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Paul F. Holloway
and L. Bernard Garrett
Langley Research Center
Hampton, Virginia

National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

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SUMMARY

The technological and economical impact of a large central power station in Earth orbit on the performance and cost of future spacecraft and their orbital-transfer systems are examined. It is shown that beaming power to remote users cannot be cost effective if the central power station uses the same power-generation system that would be readily available for provision of onboard power. Similarly, microwave transmission and reception of power through space for use in space cannot be cost competitive with onboard power or propulsion systems - the size of the receiver is prohibitive. Laser transmitters and receivers are required to make central power stations feasible.

Analysis of the cost effectiveness of meeting the electrical-power demands of an Earth-orbiting spacecraft from a central power station indicates that this application cannot justify the investment required for a central power station. However, cost benefits (within the bounds of the assumptions made herein) are of a sufficient magnitude to justify the research and development activities necessary to enable the central power station. Direct nuclear-pumped or solar-pumped laser power-station concepts are particularly attractive with laser thermal and laser electric propulsion systems. These power stations are also competitive, on a mass and cost basis, with a photovoltaic power station. Based on these results, key technology needs which must be met to enable a viable central power station in the future are identified.

INTRODUCTION

Today's space planners are increasingly intrigued by the potential of large space systems, particularly large multipurpose platforms, manned or unmanned. Underlying this interest is a strong, albeit mostly intuitive, belief in the "economy of scale." On Earth, one economy-of-scale system that has proven very successful (at least in terms of relative costs) is the central power utility plant. Application of this approach in space seems a logical focus for space mission analysts since it is anticipated that power demands in orbit will increase exponentially over the next few decades as applications and industrialization activities expand. In fact, it is generally accepted that the rate of space industrial development will depend primarily on the cost of transportation to, through, and from space, and on the cost of electrical power in space.

The purpose of this paper is to initiate that process by conducting a first-cut evaluation of the utility of a central power station in Earth orbit. Two classes of users are considered: (1) Earth orbiting satellites requiring electrical power for routine operations to meet mission goals, and (2) orbital-transfer vehicles (OTV) requiring power for propulsion.

Three concepts for central, space-based power stations are considered. The first is a photovoltaic array system representing normal state of the art for proven technology with the same assumptions for costs, weight, and efficiency used for the onboard baseline system. The second is a direct nuclear-pumped laser based on a rapidly evolving technology. Finally, a direct solar-pumped laser system based on an exciting new technology that is just now emerging in the laboratory is evaluated.

Both microwave and laser transmission of energy from the central power station to the users are considered.

For comparison purposes, the baseline electrical power system is assumed to be photovoltaic power provided with conventional onboard systems at costs, weights, and efficiencies projected to be attainable by the end of this century. The OTV remote energy application for laser thermal and laser electric propulsion systems is compared with projected technological advances in conventional chemical and solar electric propulsion stages.

The technologies required to enable the systems discussed are delineated. The authors hope that this paper will provide the stimulus for further analysis and discussion that will ultimately provide the necessary direction to effectively focus the near-term technology efforts and maximize the utilization of these technologies in the future.

The authors gratefully acknowledge the many contributions to this paper made by John J. Rehder, who conducted the orbital-transfer analyses, and Dr. Nelson W. Jalufka, who provided the majority of inputs on the direct-pumped laser systems.

COMPARISON BASELINE SYSTEMS

Onboard Photovoltaic Power

Silicon solar cells have been used extensively for onboard power, but these applications have been limited to less than a few kilowatts. Continued development of these systems, aimed primarily at increasing the ratio of power to weight and at reducing costs, can be expected. As power demands increase, other cell materials, such as gallium arsenide (GaAs), offering higher efficiency will become increasingly attractive. Efficiencies (ref. 1) of 18.6 percent have already been achieved with GaAs solar cells in the laboratory compared with the customary 12 to 15 percent for production silicon cells (ref. 2). In addition, the higher operating-temperature capability (ref. 3) of GaAs, its radiation resistance (ref. 4), and self-annealing characteristics (ref. 5) promise reduced size for a given power output and longer life with reduced maintenance. A weight penalty for the use of GaAs rather than silicon might be expected. However, if GaAs annealing is as effective as it currently appears, double-cover glass radiation shields will not be required. This factor, coupled with the potential for development of thin (approximately 10 μm) high-efficiency cells, would give GaAs a power-to-weight ratio advantage over silicon. Regardless of the final outcome, analyses conducted during this study have shown that total costs are insensitive to the weight differences associated with a very pessimistic GaAs weight projection. Hence, the onboard power systems of the future are assumed in this study to be GaAs photovoltaic arrays with an efficiency of 20 percent (ref. 6).

Onboard Propulsion

Chemical orbital-transfer vehicles.- The baseline chemical OTV (fig. 1) uses spherical propellant tanks and a lightweight composite truss structure in a configuration developed for an earlier study (ref. 7). A hydrogen-oxygen rocket engine with a specific impulse of 476 seconds is assumed. The payload, propellant, and vehicle dry weights are about 100 000, 280 000, and 20 000 kg, respectively. For space-based operations, 7-day round-trip times are assumed from low-Earth orbit (LEO) to geosynchronous-Earth orbit (GEO), with a 50-flight lifetime.

Solar electric propulsion system orbital-transfer vehicles.- Solar electric propulsion system (SEPS) cargo OTV's have been studied extensively. (See, for example, refs. 8 and 9.) A representative configuration (ref. 8) is shown in figure 2. Argon ion thrusters are assumed to provide a specific impulse I_{sp} of 6000 seconds. The payload, propellant, and vehicle dry weights are about 100 000, 17 000, and 24 000 kg, respectively. With an initial thrust-to-weight (T/W) ratio of 5×10^{-5} and 3.3 MW electrical power (MW_e) delivered to the thrusters, a round-trip time from LEO to GEO of 173 days results. Although the test results to date on the self-annealing characteristics of GaAs solar cells (ref. 5) are very promising, the total radiation environment has not yet been simulated. This fact, coupled with the lifetime required of the continuous burn thrusters for the long trip durations, led the authors to assume a three-flight lifetime for this space-based OTV.

The chemical and SEPS orbital-transfer performance characteristics are summarized in appendix A (see table A1).

ADVANCED CONCEPTS

Space-Based Central Power Stations

Three central-power-station concepts located in GEO are considered: a solar-powered photovoltaic array, a direct nuclear-pumped laser, and a direct solar-pumped laser power station. In all of these systems, it is assumed that power is beamed to remote users via laser or microwave beams. For all three concepts, the major systems and subsystems are sized for a total of 100 MW radiated at the transmitter.

Transmitter and receiver systems.- A selection of transmitters and receivers is required for the development of central power stations addressed in this study. Both microwave and laser energy transmission/reception are possible over the long distances in space that would be associated with a central power station. The sizes of the transmitter and receiver for such systems are functions of their operating wavelength and transmission distance or range, not necessarily power level. Transmitter and receiver sizes versus range for diffraction-limited microwave and laser systems operating at the various wavelengths λ applicable to each system are shown in figure 3.

To transfer power over geosynchronous distances on the order of 40 000 km, microwave transmitter and receiver diameters of 1 to 10 km will be required. However, laser systems, because of their shorter wavelengths, can operate with much smaller transmitter and receiver diameters, ranging from 5 to 30 m.

Consider now the prospects of remote versus onboard power for these two types of transmitter/receiver systems. For a microwave receiver (rectenna) of 2-km diameter, the equivalent area of onboard photovoltaic cells would produce almost 1 GW_e.

For a 20-m diameter laser receiver, the equivalent area of onboard solar cells would produce approximately 100 kW_e power. Several users in the tens to hundreds kW_e power range are expected in future missions (ref. 10); however, no missions have been defined which would require the 1 GW_e power commensurate with the microwave receiver size. Nonetheless, if power levels of that magnitude were required, it could be provided by an onboard system at a lower cost than that required for the microwave transmitter and receiver systems. Thus, only laser transmitter and receiver systems are considered in the remainder of this paper.

Two types of receivers are compatible with laser energy transmission - photovoltaic arrays for direct conversion to electricity, and optical collectors that focus the concentrated laser energy on thermal conversion engines. A specially tuned laser transmitting near the visible wavelength (5000 to 9000 Å, 1 Å = 0.1 nm) would increase photovoltaic conversion efficiencies 40 to 50 percent (ref. 11). Laser thermal conversion system efficiencies could range between 50 and 75 percent. (See, for example, ref. 12.)

Photovoltaic array.- GaAs solar cell arrays with 20-percent conversion efficiency and electric discharge laser systems with a 30-percent efficiency are assumed. A solar-powered photovoltaic central-power-station concept with laser energy transmission systems is shown in figure 4. Array dimensions of 1800 m by 600 m achieve 100 MW laser total power (100 MW_L) output at the transmitters. Two independent, high-energy electric discharge laser (EDL) systems, each about 15 m square and 40 m long (ref. 13) radiate power to 30-m diameter laser transmitters. A cycle schematic of this approach is shown in figure 5. Passive heat-rejection systems incorporated in the photovoltaic array radiate the unusable solar energy. Heat-pipe radiators arranged in a planar array with a total area of 70 000 m^2 (based on an estimated specific area of 0.25 m^2/kW_T (subscript T is for thermal power) for 500 to 700 K rejection temperature) are extended radially from the laser system to reject the unusable thermal energy in the laser.

Since a 30-percent electrical-to-laser energy conversion efficiency is assumed, the GaAs solar array is required to produce 330 MW_e to yield 100 MW_L output. The low voltage array output must be processed to provide the relatively high voltage (kV range) required to drive the EDL. The laser system consists of subsonic or supersonic diffusers, the laser cavity and beam optics, compressor, heat exchanger, and the lasant gas makeup system. CO and CO_2 gases are the leading lasant candidates. Monson (ref. 14) estimated open-cycle efficiencies of 60 percent and 25 percent for CO and CO_2, respectively, resulting in closed-cycle efficiency estimates of 29 and 18 percent. One technique of achieving the higher 30-percent efficiency would utilize turbogenerator bottoming cycles (not shown in the cycle schematic) to recover waste heat from the laser.

With a closed-cycle operation, the lasant gas may be recycled. For the CO_2 system, a temperature of 700 K is anticipated at the laser gas-output side. A heat exchanger and radiator system is required to dispose of waste heat. The CO system must operate at low temperature to achieve high efficiency, and a refrigeration cycle is required. Although this cycle would also generate waste heat, it would lower the temperature of the gas output so that no further cooling would be required.

The laser and gas loop of the system involves extending the application of existing technologies to the long-life closed-cycle operations required. Open-cycle EDL's have demonstrated efficiencies in the 30- to 40-percent range, and output power at hundreds of kilowatts for short periods of time (refs. 15 and 16). Thus, this is the most technologically advanced of the three central-power-station concepts considered in this analysis.

Direct nuclear-pumped laser.- The direct nuclear-pumped laser (DNPL) power-station concept shown in figure 6 is built around a gas-core reactor fueled with UF_6 as proposed by Rodgers (ref. 17). The lasant is mixed with UF_6 so that the laser generation system is integral with the reactor. Fission fragments from the nuclear reactions collide with the lasant gas constituents, exciting the gas to levels sufficient to produce lasing. One possible design of a nuclear-pumped laser taken from Rodgers (ref. 17) is shown in figure 7. The physical dimensions are for a total reactor power of 100 MW. If the nuclear-to-laser power conversion efficiency reached the projected 10 percent (ref. 17), then this system would output 10 MW_L. This power-intensive nuclear reactor system is capable of operating between 2 and 2000 MW. Thus, the overall 5-m diameter and 6-m length should be representative of a system with 100 MW_L output. Multiple or ganged laser cavities are used to mitigate thermal effects associated with the high-power system. Heat-pipe thermal radiators of 400 000 m^2 are required if all excess heat from the nuclear-to-laser energy conversion process is radiated to space. However, Rodgers suggests (ref. 17) that a bottoming turbogenerator cycle can be used to recover 9 percent of the waste heat as electrical power for onboard use.

A schematic for long-term, closed-cycle operation of the direct nuclear-pumped laser power station (again based on the work of Rodgers (ref. 17)) is presented in figure 8. Subsystem power requirements based on projected efficiencies and representative operating temperatures are noted in the figure. A nuclear-to-laser power conversion efficiency of 10 percent is assumed. This results in a 100-MW_L output. Fuel and laser gas reprocessors and makeup systems are added for long-term, closed-cycle space operations.

Since UF_6 would be depleted by the fission process in the reactor, the residual fission fragments must be removed and the depleted UF_6 replaced. Some lasing gas may also have to be replaced. A fuel/lasant reprocessor would remove undesirable elements produced in the fission process. The transuranium elements could be injected back into the reactor core and transmuted into either stable forms or usable fuel.

Boody et al. (ref. 18) note that experimental nuclear pumping of a CO lasant has yielded 1-percent conversion efficiency, and project that a 10-percent efficiency is achievable in future systems. Rodgers (ref. 17) points out that theoretical maximum efficiencies of 7 and 13 percent have been estimated for XeF and I_2 nuclear-pumped lasers. DeYoung (ref. 19) reports on a ^{3}He-Ar nuclear-pumped laser that has yielded a kilowatt of power. This output power represents quantum leaps (six orders of magnitude, ref. 20) that have been achieved in output power in the last 5 years.

Direct solar-pumped laser.- Direct solar-pumped laser (DSPL) power-station concepts and future performance estimates have been projected by Monson (ref. 14), Rather et al. (ref. 21), and Taussig et al. (ref. 22). The technology for solar-pumped lasers is still in the earliest laboratory stages, and insufficient data are available to accurately quantify overall system performance. However, based on a survey of the literature and ongoing experimental efforts, an overall solar-to-laser energy conversion efficiency in the range of 1 to 20 percent is assumed.

A conceptual design of a 100-MW_L direct solar-pumped laser power station is shown in figure 9. For this study, efficiencies of 10 percent and 1 percent are assumed, requiring collector diameters of 1000 and 3000 m, respectively, to concentrate the low-level solar radiation (1.4 kW/m^2) on the transparent laser tubes. The construction of a 100-MW_L laser will be limited by optical elements such as mirrors and windows. Therefore, this analysis uses an array of 50 laser tubes (each 1 m in diameter and 50 m in length) in a cylindrical pattern of 30-m diameter as shown in figure 10. Improvements during the next 20 years in areas such as transmission through optical elements should be significant, but may still be insufficient to permit construction of a 100-MW_L laser in a single unit.

Assuming that a solar filtering reflector material can be developed to reflect only the portion of the solar spectrum usable for lasing (20 percent), and that 50 percent of this reflected solar energy goes into lasing energy (for a 10-percent overall solar-to-laser energy conversion), then approximately 25 000 m^2 of heat-pipe thermal radiators are needed for the laser. High-emissivity materials on the back side of the solar concentrator could be used to passively radiate the unusable solar energy absorbed by the concentrator.

Solar energy, if sufficiently concentrated, can induce lasing in selected gases. Although this technology is in its infancy, the potential exists for relatively low overall cost because of simplicity of operation. Conversion efficiency of 0.1-percent solar-to-laser energy was recently achieved at Langley Research Center (ref. 23). The cycle schematic for a direct solar-pumped laser (DSPL) is shown in figure 11. Subsystem power requirements and representative operating temperatures are noted on the schematic for the 10-percent solar-to-laser energy conversion efficiency. As mentioned above, the 10-percent overall conversion efficiency assumes a 50-percent filtered solar-to-laser radiation conversion efficiency, an efficiency approached by an NOCℓ lasant absorbing in the far uv range to 6500 Å. Other lasants such as IBr or C_3F_7I will not achieve a 50-percent solar-to-laser conversion efficiency, and a system having 5-percent efficiency (worst case) representing a 1-percent overall conversion efficiency is included in the subsequent mass and cost analyses. A gas temperature of no more than 700 K is anticipated because higher temperatures are detrimental to known lasing gas-inversion processes. Several laser systems under consideration employ molecules which dissociate prior to lasing and do not regenerate themselves. Consequently, an onboard gas reprocessor may be required to reproduce the lasant gas by other means (chemical, etc.).

Of the three systems studied, the DSPL potentially presents the least challenge to achieving the long-life space power-station operations required. This makes the DSPL an attractive candidate even at 1-percent overall efficiency. Laboratory efforts are under way to characterize candidate lasant gases and expand the bandwidth of usable solar energy. The large, lightweight solar concentrator presents technological challenges in the design, on-orbit assembly, and operational control of the spacecraft.

Remotely Powered Propulsion Systems

If a space-based central power station is available, new options are possible for orbital-transfer vehicles. For this study, two OTV concepts tailored to capitalize on the central power station are compared with the more conventional chemical and SEPS OTV concepts.

Laser thermal propulsion.- The laser thermal propulsion system (LTPS) shown in figure 12 is similar to that previously presented in reference 24. The hydrogen propellant is heated by the laser beam from the central power station. The laser thermal engine has a thrust of 10 000 N and an I_{sp} of 1500 seconds. This results in an exhaust power of 70 MW and a start-burn thrust-to-weight ratio of 0.03. To reduce gravity losses resulting from the low T/W and the duration of the individual engine burns, the LEO-to-GEO transfer trajectory uses 10 perigee burns of about 15 minutes each and a 1.5-hour circularization burn. The payload, propellant, and vehicle dry masses are about 20 000, 9000, and 2200 kg, respectively. Fourteen-day round-trip times are assumed to allow for cargo unloading and OTV maintenance. A 50-flight lifetime is assumed for a total thruster-operation time of about 400 hours.

Laser electric propulsion.- The laser electric propulsion system (LEPS) shown in figure 13 is similar in most respects to the baseline SEPS OTV. The principal differences are the size and makeup of the solar-cell array. The array is much smaller (20-m diam) and is assumed to be more efficient (50-percent laser-to-electrical power conversion) because the laser beam is more concentrated than sunlight and has a narrow spectral band. This band, with enabling technology developments in infrared-to-visible wavelength frequency conversion, can be made to match the absorption characteristics of the solar cells. For this OTV, the payload, propellant, and vehicle dry mass are about 100 000, 14 000, and 11 000 kg, respectively. Round-trip time from LEO to GEO of 158 days is required.[1] The three-flight lifetime assumed for the SEPS OTV is also used for the LEPS for a total thruster-operation time of about 11 000 hours.

The LTPS and LEPS orbital-transfer performance characteristics are also summarized in appendix A, table A1.

CENTRAL-POWER-STATION MASS AND COST ESTIMATES

Comparative mass and cost estimates for the major components of the candidate advanced systems are based on 100 MW_L output at the transmitter. The assumptions made here are the basis for the performance characteristics and the development of the cost-estimating relationships presented in appendix B. Summaries of these mass and cost estimates for each of the central-power-station concepts are presented in figures 14 and 15, respectively. Details of these estimates are discussed in the sections which follow.

Photovoltaic Power Station

Mass estimate.- The mass of the GaAs array is calculated assuming 1.5 kg/kW_e at the array busbar, based on reference 25. The mass of the spacecraft systems (array supporting structure, stability, and control) is assumed to be from 10 to 12 percent of that for the array. Previous work has shown that the specific mass of the electric-discharge laser ranges from 0.5 kg/kW_L (ref. 19) to 1.4 kg/kW_L (ref. 10). For this analysis, a 30-percent efficiency and a specific mass of 0.6 kg/kW_L is assumed. The heat-pipe thermal radiator systems for laser waste-heat rejection at 700 to 800 K are estimated to have a mass of 0.23 kg/kW_T of heat radiated. (See, for example, ref. 22.) The 30-m-diameter laser-transmitter sytems are projected to weigh 30 000 kg each (ref. 21). Hence, the approximate masses for the resulting systems of the power station are:

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[1] LEPS/SEPS trip times ignore occultation. Actual trip times would be about 10 percent higher, but this effect was not of sufficient magnitude to warrant inclusion herein.

System	Mass, kg
GaAs array (330 MW_e)	495 000
Spacecraft systems (structure, controls)	60 000
EDL (100 MW_L)	60 000
Thermal radiator (for 230 MW_T)	55 000
One laser transmitter (30-m diam)	30 000
Total spacecraft mass, kg	≈700 000

Cost estimate.- Projected cost estimates for photovoltaic arrays and electric-discharge lasers vary by several orders of magnitude. Conway et al. (ref. 6) project costs of \$100 000 to \$300 000/kW_e output at the array busbar for advanced GaAs systems. Conversely, a solar power satellite (SPS) analysis (ref. 25) projects costs in the range of \$300 to \$5000/kW_e for mass-produced arrays. Coneybear (ref. 16) observed that a similar disparity exists in the cost estimates for the high power EDL. He projects decreasing costs per kW_L output with increasing power levels. At 100 kW_L, his estimates range from \$300 to \$800/kW_L output. Similarly, Jones et al. (ref. 13) estimate \$48 000/kW_L output for a single 910-kW_L laser and \$300 per kW_L for multiple buys of a 910-MW_L output laser system.

A cost of \$25 000 per kW_e is assumed herein for the 20-percent efficient GaAs array. EDL systems are costed at \$10 000/kW_L output. Power-station launch and orbital-transfer (from LEO to GEO) costs are estimated at \$1000/kg and \$50/kg, respectively. The orbital transfer costs are derived from appendix A and assume the use of reusable ion-thruster systems. Power for the thrusters is assumed to be provided by the first unit power station itself. Seven ion-thruster systems, each providing orbital transfer for 100 000 kg at a cost of \$30 million each (see appendix A) are utilized for the 700 000-kg power-station transfer. Upon completion of the transfer, these thruster systems are returned to LEO for integration with cargo-carrying OTV's. Prorated costs for the one-way power-station orbital-transfer trip are thus \$35 million. Research and development (R & D), design, development, test, and evaluation (DDT & E) costs are assumed to total \$1 billion (i.e., \$500 million each).

Hence, the approximate costs for the 100-MW_L photovoltaic array/EDL power station are:

Cost element	Cost, millions of dollars
First unit	
Array (330 MW_e at \$25 000/kW_e)	8 200
EDL (100 MW_L at \$10 000/kW_e)	1 000
Transmitter (30-m diam), each	100
Launch (700 000 kg at \$1000/kg)	700
Orbital transfer (700 000 kg at \$50/kg)	35
R & D	500
DDT & E	500
Total spacecraft cost	≈11 000

Direct Nuclear-Pumped Laser Power Station

Mass estimate.- The estimate of 140 000 kg (ref. 17) has been assumed for the gas-core reactor laser system. The fuel-reprocessor and waste-heat disposal system specific masses of 0.04 and 0.02 kg/kW nuclear power, respectively, were taken from Williams and Clement (ref. 26). The mass of the turbogenerator/compressor is based on 0.27 kg/kW_e generator power (ref. 21), and the radiator mass assumes 0.23 kg/kW_T of waste heat (ref. 22). Williams and Clement have also estimated that 2250 kg/m^2 of nuclear shielding (shadow shield) are required for a 23 000-MW nuclear power system. Scaling this to 1000 MW nuclear power yields 100 kg/m^2 of shielding to enclose the 5-m diameter 6-m long nuclear reactor, the fuel reprocessing, and the waste-disposal systems. The volume of the latter two systems is assumed to be three times that of the reactor itself. The resulting system masses of the utility are:

System	Mass, kg
Reactor/laser (1000 MW nuclear; 100 MW_L)	140 000
Fuel reprocessing	40 000
Waste disposal	20 000
Turbogenerator/compressor (90 MW_e)	25 000
Thermal radiator (810 MW_T)	185 000
Nuclear shielding	60 000
One laser transmitter (30-m diam)	30 000
Total spacecraft mass, kg	≈500 000

Cost estimate.- The cost of terrestrial-based solid-fueled nuclear plants operating at 20- to 30-percent efficiency was about $\$300/kW_e$ in 1973 (ref. 27) and less than $\$1000/kW_e$ in 1976 (ref. 25). A space-based, power-intensive, gas-core reactor, with its much smaller size and higher temperature capability operating at 30-percent efficiency, should not exceed the $\$1000/kW_e$ cost of the terrestrial system. Thus, for the space-based system operating at 10-percent overall efficiency for nuclear-to-laser energy conversion, a cost of $\$3000/kW_L$ output power is assumed. The fuel-reprocessor, waste-heat disposal, and turbogenerator systems are estimated to add another $\$1000/kW_L$ to the costs, resulting in a total of $\$4000/kW_L$ output power for the direct nuclear-pumped power station. The nuclear reactor or the Brayton cycle turbogenerators can provide adequate onboard power for the orbital-transfer ion thrusters.

Extensive R & D costs would be required to develop this system. Costs of $1500 million and $500 million are assumed for the gas-core reactor and laser R & D costs, respectively. DDT & E costs for a small-scale version of the 100-MW_L flight unit are estimated to be the same as the first space-based operational unit costs.

Hence, the approximate costs for the DNPL power station are:

Cost element	Cost, millions of dollars
First unit	
DNPL (100 MW_L at \$4000/kW_e)	400
Transmitter (30-m diam), each	100
Launch (500 000 kg at 1000/kg)	500
Orbital transfer (500 000 kg at \$50/kg)	25
R & D	
Nuclear reactor	1500
Laser	500
DDT & E	400
Total spacecraft cost	≈3500

Direct Solar-Pumped Laser Power Station

Mass estimate.- System masses were computed with the Large Advanced Space Systems (LASS) computer-aided design and analysis program developed by Leondis (ref. 28). Calculations were made for both a 10-percent efficiency with a solar collector 1000 m in diameter and for a 1-percent efficiency with a collector 3000 m in diameter. The solar collector is a parabolic reflector consisting of a 0.5-mil aluminized Kapton[2] reflective surface and a high-emissivity chromium-blacked back surface to passively radiate the unusable solar energy to space. The supporting collector structure is a graphite composite truss system designed as shown in figure 16. Graphite composite elements also support the 50 quartz laser tubes shown in figure 10. Each tube is 1 m in diameter, 50-m long and 0.3-cm thick. The resulting system masses are:

System	Mass, kg	
	η = 10 percent	η = 1 percent
Solar collector		
Reflective membrane	25 000	260 000
Supporting structure	35 000	230 000
Laser (100-MW_L output)		
Laser tubes	90 000	90 000
Supporting structure	60 000	60 000
Thermal radiator	25 000 (for 100 MW_T)	440 000 (for 1900 MW_T)
Attitude control system	5 000	30 000
Laser transmitter (30-m diam)	30 000	30 000
Total spacecraft mass, kg	270 000	1 150 000

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[2] Kapton: Registered trade name of E. I. du Pont de Nemours & Co., Inc.

Cost estimate.- First-unit and DDT & E costs for the major structural components, and control systems costs were calculated with the LASS program (ref. 28) from cost-estimating relationships developed specifically for large advanced spacecraft. The computed costs are $12 000 and $34 000/$\text{kW}_L$ output power for the 10- and 1-percent solar-to-laser power systems, respectively. The solar-pumped laser DDT & E costs were calculated at 2.5 and 1.6 times the first-unit costs for the 10- and 1-percent systems, respectively. Most of the costs are associated not with the laser system, but with the large-spacecraft (structure and control systems) DDT & E effort required to develop flight-qualified units of a size unprecedented in space or on Earth. Laser-system R & D costs of $500 million are assumed for both DSPL power stations.

The DSPL may not be capable of providing power to reusable thruster systems for orbital transfer of the first unit from LEO to GEO. Use of chemical OTV's would cost approximately $90 million and $360 million for the 10-percent and 1-percent DSPL's, respectively, including propellant launch costs.

Hence, the approximate costs for the DSPL power station are:

Cost element	Cost, millions of dollars
10-percent solar-to-laser DSPL:	
DSPL (100 MW_L at $12 000/$\text{kW}_L$)	1200
Transmitter (30-m diam), each	100
Launch (270 000 kg at $1000/kg)	270
Orbital transfer (chemical OTV)	90
R & D	500
DDT & E	3000
Total cost for 10-percent-efficient DSPL	≈5200
1-percent solar-to-laser DSPL:	
DSPL (100 MW_L at $34 000/$\text{kW}_e$)	3 400
Transmitter (30-m diam), each	100
Launch (1 150 000 kg at $1000/kg)	1 150
Orbital transfer (chemical OTV)	360
R & D	500
DDT & E	5 400
Total cost for 1-percent-efficient DSPL	≈10 900

Comparative Analysis

Mass estimates for the candidate central power stations are shown in figure 14. On a comparative mass basis, the 10-percent-efficient, direct solar-pumped laser power station is most attractive. However, the authors estimate that the uncertainties in system and subsystem masses could result in an error band for the overall power-station masses on the order of 0.5 to 2. With this level of uncertainty, if the DSPL efficiency is much less than 10 percent, all the central-power-station concepts would be competitive on a mass basis.

On a relative mass basis, certain systems consistently show mass advantages over other systems for the various power stations. For example, the DSPL reflector/concentrator consistently has a lower mass per unit area than the photovoltaic array (0.03 vs 0.4 kg/m^2 assumed in this analysis). To a first-order approximation, supporting structural and control-system masses per unit area for the solar concentrator or solar array should be about the same. Rigid-body control-system masses would be somewhat higher for the photovoltaic array. However, there are offsetting surface figure-control actuator masses required by the DSPL concentrator for focusing the solar radiation on the laser tubes. Active surface controls should not be required for the photovoltaic array, since local excursions from solar normal (±5 percent) would have negligible influence on performance.

Relative changes in the efficiencies of the DSPL power-station system (even for the same overall efficiency) would significantly modify the systems' masses. For example, in the case of the 1-percent DSPL, if only 10 percent of the solar spectrum is usable for lasing (rather than the assumed 20 percent) and the laser is 10-percent efficient (rather than the assumed 5 percent), the solar-collector mass would be double that shown in figure 14, and the thermal radiator mass would decrease by a factor of two. The net effect on the total power-station mass would be negligible in this instance.

A relatively heavy waste-heat rejection system is required for the DNPL power station because of the low operating temperatures. Future research efforts may produce lasant gases which lase at higher temperatures. If so, the overall nuclear-pumped laser cycle could be operated at higher temperatures than those shown in figure 8. This would improve the efficiency of the bottoming Brayton cycle, reduce the amount of waste heat to be rejected, and raise the heat-rejection temperature. This combination of changes would lead to a reduced radiator mass requirement and result in a DNPL power station equally competitive on a mass basis with the 10-percent DSPL power station.

Summary cost comparisons for each of the major systems, including launch costs of $1000/kg of power-station mass, are shown in figure 15. Cost of the DNPL power station is projected to be about a factor of 3 less than the probable costs of the lower-efficiency DSPL and the photovoltaic-array/EDL power stations. The costs for the photovoltaic-array power station are dominated by the cost of the photovoltaic array itself, whereas the DSPL and DNPL costs are associated principally with the smaller-scale laboratory research and development and the space-prototype DDT & E costs - not the first operational unit. Even with the low photovoltaic-array cost estimates used in this analysis ($25 000/$kW_e$), the direct-pumped laser power stations are clearly candidates for future space-to-space power systems. Failure to reduce the array costs to this level would give an even more overwhelming advantage to the direct-pumped laser systems over the current state-of-the-art photovoltaic-array/EDL approach.

USER BENEFITS

Potential benefits of space-based central power stations are examined for two classes of future users: (1) Earth-orbiting satellites requiring electrical power, and (2) orbital-transfer vehicles requiring power for propulsion.

Earth-Orbiting Satellites

Cost-estimating relationships are developed in appendix B for both onboard and remotely powered satellites. It is shown in appendix B that the beaming of continuous power to electrical users is never cost effective when the same fundamental power-generation system that is used on the central power station is readily available as an onboard system. Thus, the photovoltaic-array central power station can never compete with onboard photovoltaic arrays. This is due simply to the additional inefficiencies introduced in the energy conversion, transmission, and reconversion systems which are not required for onboard, self-powered systems. At projected system efficiencies, the cost and size of the photovoltaic array on the central power station would be at least seven times greater than the corresponding total cost and size of arrays for self-powered satellites.

Onboard and remote electrical power cost ranges for user satellites are shown in figures 17 and 18 for the DNPL and the DSPL power stations, respectively. The estimated cost per kW_e to the user is plotted versus the average power required by each user. The figures indicate that remotely powered satellites would be marginally competitive at best, with \$100 000 to \$300 000/kW_e solar arrays, and then only in the 10- to 100-MW average-power-level ranges. Mass-produced solar array costs could possibly decline to the solar-power satellite-analysis estimates (ref. 25) of \$300 to \$500/kW_e. At these optimistically low costs, remotely powered satellites would not be cost competitive at any power level with onboard self-powered satellites.

Although no orbiting satellite users are identified in the NASA mission model (ref. 10) that require power levels above hundreds of kilowatts, it is speculated that in the distant future space industrialization activities will expand to large-scale manufacturing plants requiring megawatts of power. Thus, on the surface (should solar-array costs remain sufficiently high to provide a cost advantage to remotely power systems from 10 to 100 MW_e) the question of development of a space-based power station to remotely power a number of satellites of over 10 MW_e appears to be one of timing (perhaps by the middle of the next century). However, a more logical question would be to ask if there is a less costly alternative to the photovoltaic-array onboard power system for very large power needs. For example, a power-intensive nuclear system at \$1000 to \$10 000 per installed kW_e could be installed onboard at a significantly lower cost to the user than that for the purchase of power from a central power station.

Therefore, it is concluded that the implementation of a central space-based power station for the sole purpose of remotely powering Earth-orbiting satellites cannot be justified economically. However, if other applications lead to the development of such a system, orbiting satellites could use excess power available in a cost-effective manner. The orbital-transfer application discussed in the next section may provide this economic justification.

Remotely Powered Propulsion Systems

The results presented here are an expansion of an earlier study reported by Garrett and Hook (ref. 29). The comparison of onboard propulsion with remotely powered propulsion is based on the round-trip delivery of cargo from LEO to GEO. All OTV's are assumed to be space-based. An advanced chemical system is compared with a remotely powered laser thermal propulsion system (LTPS), and a solar electric propulsion system (SEPS) is compared with a remotely powered laser electric propulsion system (LEPS). The OTV performance characteristics have been discussed and are summarized in table A1. Overall cost-estimate data used in this analysis of competing transportation vehicles are given in table A2.

Rather than use a specific mission need projection for a specific time period, the scenario considered (fig. 19) assumes delivery of 1 000 000 kg mass from LEO to GEO in the first year of operation of the central power station. The mass delivery demand then increases at a rate of 10 percent annually thereafter. Thus, in 20 years the payload to GEO demand has increased by a factor of 6. The SEPS, LEPS, and chemical systems deliver the payload in increments of 100 000 kg per trip. Thermal constraints (caused by focusing many megawatts of power on small area windows and cavities) are assumed to limit the LTPS to 20 000 kg of cargo per trip, which is consistent with the delivery of 70 MW thruster power. Initially, one advanced, single-stage, chemical OTV or three laser-powered LTPS OTV's are required. Alternatively, five SEPS or LEPS OTV's would be required because of the long trip times (approximately 180 days per round trip) associated with these systems. The number of operational vehicles required is shown for each propulsive system based on the 50-trip lifetime assumed for chemical and LTPS OTV's and on the 3-trip lifetime assumed for SEPS and LEPS. Also noted in parentheses is the cumulative number of vehicles retired from service.

The total power requirements for the SEPS/LEPS and for the LTPS OTV's are noted on the ordinate of figure 19. Each LEPS OTV requires continuous power, whereas, since the LTPS requires power only during brief perigee and orbital circularization phases, power from the central power station can be cycled between the multiple LTPS OTV's. Therefore, only one transmitter is required.

Cumulative cost comparisons for the total OTV system and all launch costs required, including those for the cargo, are shown in figures 20 and 21 for the competitive OTV systems. The costs for chemical systems, because of the massive propellant requirements, are dominated by the launch costs. Costs for the SEPS are almost equally divided between launch and photovoltaic-array costs.

Estimated cumulative cost advantages of the remotely powered LTPS over the chemical OTV and the remotely powered LEPS over the SEPS are shown in figure 22. The remotely powered systems costs include amortization of a space-based DSPL central power station ($\approx$200-MW$_L$ output) which has been sized to meet the cumulative power requirements of the OTV's in the 20th year. Cumulative costs savings in a 30-year period for remotely powered over conventional OTV's are projected to be \$270 billion for LTPS over chemical and \$60 billion for LEPS over SEPS. The use of the alternative DNPL power station would show similar cost advantages for the remotely powered systems. The photovoltaic-array central power station, when used for LEPS remote power, would be only marginally competitive with SEPS because of the inefficiencies of the laser-power energy conversion, transmission, and reconversion processes. However, a photovoltaic-array central power station providing remote power to a LTPS would show a cost savings on the order of \$200 billion, even if GaAs costs reach the upper estimate of \$300 000/kW$_e$. The conclusion that the remotely powered orbital-transfer systems (LTPS and LEPS) are more cost effective than conventional systems (chemical and SEPS) would not change unless the central-power-station costs increase by at least an order of magnitude above that assumed in this analysis or unless launch costs decrease by more than an order of magnitude. Studies of heavy-lift launch vehicles which might be developed for launching solar-power satellites (see, for example, ref. 30) have led to projections of launch costs in the \$50/kg range, compared with the \$1000/kg assumed in this analysis. If future payloads could be launched at \$50/kg, then the remotely powered LTPS (including amortization of the central power station) and the chemical OTV's would cost about the same. The LEPS-over-SEPS cost advantage over a 30-year period would remain at about $50 to $60 billion because of the difference in the solar-array costs of the two systems if launch costs were reduced to $50/kg.

Consequently, even if the more optimistic cost projections for onboard solar arrays and launch come to fruition, central-power-station concepts for remotely powering orbital-transfer vehicles show sufficient relative economic advantages over advanced conventional OTV's. This justifies the pursuit of laboratory experiments and technology developments along several fronts.

Other Applications

Given the apparent economic justification for a space-based central power station for remotely powered orbital transfer, the application of this capability to other users may be considered. Within the time frame of a central power station, for example, laser-powered aircraft may be feasible (ref. 31). Similarly, remotely powering spacecraft beyond Earth orbit could be easily accomplished from a central power station designed to support remotely powered propulsion OTV's.

Farther downstream, a central power station could be a major step in enabling mining of the moon and asteroids to replace depleted Earth resources. This capability might even make feasible the recovery of asteroids.

The ultimate application of a central power station in space is left to the imagination of the reader and future generations as yet unborn. Nonetheless, it is fair to say that if a system such as the central power station can be justified for a single use - such as remotely powered propulsion - the spinoff applications will be numerous and diverse.

FUTURE WORK

As stated in the "Introduction," the authors hope this paper will stimulate further analysis that will serve to provide near-term direction to development of the technology required in the long term to fully reap the benefits available from exploitation of space. Although the three space-based central power stations considered in this paper are among the leading contenders for future space power-generation, they are by no means an exhaustive set. An indirectly pumped solar laser, for example, would have basically the same characteristics as the DSPL system, except that the laser cell would be surrounded by a blackbody cavity which would be heated by solar radiation. This concept allows the peak of the solar spectrum to be shifted to match the peak absorption wavelength of the lasing gas. Overall solar-to-laser energy conversion may be improved over DSPL systems. However, the development of high-temperature, long-life materials for the laser windows will be required.

Another promising approach would use a high-efficiency gas-core reactor operating at high temperatures to create electricity via turbogenerators and possibly magneto-hydrodynamic (MHD) systems to drive relatively high-efficiency CO EDL's. This might result in improved efficiencies over direct nuclear-pumped projections and reduce the thermal radiator sizes by at least an order of magnitude because of less waste heat and higher rejection temperatures. However, this system requires the development of ultra-high-temperature materials and, in some cases, materials resistant to corrosive chemical processes prior to commitment to space operations. Williams and Clement (ref. 26) provide performance, mass, and cost estimates for the gas-core reactor/MHD system.

The general area of converters for laser light deserves special attention. While the conversion systems treated in the present paper have efficiencies in the range of 50 percent, the theoretical possibility of significantly higher conversion efficiencies should be recognized. Because of its nearly monochromatic, coherent nature, laser light is essentially a zero-entropy medium. Hence, most of the energy in laser light is potentially available for conversion rather than being in a disordered, unavailable form. Creative new approaches to converter design, capitalizing on this potential, would significantly enhance the central-power-station benefits discussed in this paper.

The analysis presented herein, while only a first-cut approximation at best, identifies potential cost savings and increased mission flexibility of sufficient magnitude to readily justify more refined and detailed studies. The space-based central power plant may well be a suitable focus for the next quantum step toward a true "space age."

TECHNOLOGY NEED IMPLICATIONS

A cost-savings potential has been established for advanced, space-based central power stations for remotely powered propulsion applications. With this economic justification, a central power station may also be cost effective in providing electrical power needs for Earth-orbiting satellites or in enabling a variety of other space missions which are beyond the realm of possibility today.

The techonology feasibility is quite another situation. Many of the technologies that must be developed in order to make a central power station a reality are identified in this paper. The most pressing need is for experimental and theoretical research to address, on a small scale, those fundamental technologies that are critical to future central power stations. The primary critical technology needs for the central power stations relate to the efficiency of the power conversion. Mass and cost sensitivities are appropriate figures of merit to consider in the assessment of technology needs at the systems level. A dramatic variation in total mass and cost is shown in figures 14 and 15 in the comparison of the 10-percent-efficient and 1-percent-efficient DSPL power stations. The cost and mass increases of the 1-percent-efficient system (relative to the 10-percent efficiency) are driven primarily by the necessary increase in solar-collector and thermal-radiator sizes, not by changes in the laser system. Similar relationships exist for the other central-power-station concepts.

A listing of first-order research and technology needs which are critical to enabling the laser systems and their attendant large spacecraft is presented in table 1. For any of the laser systems possible, long-life, closed-cycle operation and low maintenance are mandatory.

TABLE 1.- KEY RESEARCH AND TECHNOLOGY NEEDS

Solar-pumped laser
- More efficient lasing system (>1 percent)
- Long-life, closed-cycle operation
- High-temperature lasing media
- Chemically stable lasing gas
- High-power optics

Nuclear-pumped laser
- High-power gaseous-core laser reactor (>1 MW)
- Long-life, closed-cycle operation
- Physics of fission-fragment/lasing-gas interactions
- High-temperature lasing gases (>700 K)
- High-power optics

Spacecraft and OTV
- Large highly accurate adaptive optical collectors and transmitters
- Laser-to-electrical power converters
- Large high-temperature thermal radiators
- High-accuracy distributed control systems
- High-temperature materials
- Long-life highly reflective materials
- In-orbit assembly

Availability of power-intensive systems will be a controlling factor governing the rate of space utilization and industrialization over the next century. Unfortunately, the funding support for research and technology development work in this field is small, even though the funding needed for advanced power systems is very modest relative to the potential benefits. For example, the nuclear power program for space applications has suffered fitful starts and terminations over the last 2 decades and is almost nonexistent today. Solar-pumped lasers are in the early laboratory stage and even after the technology is developed will require at least a decade to achieve spaceflight readiness.

A forecast for generic space power systems development is shown in figure 23. This scenario projects incremental increases in installed photovoltaic-array power up to 1 MW_e for orbiting satellite needs. Above 1 MW_e, the photovoltaic-array sizes become so large that spacecraft control considerations will dictate the development of more compact power-intensive systems such as nuclear reactors. These power-intensive systems could be available after the turn of the century to support applications requiring onboard power above the 1-MW_e level. Eventually, incremental improvements in power-intensive systems and direct-pumped laser systems should increase output capabilities, and the minimum-power threshold could be lowered to make these systems economically competitive with advanced photovoltaic arrays. Perhaps by the year 2020, space-transportation traffic volume (propulsion), coupled with other power demands, could lead to the implementation of a central power station with an output level of 10 to 100 MW.

Even in that distant time, 40 years in the future, the scope of feasible space activity will be heavily reliant on the success achieved in our research laboratories during the next 2 decades. Further analysis is critical to solidifying the need for and providing direction for advanced energy-generation research.

CONCLUDING REMARKS

The need for a central power station in the future depends on many factors. Beaming power to remote users cannot be cost effective if the central power station uses the same power-generation system that would be readily available for provision of onboard power. Similarly, microwave transmission and reception of power through space for use in space cannot be cost competitive with onboard power or propulsion systems - the size of the receiver is prohibitive. Laser transmitters/receivers are required to make central power stations feasible.

Analysis of the cost effectiveness of meeting the electrical-power demands of an Earth-orbiting spacecraft from a central power station indicates that this application cannot justify the investment required for a central power station. However, cost benefits (within the bounds of the assumptions made herein) are of a sufficient magnitude to justify the research and development activities necessary to enable the central power station. Direct nuclear-pumped or solar-pumped laser power-station concepts are particularly attractive with the laser thermal propulsion system and/or the laser electric propulsion system. These systems are also competitive, on a mass and cost basis, with a photovoltaic power station.

The most critical assumption that leads to the above conclusions is that the launch costs from Earth to LEO will remain in the range of $1000/kg currently quoted for the space transportation system. However, if Earth-to-orbit launch costs were reduced significantly (at least an order of magnitude), the remotely powered laser thermal propulsion system would be comparable in cost to the chemical OTV. In this event, a single use (propulsion of OTV's) would not be sufficient to justify a central power station; however, multipurpose uses might still provide a convincing justification.

Langley Research Center
National Aeronautics and Space Administration
Hampton, VA 23665
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APPENDIX A

COST DATA FOR CONVENTIONAL AND REMOTELY POWERED ORBITAL-TRANSFER VEHICLES

Four orbital-transfer vehicles (OTV) are considered in the comparison of conventional and remotely powered transportation of cargo from low-Earth to geosynchronous Earth orbits. An advanced chemical system is compared with a remotely powered laser thermal propulsion system (LTPS) and a solar electric propulsion system (SEPS) is compared with a remotely powered laser electric propulsion system (LEPS). Data on the assumed characteristics and performance of the competing transportation vehicles are given in table A1. Overall cost data estimates are shown in table A2. OTV performance and cost data were obtained from references 7 to 9 and 24 and from in-house vehicle-analysis programs and data bases.

TABLE A1.- TRANSPORTATION-VEHICLE PERFORMANCE CHARACTERISTICS

Characteristics	OTV system			
	CHEM	SEPS	LEPS	LTPS
Propellant	LOX/LH_2	Argon	Argon	LH_2
Specific impulse, sec	476	6000	6000	1500
Round-trip time, days	7	173	158	14
Lifetime, number of round trips	50	3	3	50
Cargo delivered per trip, kg	100 000	100 000	100 000	20 000
Power requirements, kW_e		3300	3000	70 000
Collector/receiver system		GaAs array	GaAs array	Laser concentrator
- Efficiency, percent		20	50	60
- Size, m^2		12 500	314 (20-m diam.)	314
Mass fractions, percent				
- Dry	5	18	9	7
- Propellant	70	12	11	29
- Cargo	25	70	80	64
Round-trip fuel requirements, kg	275 000	18 000	14 300	9900 (for 20 000 kg cargo per trip)

TABLE A2.- TRANSPORTATION-VEHICLE COST ESTIMATES

Transportation vehicle	Costs	
	Unit or subsystem	System, millions of dollars each
Launch to low-Earth orbit	\$1000 per kg	
Chemical OTV (LOX/LH_2)		40
SEPS OTV (3.5 MW_e)		146
- Solar array and OTV subsystems	\$116 million per OTV	
- Ion thrusters	\$ 30 million per OTV	
LEPS OTV (3.0 MW_e)		
- Laser receiver and OTV subsystems	\$3.3 million per OTV	33
- Ion thrusters	\$30 million per OTV	
LTPS OTV (70 MW_e)		40
Propellant:		
- Argon	\$0.40 per kg	
- LOX/LH_2	\$0.47 per kg	
- LH_2	\$2.20 per kg	

APPENDIX B

DEVELOPMENT OF COST-ESTIMATING RELATIONSHIPS FOR ONBOARD AND REMOTE ELECTRIC POWER-GENERATION

Introduction

Cost-estimating relationships (CER) are developed for onboard and remote electric power-generation for Earth orbiting satellites. The baseline onboard system used for comparison is the advanced gallium arsenide (GaAs) photovoltaic array. For remote-power applications, three central-power-station systems are considered: (1) an advanced GaAs photovoltaic array which powers electric discharge lasers (EDL); (2) direct nuclear-pumped lasers (DNPL); and (3) direct solar-pumped lasers (DSPL). The remote receivers are highly efficient photovoltaic arrays in which the laser transmission frequency has been tuned to the spectral bandwidth in which the laser-to-electrical energy conversion process is most efficient.

The CER's are developed in terms of cost per kilowatt of electrical power (kW_e) to the satellite user. The sources for cost and performance estimates are quoted in the main body of the paper. Capital letters C and M denote the total costs and mass, respectively. Lower case c and m denote unit costs and mass, respectively.

Onboard Power CER's

The onboard photovoltaic array is assumed to be a state-of-the-art system available in the same time frame as that associated with the advanced concepts. Additional research and development costs are not required to space-rate the system. Thus, the relative cost[3] per kW_e to an electrical user of onboard power from a solar photovoltaic array is assumed to be

$$c_{OB} = c_{SA} + m_{SA}c_L \tag{B1}$$

where

c_{OB} cost (dollars) per kW_e to user for electrical onboard power, $\$/kW_e$

c_{SA} cost (dollars) per kW_e for solar array

c_L launch cost (dollars) per kg of solar array

m_{SA} unit mass (kg) of solar array per kW_e

---

[3] Costs are relative since certain subsystem costs (such as batteries) are about the same to the user with either onboard arrays or remote receiver systems.

Solar-array costs are estimated at a nominal value of \$100 000/kW$_e$. A unit mass of solar array and support structure of 2 kg/kW$_e$ and a nominal launch cost based on Space Transportation System (STS) estimates of \$1000/kg are assumed. The resulting CER for onboard power for a solar photovoltaic array is

$$c_{OB} = 100\ 000 + (2)(1000) = \$102\ 000/\text{kW}_e \tag{B2}$$

This is the estimated cost to the user in dollars per kW$_e$.

CER's For Remotely Powered Satellites

To a first-order approximation, the relative costs of remote power to electrical users consist of the following major cost elements:

(1) First-unit costs for central power station

(2) Design, development, testing, and evaluation costs for central power station

(3) Research and technology development costs for advanced power subsystems

(4) User receiver system costs

(5) Launch costs for the first unit and user receivers

Operations and maintenance costs and orbital-transfer costs from low-Earth orbit (LEO) to geosynchronous-Earth orbit (GEO) for the first unit are assumed to be secondary and are neglected in this analysis.

The total costs C_{RP} to all users for remote power are

$$C_{RP} = C_{DDT\&E} + C_{FU} + C_{L,FU} + \left(C_{R\&T}\right)_{PS} + C_{REC} + \left(C_L\right)_{REC} \tag{B3}$$

where

$C_{DDT\&E}$	design, development, testing, and evaluation costs (dollars) for central power station
C_{FU}	first-unit cost (dollars) for power station
$C_{L,FU}$	launch costs (dollars) for power station
$\left(C_{R\&T}\right)_{PS}$	research and technology development costs (dollars) for power station subsystems
C_{REC}	cost (dollars) for all remote-user receivers and energy reconversion systems
$\left(C_L\right)_{REC}$	launch costs (dollars) for all remote user receivers and energy reconversion systems

DDT & E costs can range from a small fraction to a large multiple of the first-unit costs depending on the relative power-output capabilities of the ground-based engineering test units and the space-based first unit. For this analysis let

$$C_{DDT\&E} = aC_{FU} \tag{B4}$$

where a is an analyst-specified fraction (<1) or multiple (>1) of the first-unit central-power-station system costs.

The first-unit costs C_{FU} can be written as

$$C_{FU} = C_{PP} + C_{EC} + C_{T} \tag{B5}$$

where

C_{PP}	cost (dollars) of central power plant generating system
C_{EC}	cost (dollars) of laser energy conversion system
C_{T}	cost (dollars) of laser transmission system

Substituting equations (B4) and (B5) into (B3) yields

$$C_{RP} = (a + 1)\left(C_{PP} + C_{EC}\right)_{FU} + \left(M_{PP} + M_{EC}\right)_{FU}c_{L}$$
$$+ (a_T + 1)C_T + M_Tc_L + C_{R\&T} + C_{REC} + M_{REC}c_L \tag{B6}$$

where M_{PP}, M_{EC}, M_T, and M_{REC} are the masses in kilograms of the power-plant generating system, the laser energy conversion system, the laser transmission systems, and laser receiver systems of the remote user, respectively. Note that a_T is similar to a, representing the relationship of the DDT & E cost for the laser transmission system relative to the first space-based unit cost.

Equation (B6) shows the total costs for the central power station and all user receiver systems. To develop the CER's in terms of the user cost per kW_e of power delivered to the user, it is necessary to recast equation (B6).

The cost per kW_e of user power c_{RP} at the user busbar for each individual user is

$$c_{RP} = \frac{C_{RP}}{\sum_{i=1}^{N} P_i} \tag{B7}$$

where P_i is the average power in kW_e required by the ith user. If it is assumed that all N users require the same level of average power, then

$$\Sigma P_i = NP \tag{B8}$$

where N is the total number of users and P is the average power in kW_e required by each user. Thus, the cost per kW_e of power delivered to a remote user in dollars per kW_e is

$$c_{RP} = \frac{C_{RP}}{NP} \tag{B9}$$

Costs and masses of systems are generally quoted in terms of dollars per kilowatt at the busbar of the system or subsystem under consideration; that is, power-generating systems are costed on the basis of the output power at the busbar, and laser energy conversion systems are costed on the basis of output power from the laser. Because of inefficiencies in the laser energy conversion and transmission system and in the remote receiver and reconversion system, a power-plant output capability greater than ΣP_i is required, thus increasing the costs to the user. For example, in order to deliver 1 kW of power to a remote user, the output power at the power-plant busbar must be increased by the reciprocal of the product of the laser energy conversion and transmission system efficiency, η_{EC} and the remote receiver and reconversion system efficiency η_{REC}. Thus, both the costs and, to a first-order approximation, the mass of the power plant, are increased by $1/\eta_{EC}\eta_{REC}$. Likewise, the laser energy conversion output capacity has to be increased by $1/\eta_{REC}$. Thus, equation (B6) can be written in terms of the system efficiencies, the number of users, and the average power required by each user for equation (B9) to yield

$$c_{RP} = (a + 1)\left(\frac{c_{PP}}{\eta_{EC}\eta_{REC}} + \frac{c_{EC}}{\eta_{REC}}\right)_{FU} + \left(\frac{m_{PP}}{\eta_{EC}\eta_{REC}} + \frac{m_{EC}}{\eta_{REC}}\right)_{FU} c_L$$

$$+ \left[(a_T + 1)c_T N_T + m_T N_T c_L + C_{R\&T}\right]\frac{1}{NP} + \left(c_{REC} + m_{REC} c_L\right)\frac{1}{P} \tag{B10}$$

Equation (B10) is the *generalized equation for cost per* kW_e *of power delivered to a* remote user, where

c_{PP}	cost (dollars) per kW_e output at power plant busbar
c_{EC}	cost (dollars) per kW_L output at laser transmitter
m_{PP}	unit mass (kg) of power plant per kW_e output at busbar
m_{EC}	unit mass (kg) of laser system per kW_L output at transmitter
c_T	cost (dollars) of one transmitter
N_T	number of transmitters
m_T	mass (kg) of one transmitter
c_{REC}	cost (dollars) of one user's receiver/reconversion system

Normally, $N_{REC} = N$ (i.e., one receiver per remote user). The number of transmitters N_T is equal to N when remote systems require continuous power and less than N when any of the users require intermittent power.

For users requiring continuous power, the cost equation becomes

$$c_{RP} = (a + 1)\left(\frac{c_{PP}}{\eta_{EC}\eta_{REC}} + \frac{c_{EC}}{\eta_{REC}}\right)_{FU} + \left(\frac{m_{PP}}{\eta_{EC}\eta_{REC}} + \frac{m_{EC}}{\eta_{REC}}\right)_{FU} c_L + \frac{C_{R\&T}}{NP}$$

$$+ [(a + 1)c_T + m_T c_L + m_{REC} c_L]\frac{1}{P} \tag{B11}$$

The above equation is valid for central power stations where the power-plant system can be treated separately from the laser generation system (i.e., photovoltaic-array/EDL systems). For the direct nuclear-pumped or solar-pumped laser power station, the nuclear or solar energy is converted directly to laser energy with no intermediate electrical power-generation step in the cycle. The direct-pumped systems cost equation then becomes

$$c_{RP} = (a + 1)\left(\frac{c_{PP} + c_{EC}}{\eta_{REC}}\right)_{FU} + \left(\frac{m_{PP} + m_{EC}}{\eta_{REC}}\right)_{FU} c_L + \frac{C_{R\&T}}{NP}$$

$$+ [(a_T + 1)c_T + m_T c_L + m_{REC} c_L]\frac{1}{P} \tag{B12}$$

Cost, mass, and performance estimates are discussed in the main body of the paper for each of the three candidate central power stations and the remote-user receiver systems. The specific values assumed in the development of the CER's for the trade study between onboard and remotely powered Earth-orbiting satellites are developed in the main body of the paper. The resulting CER's are developed below for the remotely powered systems.

APPENDIX B

CER for Solar-Array/EDL Central-Power-Station Transmitting to Remote-User GaAs Photovoltaic-Array Receiver

It can be shown that this system can never be cost competitive with an onboard photovoltaic array by comparing the cost terms in the onboard-power cost equation (B1) with the major terms in the remotely powered user cost equation (B11). Since $c_{PP} = c_{SA}$ (same photovoltaic array) equation (B11) yields the following equation:

$$c_{RP} = (a + 1)\left(\frac{c_{SA}}{\eta_{EC}\eta_{REC}} + \text{Additional terms}\right)$$

Also, since $\eta_{EC} < 1$, $\eta_{REC} < 1$, and $a \geqslant 0$, then c_{RP} is always greater than c_{OB}. Thus, it is never cost effective to beam continuous power to electrical users when the same fundamental power-generation system is on the central power station that would be readily available to user satellites for onboard use (in this case photovoltaic arrays). The additional inefficiencies introduced in the energy conversion, transmission, and remote receiver reconversion systems require increases in the power-generation-system output and thus increased costs to deliver the equivalent level of power to a remote user that would be available with an onboard installed power-generation system. For this case, the photovoltaic-array size and costs for the central power station would be at least seven times greater $(1/\eta_{EC}\eta_{REC} = 1/(0.3)(0.5) \approx 7)$ than the corresponding sizes and costs for onboard systems.

CER for Direct Solar Nuclear-Pumped Laser Power Station

Substituting the DNPL cost and mass parameters into equation (B12) yields the following CER for this power-station transmitting to remote-user GaAs photovoltaic-array receivers:

$$c_{RP} = (1 + 1)\left(\frac{4000}{0.5}\right) + \left(\frac{4.6}{0.5}\right)(1000) + \frac{2000 \times 10^6}{NP}$$

$$+ [(1 + 1)(100 \times 10^6) + (30\ 000)(1000) + 8.8 \times 10^6$$

$$+ (263)(1000)]\frac{1}{P} \qquad \text{(B13)}$$

Simplifying equation (B13) yields

$$c_{RP} = 25\ 000 + \frac{2000 \times 10^6}{NP} + \frac{240 \times 10^6}{P} \tag{B14}$$

This result is the estimated cost to the user in dollars per kW_e.

CER for Direct Solar-Pumped Laser Power Station

Substituting the DSPL cost and mass parameters into equation (B12) yields the following CER for this power-station transmitting to remote-user GaAs photovoltaic-array receivers:

$$c_{RP} = (2.5 + 1)\left(\frac{12\ 000}{0.5}\right) + \left(\frac{2.4}{0.5}\right)(1000) + \frac{500 \times 10^6}{NP} + \frac{240 \times 10^6}{P} \tag{B15}$$

Simplifying equation (B15) yields

$$c_{RP} = 89\ 000 + \frac{500 \times 10^6}{NP} + \frac{240 \times 10^6}{P} \tag{B16}$$

This result is the estimated cost to the user in dollars per kW_e. Equations (B14) and (B16) are used in the main body of the paper to evaluate the relative benefits of remotely powered satellites.

APPENDIX B

TABLE B1.- REMOTE-POWER SUBSYSTEM COST, MASS, AND PERFORMANCE ESTIMATES

Parameter	Type of central power station		
	Solar array/EDL	DNPL	DSPL
$\eta_{PP}\eta_{EC}$,[a] percent	6	10	10
c_{PP}, dollars per $(kW_e)_{busbar}$	100 000		
c_{EC}, dollars per kW_L	10 000		
$c_{PP} + c_{EC}$, dollars per kW_L		4000	12 000
m_{PP}, $kg/(kW_e)_{busbar}$	3		
m_{EC}, kg/kW_L	0.6		
$m_{PP} + m_{EC}$, kg/kW_L		4.6	2.4
η_{EC}, percent	30		
η_{REC}, percent	50	50	50
$C_{R\&T}$, millions of dollars	0	2000	500
c_T, millions of dollars each	100	100	100
a	0	1	2.5
a_T	1	1	1
m_T, kg (30-m diam)	30 000	30 000	30 000
c_{REC}, millions of dollars	8.8	8.8	8.8
m_{REC}, kg (20-m diam)	263	263	263
c_L, dollars per kg	1000	1000	1000

[a] $\eta_{PP}\eta_{EC}$ is the overall efficiency of the central-power-station power-generation, laser energy conversion, and laser transmission systems.

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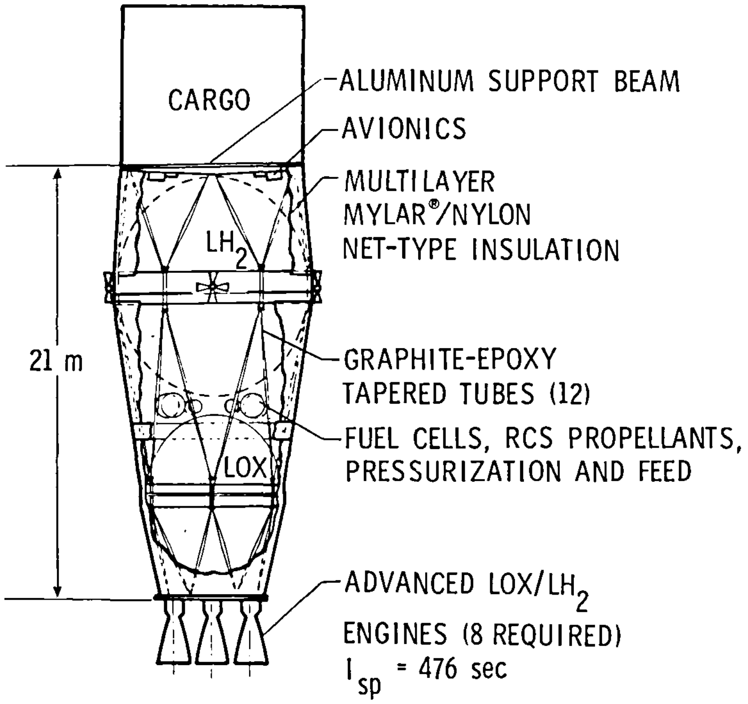

Figure 1.- Chemical orbital-transfer vehicle (OTV). (From ref. 7.)

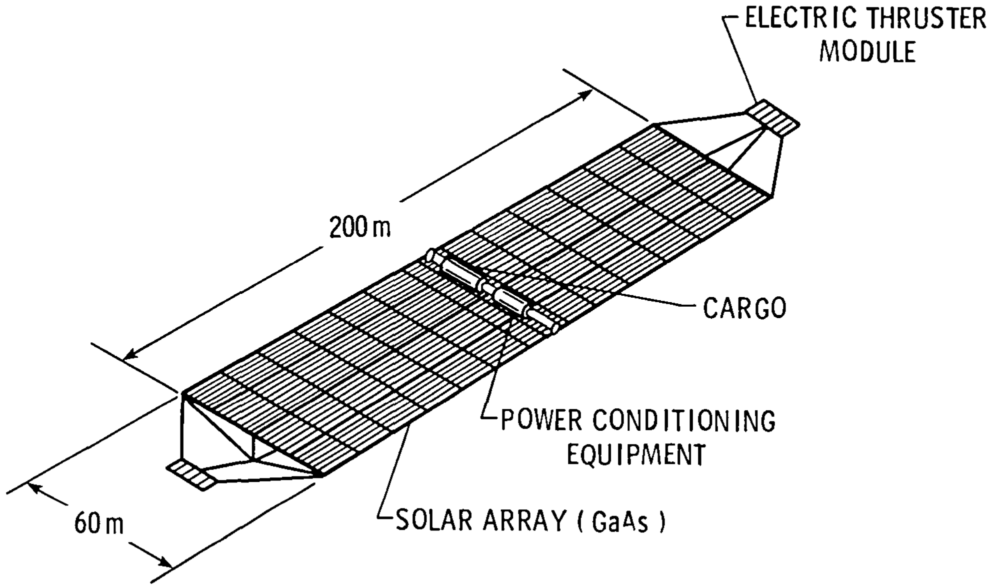

Figure 2.- Solar electric propulsion system concept.

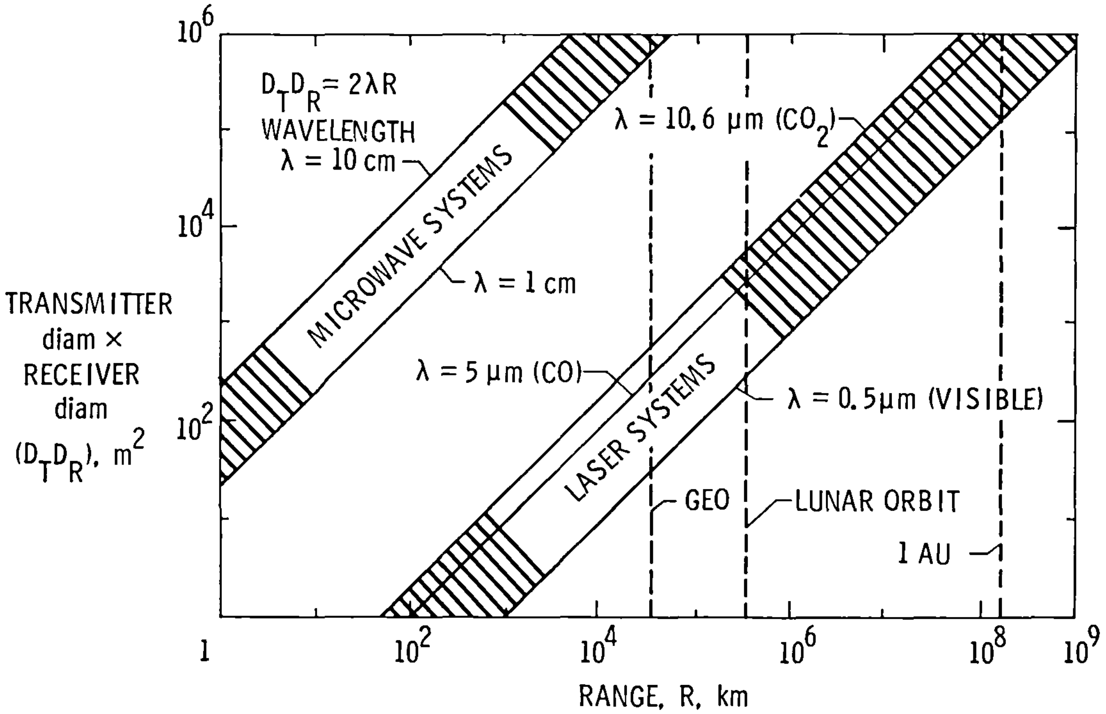

Figure 3.- Transmitter/receiver sizes versus range.

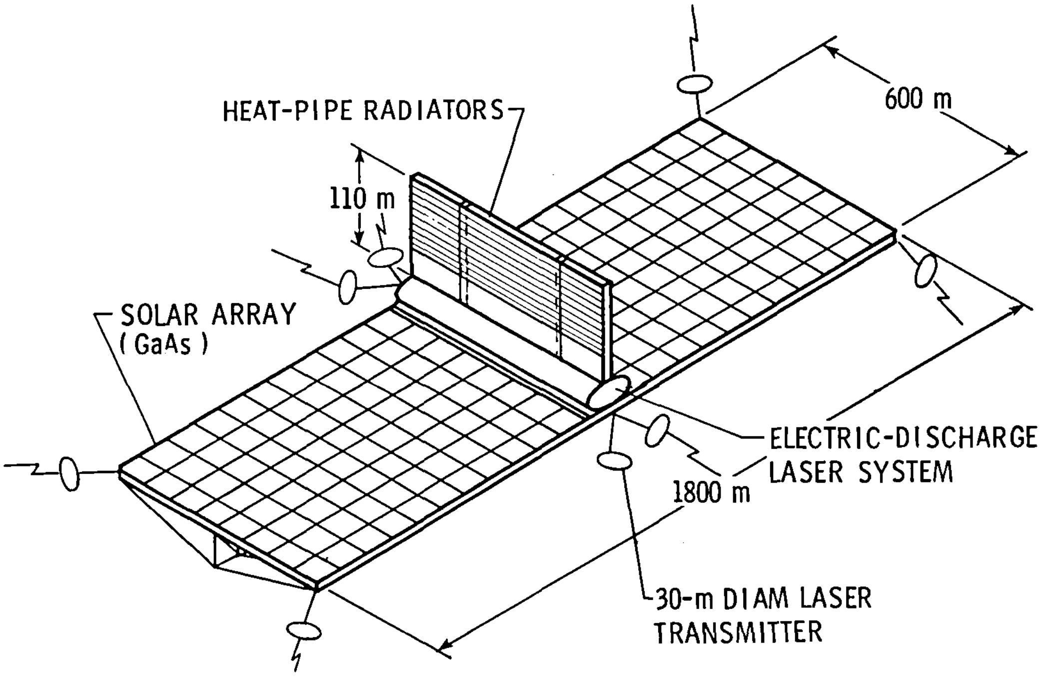

Figure 4.- Photovoltaic-array central-power-station concept. 100 MW_L.

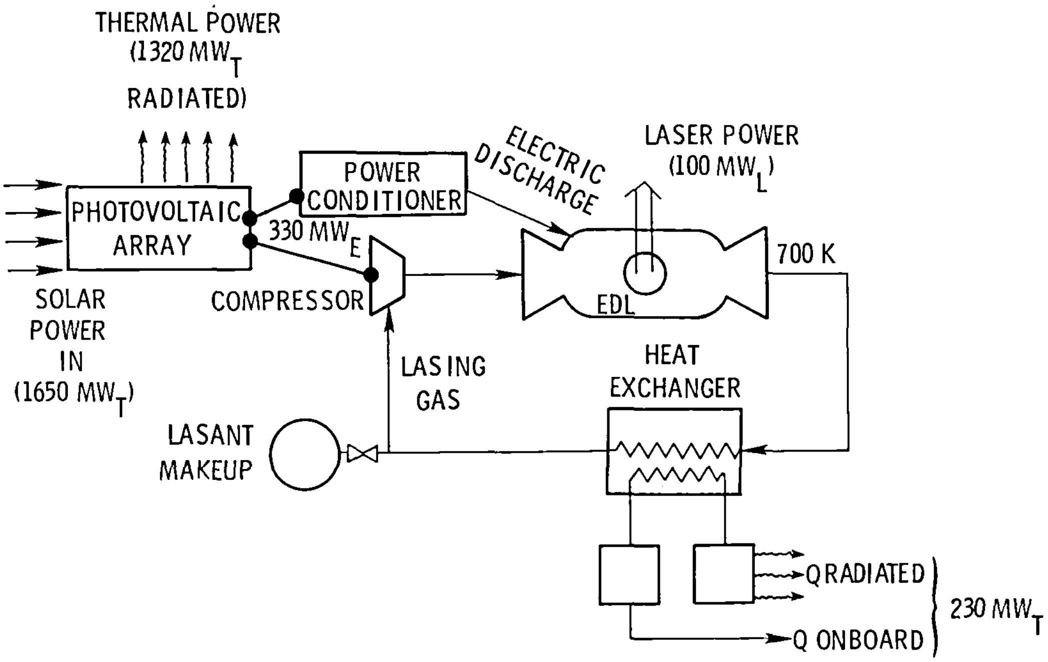

Figure 5.- Cycle schematic for solar-array powered electric-discharge laser.

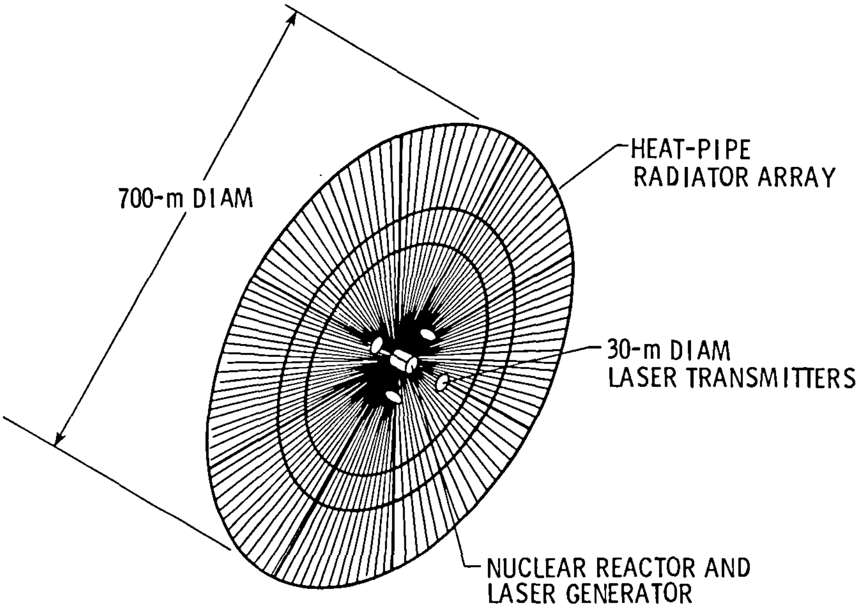

Figure 6.- Direct nuclear-pumped laser power station. 100 MW$_L$.

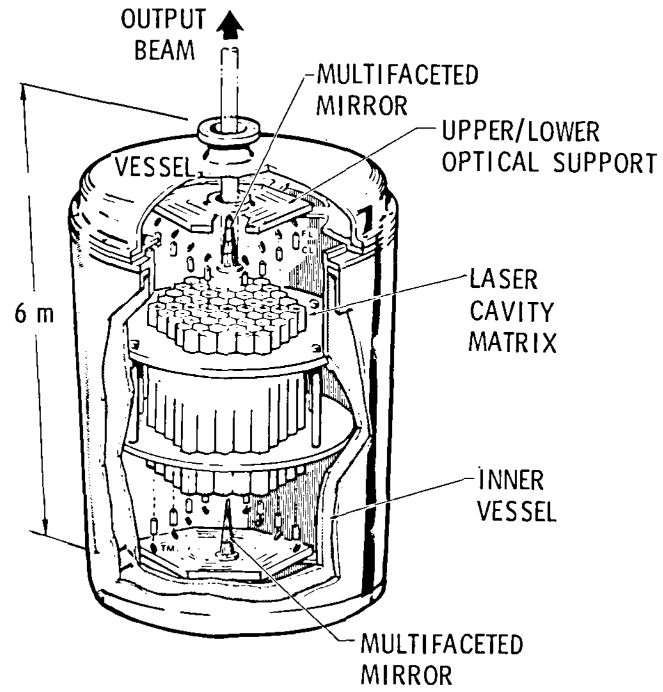

Figure 7.- Conceptual UF_6 gaseous nuclear-pumped laser reactor.

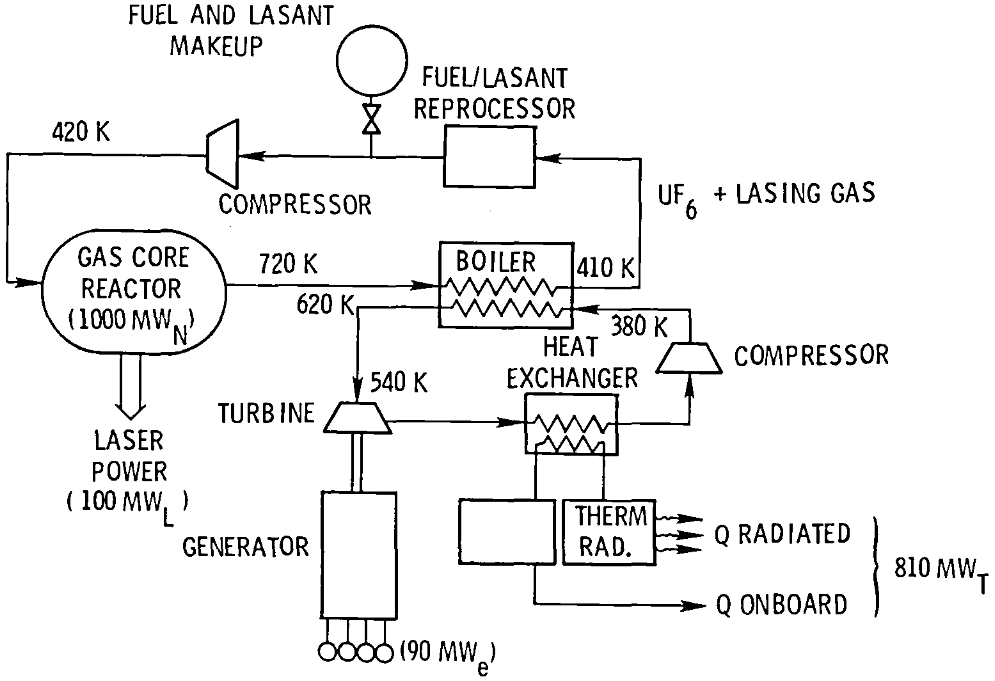

Figure 8.- Cycle schematic for direct nuclear-pumped laser.

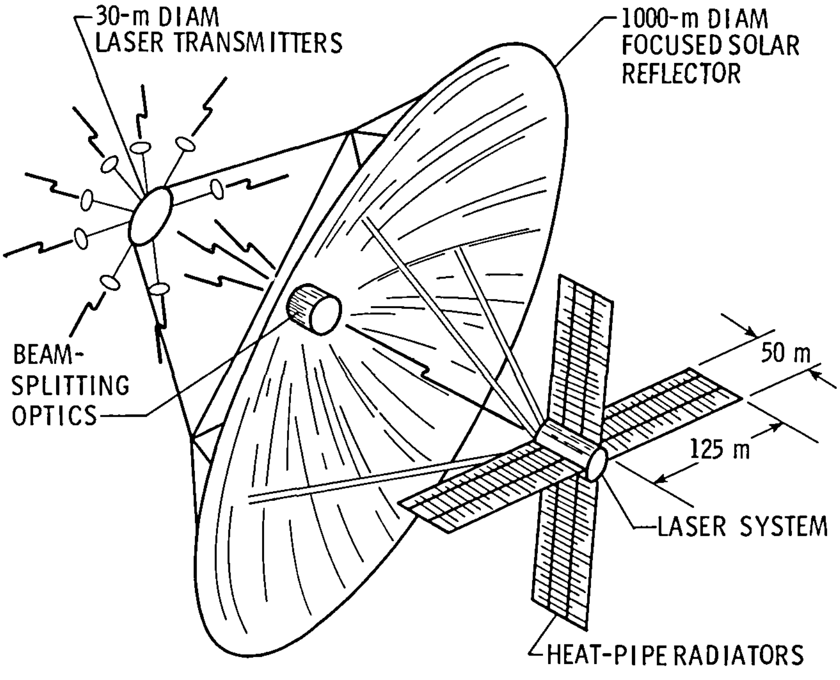

Figure 9.- Direct solar-pumped laser power-station concept. 100 MW_L.

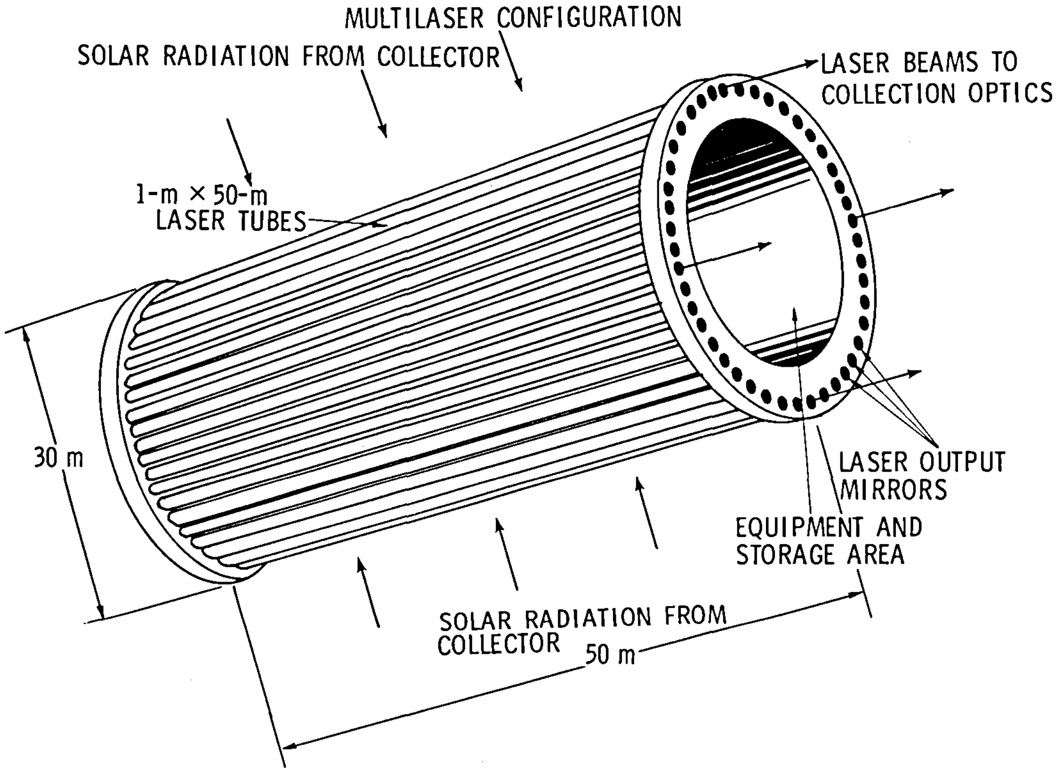

Figure 10.- 100-MW solar-power laser.

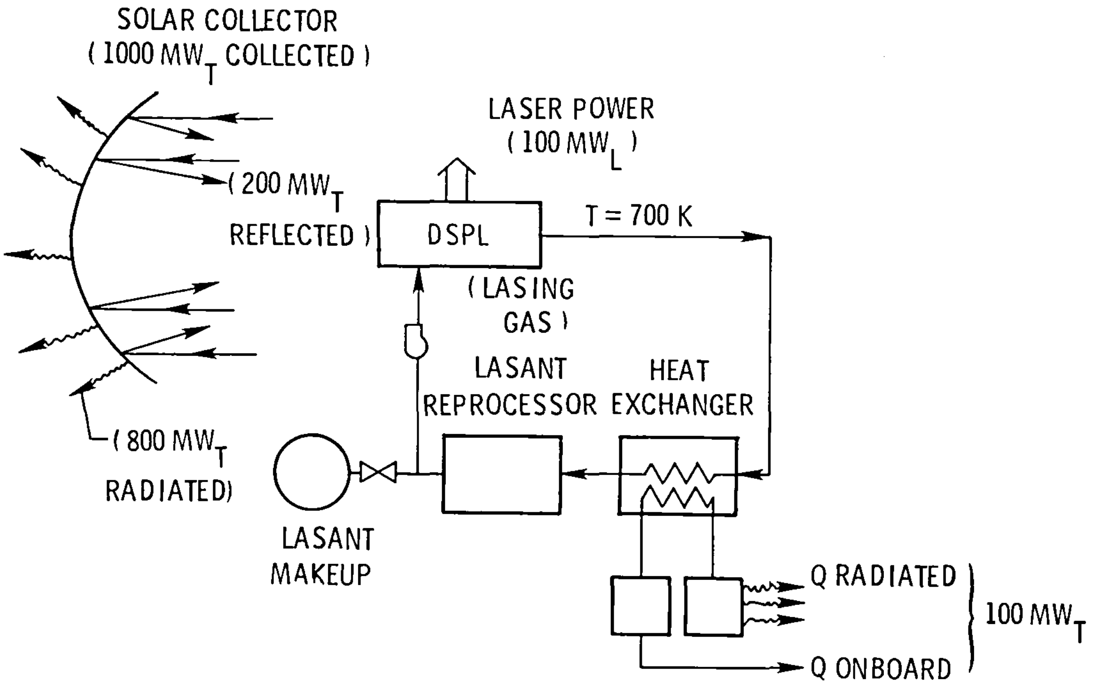

Figure 11.- Cycle schematic for direct solar-pumped laser (DSPL).

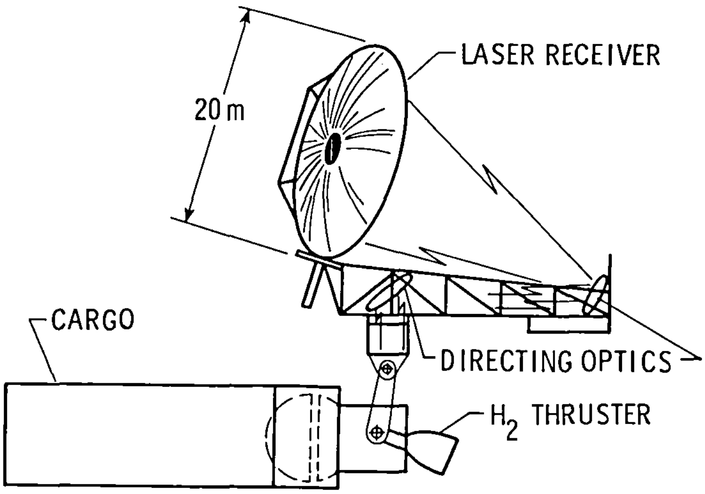

Figure 12.- Laser thermal propulsion system concept.

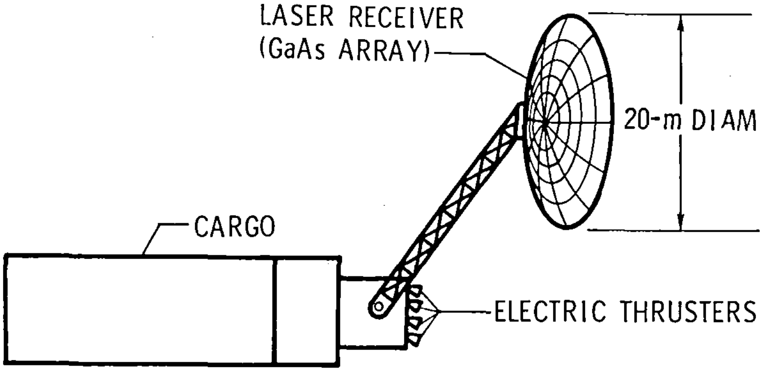

Figure 13.- Laser electric propulsion system concept.

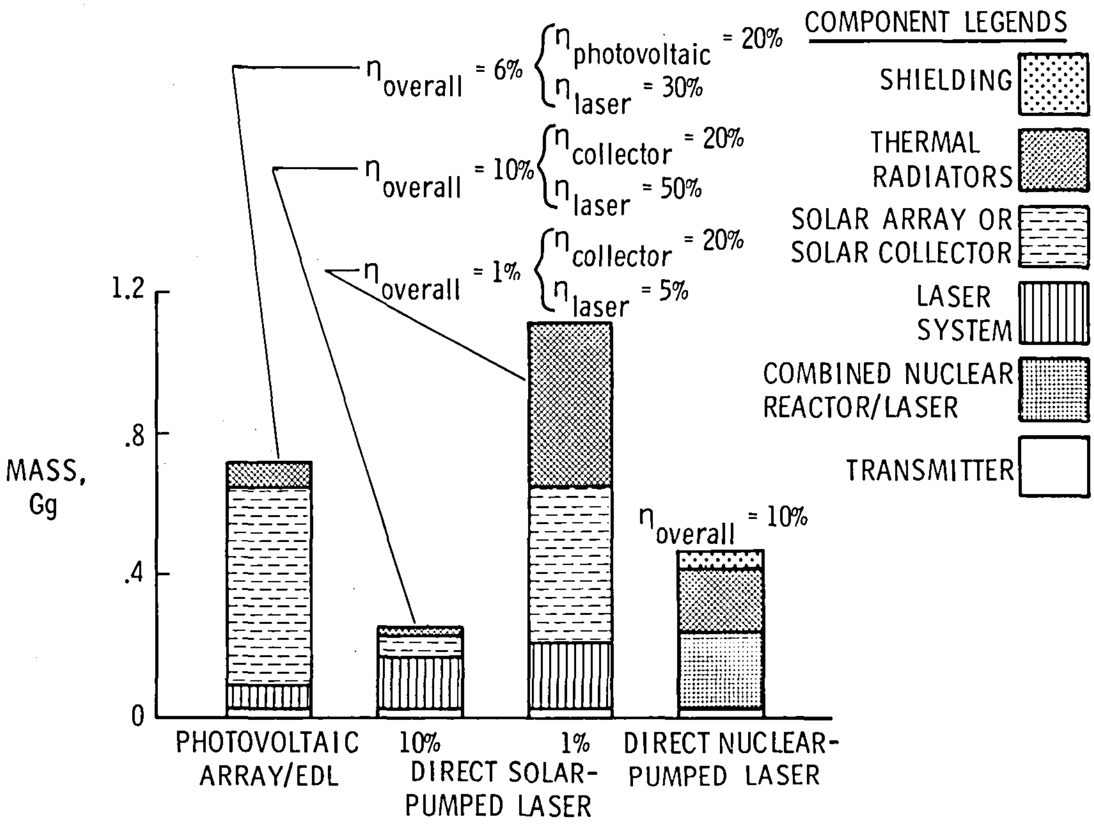

Figure 14.- Comparison of advanced power-station system masses. 100 MW_L; η = Efficiency.

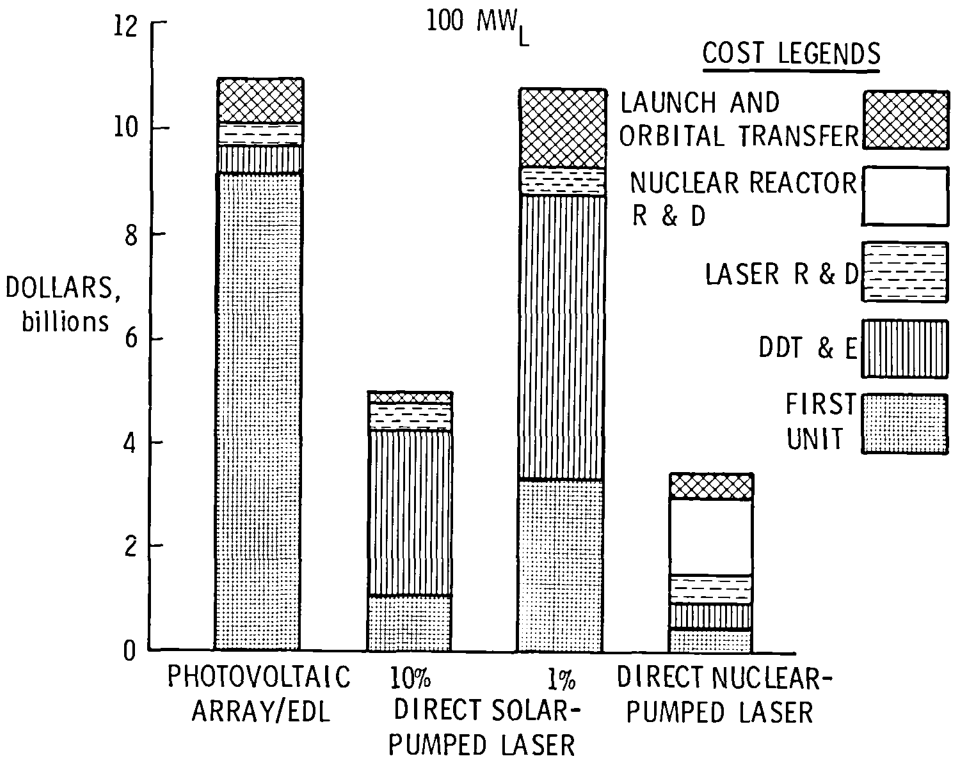

Figure 15.- Comparison of advanced power-station system costs. 100 MW_L.

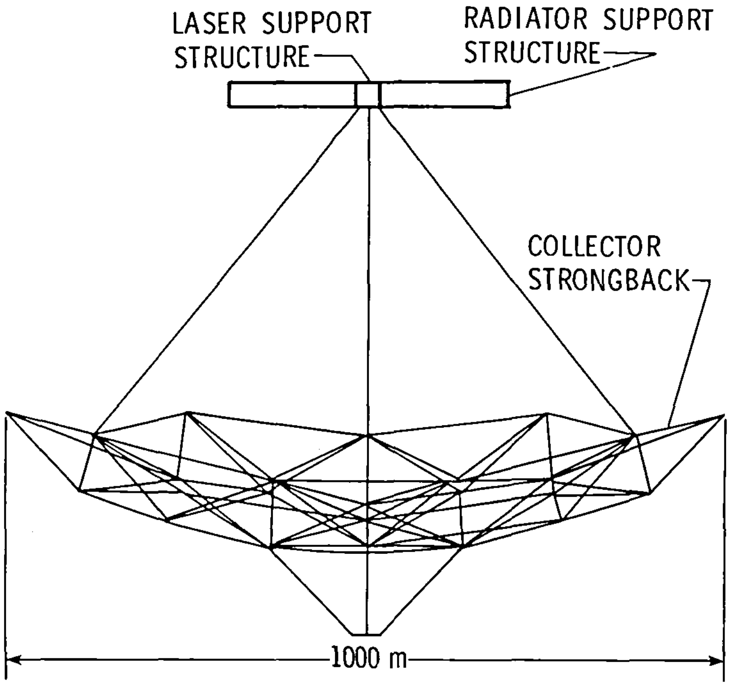

Figure 16.- Structure concept for direct solar-pumped power station.

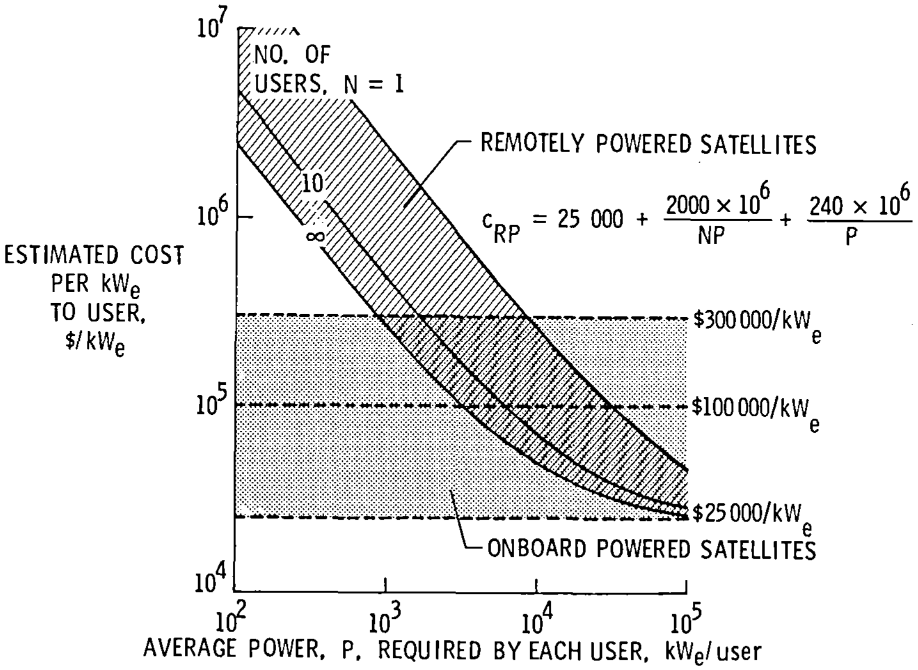

Figure 17.- Onboard and remote-power cost ranges for orbiting satellites. Direct nuclear-pumped laser (DNPL) power station.

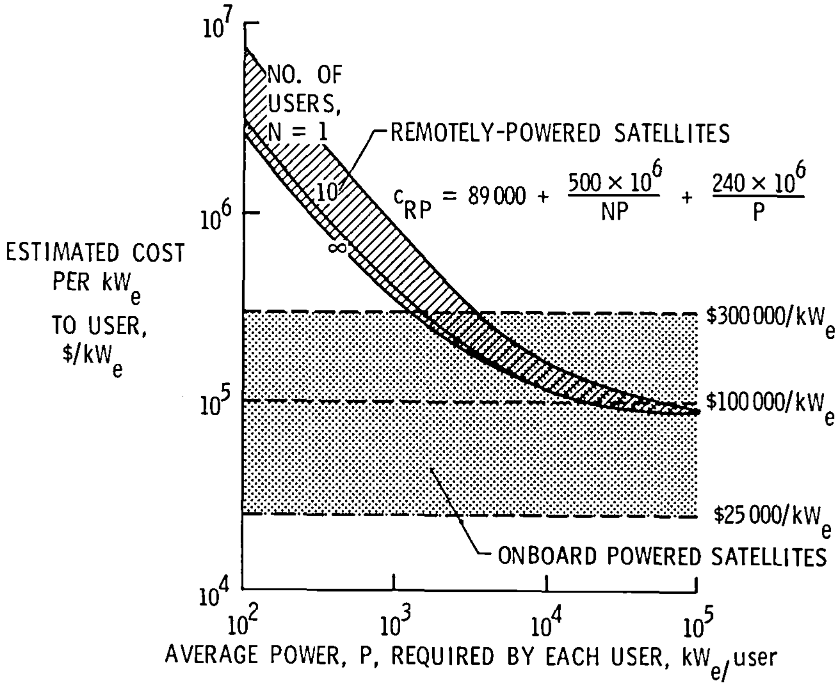

Figure 18.- Onboard and remote-power cost ranges for orbiting satellites. Direct solar-pumped laser (DSPL) power station.

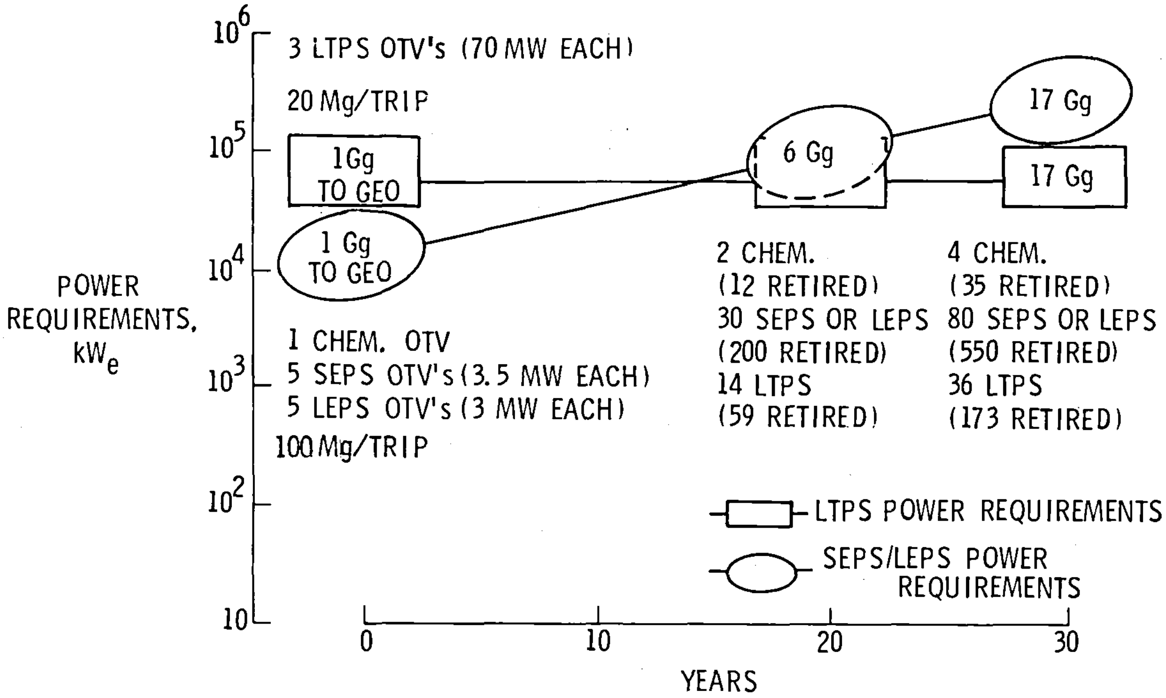

Figure 19.- Orbital-transfer scenario.

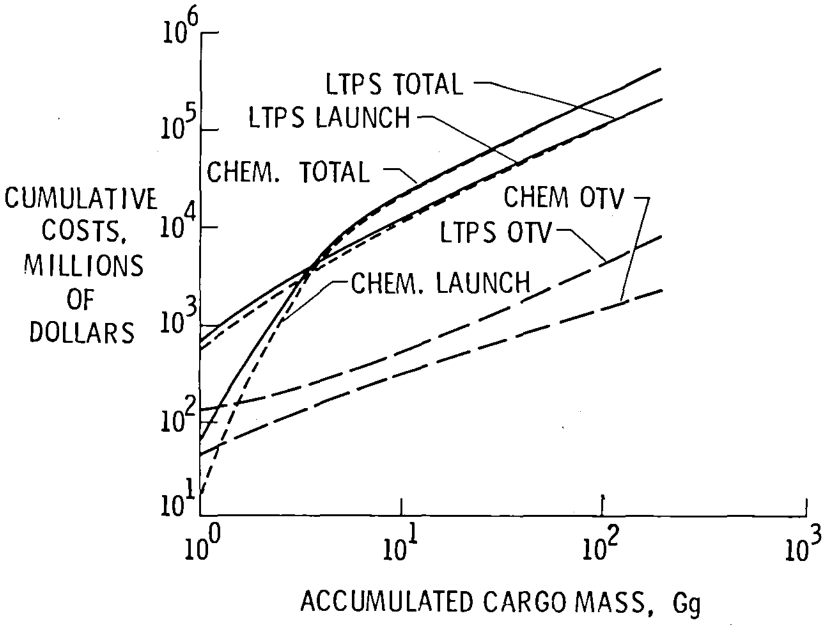

Figure 20.- Cumulative cost comparisons of chemical with remotely powered LTPS OTV's.

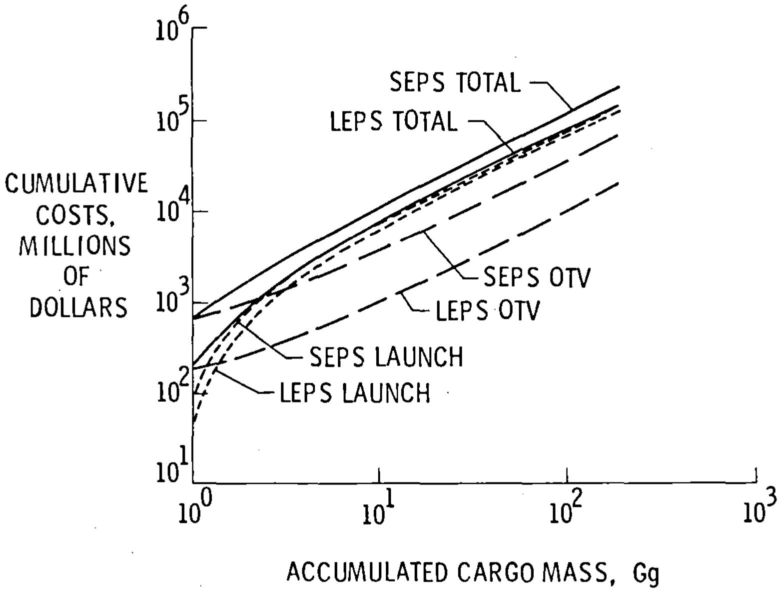

Figure 21.- Cumulative cost comparisons of SEPS with remotely powered LEPS OTV's.

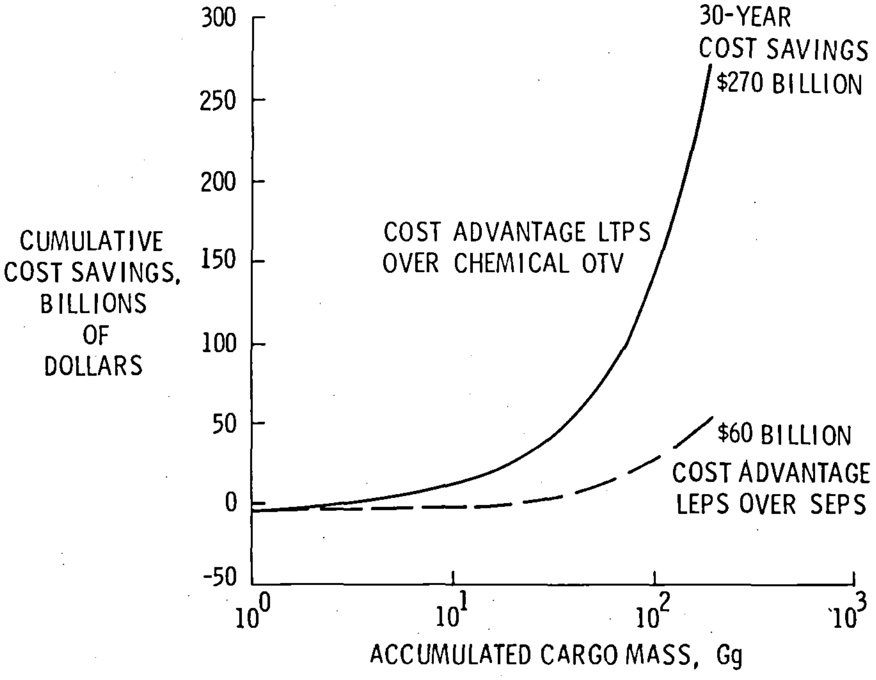

Figure 22.- Cumulative cost savings of remotely-powered over self-powered OTV's.

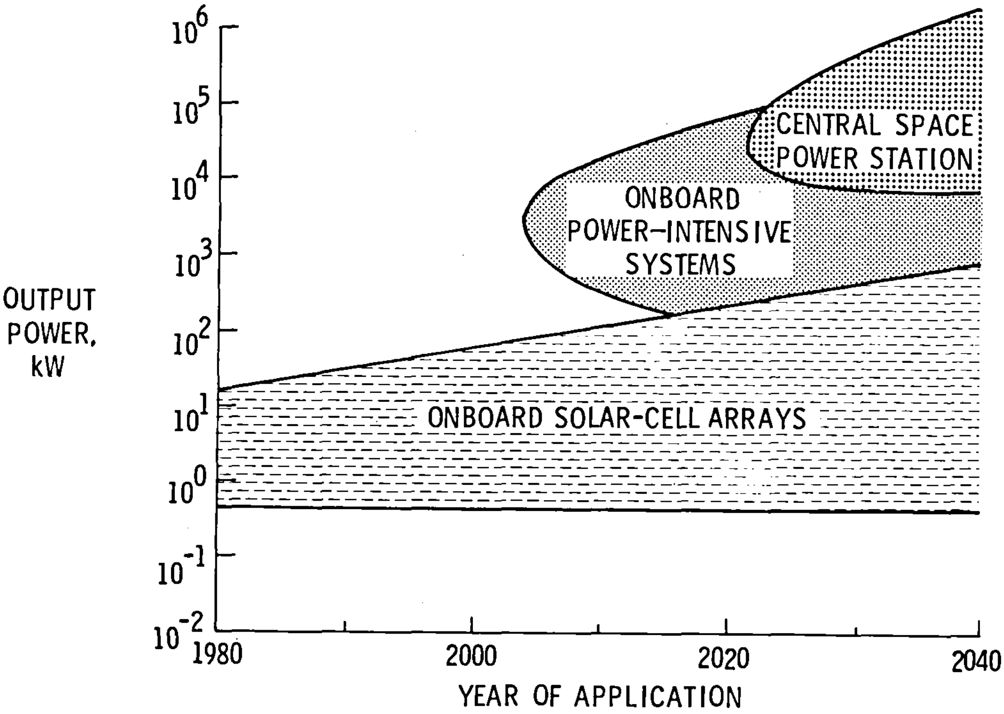

Figure 23.- Space power-development forecast.

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16. Abstract

The technological and economical impact of a large central power station in Earth orbit on the performance and cost of future spacecraft and their orbital-transfer systems are examined. It is shown that beaming power to remote users cannot be cost effective if the central power station uses the same power generation system that would be readily available for provision of onboard power. Similarly, microwave transmission and reception of power through space for use in space cannot be cost competitive with onboard power or propulsion systems. Laser transmitters and receivers are required to make central power stations feasible. Analysis of the cost effectiveness of meeting the electrical-power demands of an Earth-orbiting spacecraft from a central power station indicates that this application cannot justify the investment required for the central station. However, remote-power transmission for propulsion of orbital-transfer vehicles promises major cost benefits. Direct nuclear-pumped or solar-pumped laser power-station concepts are particularly attractive with laser thermal and laser electric propulsion systems. These power stations are also competitive, on a mass and cost basis, with a photovoltaic power station.

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