requirements jump dramatically to over 5 MWe. To meet this requirement an additional five dynamic systems must be constructed, each at the 825-kWe level and each having a landed mass of ~20 000 kg. At this point, the base will include over 140 000 kg of reactor-based systems, eight reactors, plus 14 300 kg of backup RFC's. The wisdom of deploying eight reactors is in question especially when very high power reactor systems are possible. However, we assumed that there will be a lack of timely, up-front commitments to a ~5-MWe lunar base, leading to incremental deployment as a realistic option.

For the laser-based case the PV array receiver on the lunar surface is an 80-m-diameter PV array. The size is dependent on the Earth-based laser site optics, but a 10- to 12-m-diameter beam expander on Earth will spread to an 80-m-diameter circle on the lunar surface because of diffraction and jitter. In figure 4 we see that during phase II, 12 800 kg of PV array and associated PMAD will deliver the required 50 kWe. Increasing the Earth-based laser power will permit the same PV array to satisfy power requirements of phases beyond phase II with only an increase in PMAD mass on the lunar surface. Phase III requires a ~13 000-kg laser power system, phase IV requires ~14 000 kg, phase V requires ~18 600 kg, and phase VI requires ~39 000 kg.

The laser-based lunar surface power system mass estimates assume the availability of four equally spaced laser sites at the Earth's equator. Unlike the reactor-based system, the power delivered by a laser-based system is not dependent on landed mass given a lunar-surface PV array of sufficient size. Each Earth site must deliver to the lunar surface a laser power level commensurate with load requirements. Each Earth laser site must be capable of producing ~300 kW of laser power for phase II, ~600 kW for phase III, ~1.6 MW for phase IV, ~7 MW for phase V, and over 30 MW for phase VI.

When the reactor-based system is compared with the laser-based system (fig. 4), the crossover in favor of the laser system occurs near phase III (~300 kWe) where the ISRU portion of the lunar base commences. The effectiveness of the PV/RFC option beyond phase II and the 50-kWe level is in doubt because the mass penalty for using PV/RFC starts at ~30 000 kg during phase III and grows to 1 500 000 kg at phase VI.

APPENDIX D

COST CONSIDERATIONS

In any trade study directed at determining the efficacy of a new or alternative technology, cost is the main driver. The laser beam power system, a new technology, is no exception. We have identified three missions that can possibly be enhanced with laser-powered space assets. These are LEO to GEO OTV's, Earth to lunar surface cargo, and lunar surface power. Two other missions, GEO and LEO power for spacecraft, may benefit from laser beam power but are not analyzed in this report.

Though the benefit/cost ratio study for laser power has not been completed, major cost drivers have been identified. The first is the cost of the Earth laser site and the need for four sites to cover the Earth-Moon space. The second is the cost to launch payloads into space or onto the lunar surface.

Laser Site Cost

The cost of the Earth laser sites is shown in table X. The capital investment (excluding cost-of-money effects) in the first FEL site at the 10-MW level is $500 million. Operations cost $63 million per year at full power. Subsequent sites have a capital cost of $225 million and a yearly operations cost of $49 million. Therefore, the cost of installing and operating four sites at full power is $328 million per year over a 10-year life span.

Launch Cost

The launch capacity to LEO and GEO with associated cost of several conventional chemical ELV's is shown in table XI. The cost to LEO is a nominal $12 000/kg given a 500-km LEO altitude. Above this altitude the launch cost increases because of lower payload capability. At 4000-km LEO the nominal launch cost increases to $23 000/kg. Launch payload capability to a LEO of 500 km varies from a high of 22 000 kg for a Titan IV launcher to a low of 4500 kg for a Delta 7920, 7100 kg for an Atlas II AS, and 12 000 kg for a Titan III.

The launch capacity to GEO varies from 900 kg for a Delta, 2100 kg for a Titan III, and 5400 kg for a Titan IV. The specific cost varies from $35 000/kg for a Titan IV, to $80 000/kg for a Titan III, and $50 000/kg for a Delta. The nominal cost is assumed to be ~$55 000/kg.

The launch capacity of a heavy lift launch vehicle (HLLV) is assumed to be 250 000-kg IMLEO. At this mass, ~35 000 kg can be placed on the lunar surface by purely chemical propulsion systems at a cost of $90 000/kg.

LEO to GEO to LEO OTV Launch

In comparison to LEP, the cost to deliver a 2500-kg satellite to GEO (such as a commercial communication satellite) with chemical propulsion is rather striking. An LEP OTV tug starting at a 500-km LEO altitude takes 132 days for a round-trip, requires an initial insertion of 7000 kg, and 4000 kg of resupply for subsequent trips. The Earth-to-orbit transportation cost to repeat this mission, placing 2500 kg in GEO 100 times or 10 times per year for 10 years (four OTV's required), is $4.9 billion. If the LEP OTV tug starts out at a LEO of 4000-km (2 OTV's required) instead of 500-km, the 10-year cost is $8.2 billion for the Earth-to-orbit launches. Pure conventional chemical propulsion to GEO costs \$55 000/kg (see table XI), so for 100 payloads at 2500 kg each the cost is \$13.8 billion. Therefore, the transportation cost savings for using LEP as opposed to chemical propulsion is between \$5.6 and \$8.9 billion, depending on the initial LEO altitude. This savings applies to an SEP system as well. However, an SEP system would be undesirable since it takes about 2.5 to 3.5 months longer to complete one round-trip mission than it does for an LEP system. This delta would require more tugs to enable 10 missions per year and would delay, unduly, the initiation of a revenue stream to the communication satellite owner.

Earth to Lunar Surface

Shown in the main text and in tables II and III is a possible IMLEO savings of 123 000 kg through use of an LEP OTV TLI propulsion stage. The IMLEO required to put ~35 000 kg on the lunar surface via purely chemical propulsion technology is 242 000 kg. Replacing the chemical TLI stage with an LEP OTV TLI reduces the IMLEO to ~119 000 kg for a savings of 123 000 kg.

Since both scenarios (purely chemical or LEP-augmented propulsion) require IMLEO's of >110 000 kg, a heavy lift launch vehicle is needed. Though the cost per unit mass launched into orbit for a heavy lift launch vehicle has not yet been identified, the cost is expected to be less than for present ELV's. For this paper, an assumption of \$10 000/kg was made. This is 20 percent less than for today's ELV's (see table XI).

For a \$10 000/kg launch cost and a 123 000-kg savings/mission, the benefit of a laser-powered electric propulsion lunar OTV tug is nominally ~\$1.2 billion for the first mission. Subsequent missions to the Moon using LEP OTV's would cost less than the first mission if the electric propulsion TLI stage is a tug. Therefore, if there were 1 mission per year to the lunar surface for 10 years (see table III for trip times), such an LEP OTV mission could save at least \$12 billion.

Lunar-Base Launch Cost

The comparison of costs between competing technologies for lunar-base power assumes the following propulsion systems: chemical Earth to orbit, chemical TLI, chemical lunar orbit insertion, and chemical descent to the lunar surface. Table XII shows the comparative transportation cost of landing a lunar-base power system meeting the power profile shown in figure 3 and the masses identified in figure 4. The specific cost for transportation to the lunar surface is assumed to be \$90 000/kg. Comparing the bottom-line costs in Table XII shows the PV/RFC technology is far more expensive than either the reactor or laser-based systems. A savings of over \$100 billion can be realized by not using PV/RFC's for all phases of the mission. The laser system is less costly than the reactor system: the reactor system transportation cost is \$14.4 billion (table XII), and the laser system transportation cost is \$5.4 billion. The resultant transportation cost for a laser-based power system is \$9.0 billion less than that of a reactor-based system.

Benefit/Cost Ratio

In summary, the transportation savings by using laser beam power instead of conventional technologies is between \$14.6 billion (\$5.6 + \$9.0 billion) and \$17.9 billion (\$8.9 + \$9.0 billion) over a 10-year period for two of the three missions (LEO to GEO OTV tug plus lunar-base power). The operational cost of four laser sites is \$328 million per year (see table X), and for 10 years amounts to \$3.3 billion. This does not include the cost of upgrading the Earth laser sites from 10 MW to the

30 MW of laser power required by phase VI of the lunar-base power profile. The benefit/cost ratio for these two missions (LEP OTV LEO to GEO to LEO tug and lunar base) missions is between 4.5 and 5.5. Adding the benefit accrued through utilizing an LEP instead of chemical TLI for an Earth to lunar surface transportation system drastically increases the overall benefit/cost ratio. The $12 billion launch cost savings over 10 years added to the previously calculated $14.6 to $17.9 billion gives a total saving of $26.6 to $29.9 billion over 10 years and results in a benefit/cost ratio of 8.4 to 9.4 instead of the 4.5 to 5.5 value quoted earlier.

There is concern in the laser community that the quoted capital cost for the first 10-MW FEL Earth site of $500 million is optimistic. A brief sensitivity analysis was performed to determine the effect on the benefit/cost ratio should the first laser site capital cost be increased by a factor of 2 and a factor of 4. The launch cost differential between laser-powered space assets and conventionally powered assets remain the same at the $26.6 to $29.9 billion level (see previous paragraphs). However, the operations cost of four Earth laser sites jump from $328 to $505 million per year, ($5.1 billion for 10 years) for a capital cost of $1000 million for the first site. This is based on operating assumptions and learning curve assumptions shown in table X. The resultant benefit/cost ratio is between 5.4 and 6.0 instead of 8.4 to 9.4. At $2000 million for the first site, the operations cost of four Earth laser sites jumps to $8.6 billion over 10 years. The resultant benefit/cost ratio is between 3.3 and 3.6—still greater than 1, but not as attractive.

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

Subsystem	Specific mass, kg/kWe	
	Laser EPOTV	Solar EPOTV
Advanced thruster and power processing unit	0.5	0.5
Photovoltaic array	.7	9.6
PMAD/TCS	1.8	1.8
Total	3.0	11.9

- Support systems (e.g., structures, thermal, and communications) modeled after Mariner Mk II bus.
- Advanced thrusters (specific impulse, 5000 sec; efficiency, 50 percent; NH_3 tankage, 0.12).
- Self-annealing laser PV cells have 10 times more power per kilogram than normal solar cells.
- GaAs solar cell shielding of 20 mils in front and 12 mils in back for solar EPOTV.
- 2500 kg payload to geostationary orbit.

TABLE II.—EARTH TO LUNAR SURFACE CHEMICAL PROPULSION SYSTEM

Mission stage	Mass, $kg \times 10^3$		Comments
	Discrete	Cumulative	
Payload to lunar surface	~35	~35	Cargo only or crewed assets
Chemical lunar orbit insertion and descent stage	[a]~61	~96	LLO mass
Chemical translunar injection stage (TLI)	[a]~146	~242	IMLEO

[a]Wet.

TABLE III.—EARTH TO LUNAR SURFACE CHEMICAL AND ELECTRIC PROPULSION SYSTEM

Mission stage	Mass, $kg \times 10^3$		Comments
	Discrete	Cumulative	
Payload to lunar surface	33	33	Cargo
Chemical lunar descent stage	[a]42	75	Chemical propulsion system LLO mass
EP TLI	[a]43.5	118.5	IMLEO
EP thruster and PPU	(2.5)	-------	5-MWe advanced electrodeless thruster
PV array	(3.5)	------	GaAs array
PMAD/TCS	(9.0)	------	Near-term PMAD, advanced radiators
Outbound tankage and fuel	(19.6)	------	Outbound trip time of 9.6 months
Return tankage and fuel	(3.9)	------	Return trip time of 1.8 months
Structure	(5.0)	------	

[a]Wet.

TABLE IV.–PRELIMINARY SUMMARY OF PHOTOVOLTAIC CELL CONVERSION EFFICIENCY

Cell technology	Corrected experimental conversion efficiency, percent [Intensity, 1 sun; laser wavelength, 840 nm.]			
	AM0	Continuous wave laser	Pulsed RF FEL simulation	Induction FEL simulation
Planar cells				
Silicon	16	31	---	13
Gallium arsenide	20	47	---	<1
Concentrator cells				
Silicon	15	25	19	21
Gallium arsenide	21	43	[a]2	3
Unique cells/tests				
Silicon planar (radiation damaged)[b]	11	23	---	4
Gallium arsenide concentrator (capacitor)[c]	19	35	44	7

Cell technology	Advanced laser cell technology efficiency goal, percent
Silicon	45
Gallium arsenide	60

[a]Estimated from tests performed on a similar cell.
[b]Silicon planar (radiation damaged) has been exposed to 5×10^{14} 1-MeV electrons/cm^2.
[c]Gallium arsenide concentrator (capacitor) has a 4.4-μF capacitor across the cell during FEL simulation tests to measure the effect of smoothing high laser peaks.

TABLE V.–BENEFITS OF LASER BEAM POWER

Mission	Scenario comparisons	Deliverables	Transportation cost savings: Earth-based laser site cost ratio	
			Minimum	Maximum
GEO payload	LEP OTV LEO to GEO tug with ELV to LEO versus chemical transportation to GEO	2500-kg payload (10 round-trips per year)	0.7	2.7
Lunar payload	LEP TLI tug with chemical HLLV and descent transportation versus chemical HLLV, TLI, and descent transportation	33 000 kg to lunar surface (once per year)	1.5	3.9
Lunar power	Laser PV with chemical transportation versus reactor with chemical transportation	5-MWe load (steady growth)	1.1	2.8
Total			3.3	9.4

TABLE VI.–BENEFIT/COST CROSSOVER TO GREATER THAN 1

Mission	First Earth laser site cost[a]		
	\$500 million	\$1000 million	\$2000 million
LEO/GEO/LEO OTV TUG[b]	>40 missions	>60 missions	>100 missions
Lunar surface cargo[b]	>2 missions	>4 missions	>6 missions
Lunar surface power	>2 MWe	>3 MWe	>5 MWe

[a]10 years of operation, four Earth laser sites.
[b]Electric propulsion specific mass at 3 kg/kWe.

TABLE VII.—ELECTRIC PROPULSION TECHNOLOGY OPTIONS

Device	Thruster efficiency	Specific impulse, sec	Thruster and PPU specific mass, kg/kWe	Thrust, N	Lifetime, sec
Ion thruster	0.6 to 0.80	3000 to 10 000	4 to 8	0.1 to 7	$\sim 4\times 10^{7}$
Arcjet	0.3 to 0.5	400 to 1500	3 to 8	0.1 to 7	$\sim 4\times 10^{6}$
MPD thruster	0.1 to 0.5	1000 to 10 000	1 to 8	0.6 to 20	$\sim 2\times 10^{7}$
Advanced electrodeless thruster	0.5	5000 to 10 000	0.5	1 to 20	$\sim 10^{8}$

TABLE VIII.—PMAD AND TCS SUBSYSTEMS

Subsystem elements	LEP or SEP, kg/kWe
Power management and distribution	1.4
Roll rings	.3
Switching units	.9
Interrupters	.1
Filter/cables	<.1
Contingency (10 percent)	.1
Thermal control system	0.4
Radiator	.3
Fluid/controls	<.1
Contingency (10 percent)	<.1
Total	1.8

TABLE IX.—RADIATOR PERFORMANCE

[Assumed radiator power, 700 kWt.]

Radiator temperature, K	Radiating area,[a] m^2	Radiator specific mass, kg/kWt	
		Graphite[b]	Aluminum[c,d]
300	2740	7.83	23.5
350	1190	3.40	10.2
400	637	1.82	5.46
450	380	1.09	3.27
500	243	.694	2.08
600	115	.329	.986

[a]Radiating to 230 K sink with emissivity of 0.85.
[b]Graphite composite with niobium core; 4 kg/m^2 sail area.
[c]Aluminum honeycomb with stainless steel pipes; 12 kg/m^2 sail area.
[d]Performance assumed beyond 300 K radiator temperature.

TABLE X.—ESTIMATED COST OF EARTH-BASED LASER SITE

Cost element	Estimated cost, $ million/year		Assumptions
	First site	Subsequent sites	
Capital	50.00	22.50	$500 million for first site; subsequent sites cost 45 percent of first site; 10-year life
Maintenance	25.00	11.25	5 percent per year of plant cost
Electrical power	36.00	36.00	$0.03/kWe-hr 24 hr of operation per day 250 days of operation per year 200-MWe power required for 10-MW laser power
Labor	2.00	2.00	40 people per site $50 000 per year per person
Total	113.00	71.75	10 MW of laser power per site

TABLE XI.—EARTH-TO-ORBIT LAUNCH CAPABILITY AND COST

ETO launcher	Launch cost, $ million	Altitude, km	Payload, kg	Specific launch cost, $/kg
Nominal cost to 500-km LEO, $12 000/kg Nominal cost to 4000-km LEO, $23 000/kg				
Titan IV	~200	LEO	~22 000	~9 000
Titan III	170	500 2000	12 000 8 400	14 000 21 000
Atlas II AS	120	500 4000	7 100 4 900	17 000 25 000
Delta 7920	46	500 4000	4 500 2 200	10 000 21 000
Nominal cost to GEO, $55 000/kg				
Titan IV	~200	GEO	5 400	35 000
Titan III	170	GEO	2 100	80 000
Delta 7920	46	GEO	900	50 000

TABLE XII.—LUNAR BASE POWER SYSTEM TRANSPORTATION COST

Phase[a]	Power,[a] KWe		Incremental mass, $kg \times 10^3$			Incremental cost,[b] $ billion		
	Incremental	Cumulative	PV/RFC	Reactor	Laser	PV/RFC	Reactor	Laser
0	10	-----	5.7	-----	-----	0.5	0.5	0.5
I	25	-----	14.3	-----	-----	1.3	1.3	1.3
II	25	50	28.7	11.4	12.8	2.6	1.0	1.2
III	25	75	14.3	-----	.1	1.3	0	0
IV	200	275	72.6	14.7	1.0	6.5	1.3	.1
V	900	175	281.2	14.7	4.6	25.3	1.3	.4
VI	4000	5175	1124.8	100.0	20.6	101.2	9.0	1.9
Total			1541.6	140.8	39.1	138.7	14.4	5.4

[a]See figure 3.
[b]$90 000/kg launch cost.

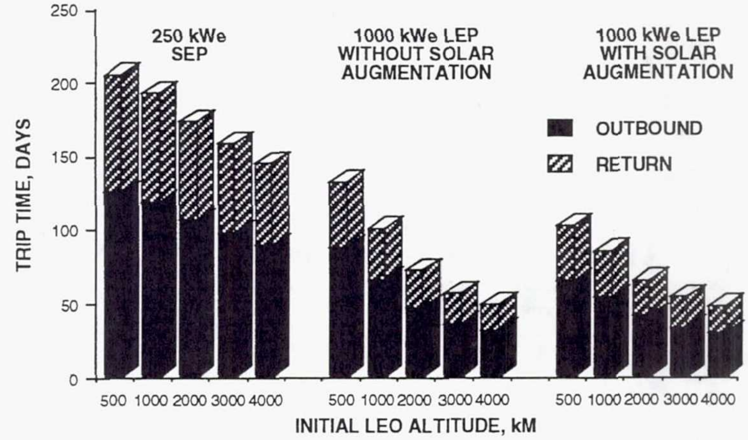


Figure 1.—LEO to GEO trip times for EPOTV tug; 7000-kg class OTV.

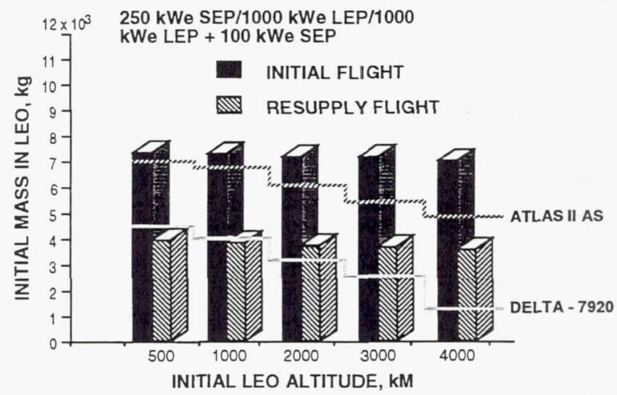
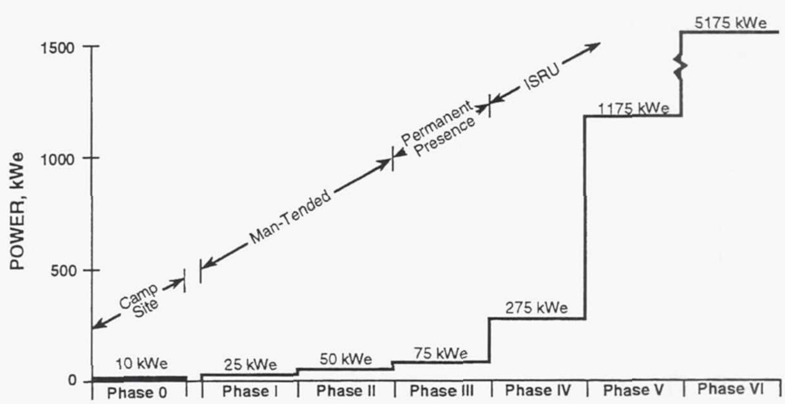


Figure 2.—Launch mass into LEO of EPOTV tug; 2500-kg payload into GEO. (250 kWe SEP or 1000 kWe LEP or 1000 kWe LEP with 1000 kWe SEP.)



Phase 0	Precursor Manned Camp Site
Phase I	Initial Outpost (Science)
Phase II	Expanded Outpost (Science & Engineering)
Phase III	Permanent Presence (Pressurized Rover)
Phase IV	ISRU (O_2 Production ~ 60 000 kg/yr)
Phase V	ISRU (H_2 Production ~ 5 000 kg/yr)
Phase VI	ISRU (He^3 Production ~ 100 kg/yr)

Figure 3.—Generic lunar surface power requirements.

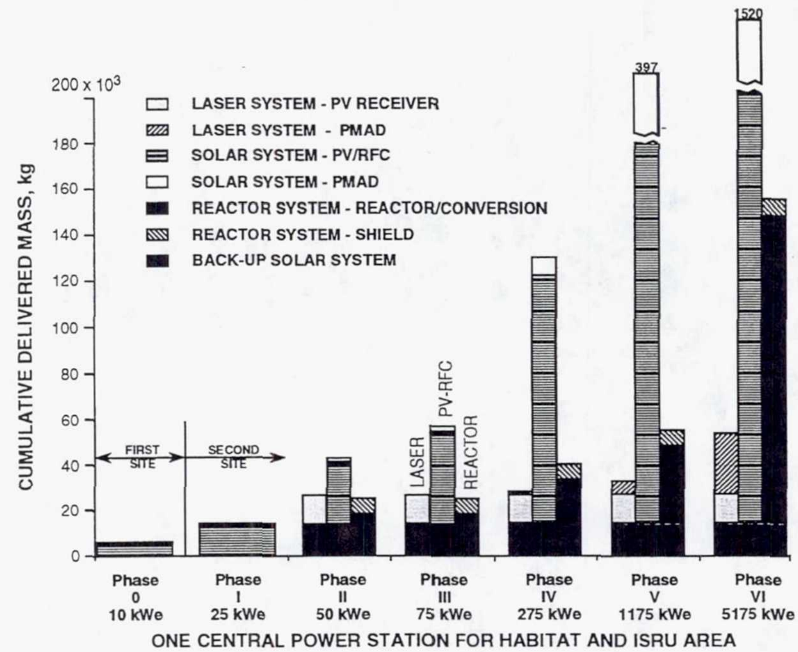


Figure 4.—Lunar surface power system options; cumulative mass delivered to the lunar surface.

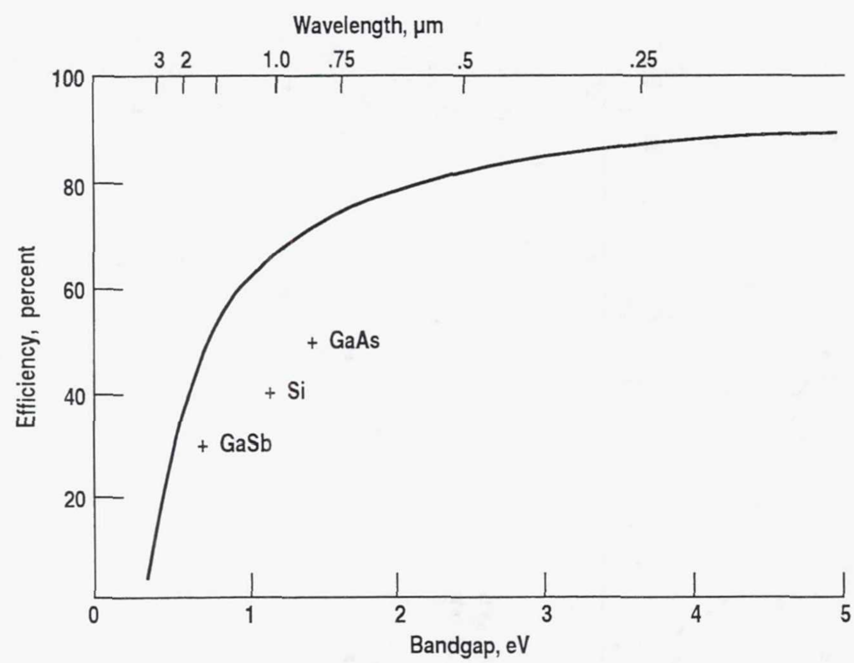
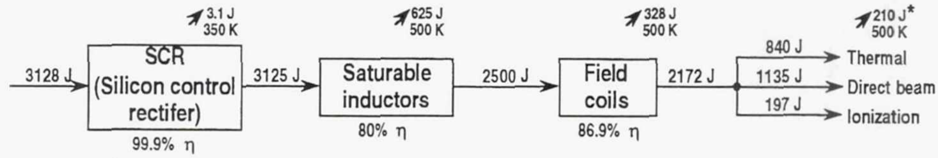
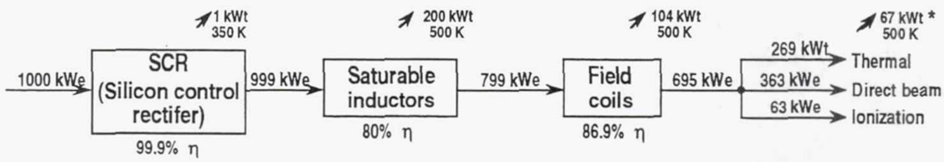


Figure 5.—Theoretical conversion efficiency of photovoltaic cells for monochromatic light. Intensity, 500 mW/cm^2; temperature, 25 °C.



(a) Energy balance. Energy rejected at 350 K, 3.1 J; energy rejected at 500 K, 1163 J.



(b) Power balance. Power rejected at 350 K, 1 kWt; power rejected at 500 K, 371 kWt.

Figure 6.—Advanced thruster efficiency, η. (*One-fourth of thermal energy reflected back to thruster to be rejected in radiator.)

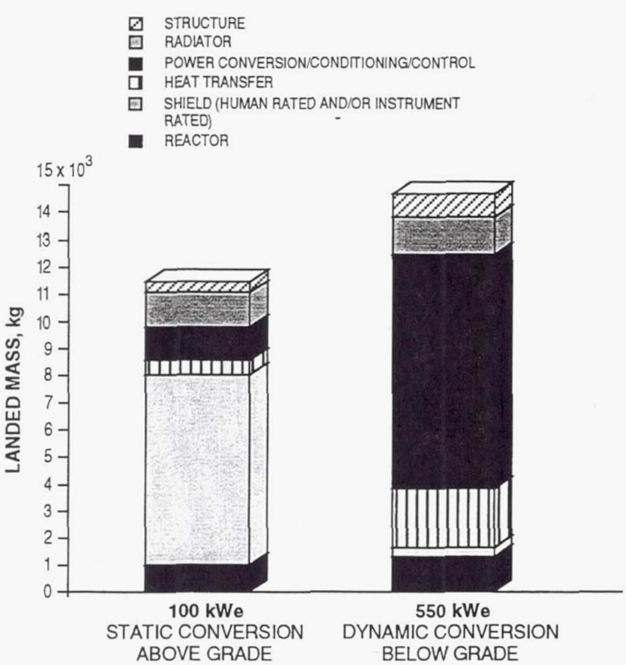


Figure 7.—Reactor-based lunar power systems; 15-year life.

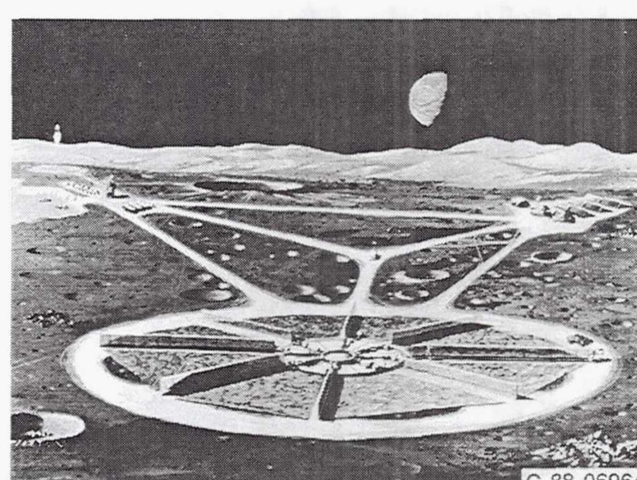


Figure 8.—825 kWe reactor system; dynamic conversion.

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13. ABSTRACT ***(Maximum 200 words)***

Earth-based laser sites beaming laser power to space assets have shown benefits over competing power system concepts for specific missions. Missions analyzed in this report that show benefits of laser beam power are low-Earth-orbit (LEO) to geosynchronous-Earth-orbit (GEO) transfer, LEO to low-lunar-orbit (LLO) cargo missions, and lunar-base power. Both laser- and solar-powered orbit-transfer vehicles (OTV's) make a "tug" concept viable, which substantially reduces cumulative initial mass to LEO in comparison to chemical propulsion concepts. Lunar cargo missions utilizing laser electric propulsion from Earth-orbit to LLO show substantial mass saving to LEO over chemical propulsion systems. Lunar-base power system options were compared on a landed-mass basis. Photovoltaics with regenerative fuel cells, reactor-based systems, and laser-based systems were sized to meet a generic lunar-base power profile. A laser-based system begins to show landed mass benefits over reactor-based systems when proposed production facilities on the Moon require power levels greater than ~300 kWe. Benefit/cost ratios of laser power systems for an OTV, both to GEO and LLO and for a lunar base were calculated to be greater than 1.

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