Chapter 5

ALTERNATIVE SYSTEMS FOR SPS

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Chapter 5

ALTERNATIVE SYSTEMS FOR SPS

A variety of systems have been proposed for collecting, transmitting, and converting solar power from space. Each system has its advantages and disadvantages, its benefits and drawbacks. Each alternative system would use one of three transmission modes — microwave, laser, or optical reflector–to transmit power to Earth where it is collected and converted to electricity or some other highly useful form of energy. Each system would use numerous subsystems to collect and convert energy in space or on the ground. This chapter will characterize the alternative systems and subsystems and discuss their potential for generating power from space. It will also describe four representative systems that serve as the technical basis for discussion of the environmental, institutional, and public acceptance issues in the chapters that follow.

In order to estimate reliably and fully the range of costs and potential technical uncertainties for a given solar power satellite (SPS) option, it would be necessary to subject it to the same detailed analysis that the reference system has undergone during the last 5 years. Unfortunately, this analysis has not been accomplished for the alternative systems. Hence, detailed comparisons between systems will not be possible. At this stage it is possible only to compare the major features of each technology and note the uncertainties that should be addressed as conceptual development of the various alternatives continues.

MICROWAVE TRANSMISSION

Because the atmosphere is highly transparent to microwaves, they constitute an obvious candidate for the SPS transmission mode. In addition, microwave technology also is well-known and is used today in a number of space and terrestrial communications and radar applications. Microwave power transmission was first demonstrated experimentally in 1964,[1] and tested in 1974.[2,3]

The Reference System[4,5,6]

The reference system was selected by the Department of Energy/National Aeronautics and Space Administration (DOE/NASA) as a basis for study. It consists of a large planar array of photovoltaic cells located in the geosynchronous orbit 35,800 km above the Earth's Equator (fig. 9). The cells convert solar energy into direct-current (de) electricity that is conducted at high voltage to a phased-array microwave transmitting antenna mounted at one end of the photovoltaic array. Klystron amplifiers convert the dc electricity to high-voltage radio-frequency power that is then radiated to Earth by slotted waveguides. A receiving antenna (rectenna) on the ground reconverts the electromagnetic radiation into electric current and rectifies it into dc. After being converted to high-voltage, low alternating current (ac), the power can then be either delivered directly to the conventional ac grid or converted back to dc at high voltage and delivered to a dc transmission network.

The amount of power delivered to the grid by each reference system rectenna has been

[1] J. F Degenford, M D. Sirkis, and W H Steir, "The Reflecting Beam Waveguide, " I E EE *Transactions 01 Microwave Theory Technology MIT-72,* July 1964, pp 445-453

[2] Richard M Dickinson, "Evaluation of a Microwave High-Power Reception-Conversion Array for Wireless Power Transmission, " Jet Propulsion Laboratory Technical Memorandum No 33-741, Sept 1, 1975

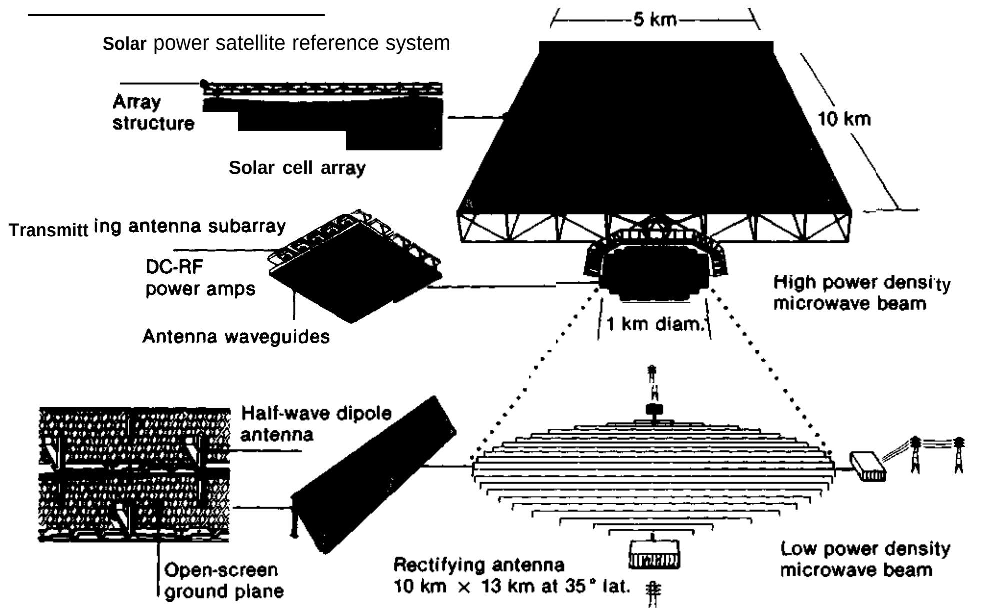
[3] Richard M Dickinson, "Microwave Power Transmitting Phased Array Antenna Research Project Summary Report, " Jet Propulsion Laboratory publication No 78-28, Dec 15, 1978

[4] Department of Energy, "Satellite Power System Concept Development and Evaluation Program Reference System Report, " report No. DOE/E R-0023, October 1978

[5] C. C. Kraft, "The Solar Power Satellite Concept, " NASA publication No JSC-14898, July 1979

[6] R O Piland, "SPS Cost Methodology and Sensitivities, " *The Final Proceedings of the* Solar *Power Satellite Program Review,* DOE/NASA Conf-800491, July 1980.

Figure 9.—Solar Power Satellite Reference System



SOURCE: C. C. Kraft, "The Solar Power Satellite Concept," NASA publication No. JSC-14898, July 1979

set at 5 gigawatts (GW)—or 5,000 megawatts (MW). The microwave transmission frequency was chosen to be 2.45 gigahertz (GHz). Maximum microwave power density at the center of the rectenna (on Earth) was set at 23 milliwatts per square centimeter (mW/cm^2), and the maximum power density at the edge of the rectenna was set at 1 mW/cm^2 (one-tenth the current U.S. recommended occupational limit). The reference design assumes that all materials would be obtained from Earth, and that the system lifetime would be 30 years with no residual salvage value.

The area of the satellite's photovoltaic array would be approximately 55 square kilometers (km^2); the diameter of the transmitting antenna 1 km. The total in-orbit mass of the complete system, including a 25-percent contingency factor, would be either 51,000 or 34,000 metric tons (tonnes), depending on whether silicon or gallium arsenide photovoltaic cells would be used.

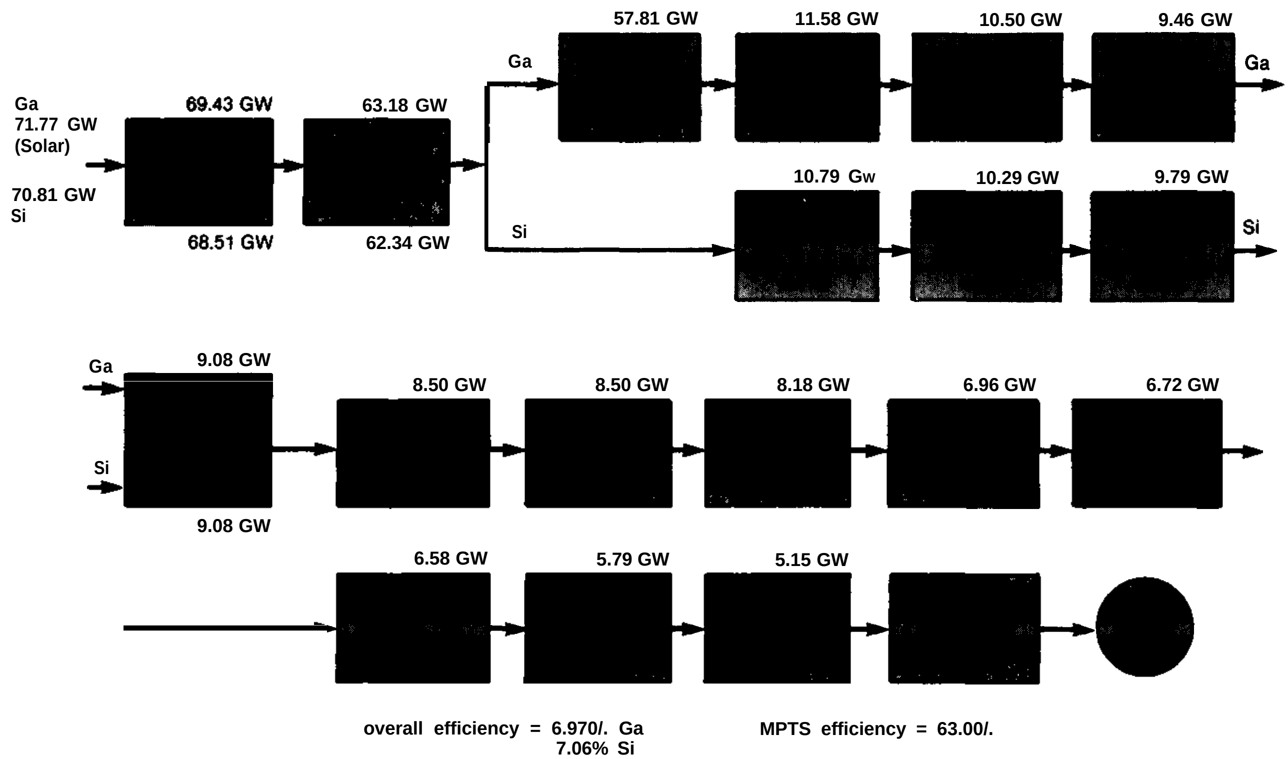
The system is designed to deliver baseload, i.e., continuous 24-hour power to the electric grid. However, some variations in delivered power would occur. A seasonal fluctuation in output due to the variation of the Sun's distance from Earth would cause variations in both incident insolation and photovoltaic cell temperature, the latter producing a consequent change in efficiency. In addition, around the spring and fall equinoxes the Earth's shadow would occult the SPS, resulting in a short period each night for about 6 weeks at local midnight (about 75 minutes maximum, at the equinoxes) where no solar radiation impinges on the satellite and therefore no power could be delivered to the grid (see ch. 9 for a discussion of this effect).

Subsystem Description

ENERGY COLLECTION AND CONVERSION

Two photovoltaic concepts were considered for the DOE/NASA reference system. One uses

Figure 10.-Satellite Power System Efficiency Chain



Abbreviation: "Ga" indicates the gallium-alum aluminum-arsenide option, "Si" the silicon option.

SOURCE: Department of Energy, "Satellite Power System Concept Development and Evaluation Program: Reference System Report," DOE report No. DOE/ER-0023, October 1978.

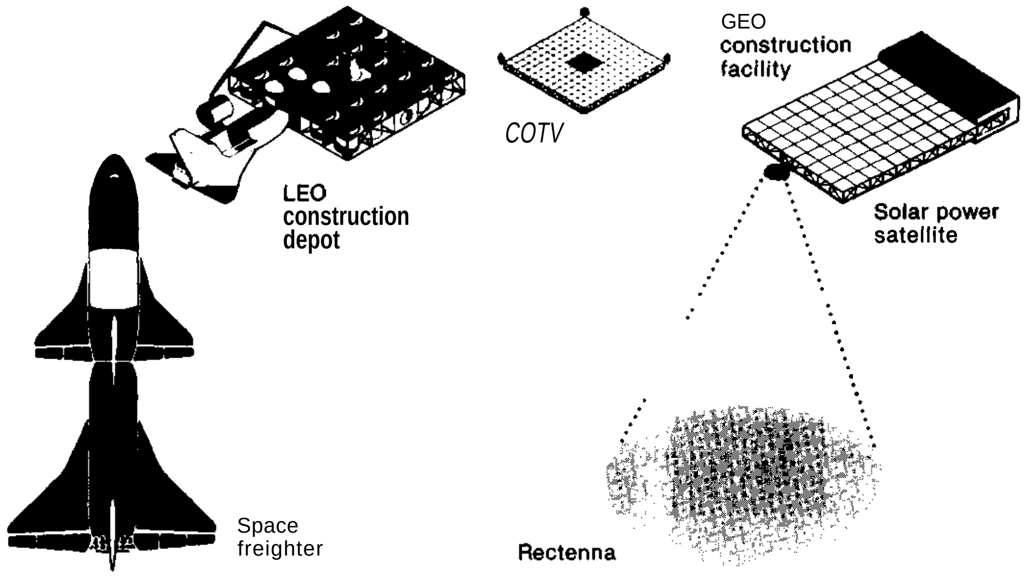
single crystal silicon converters that would receive sunlight directly; the other uses gallium-arsenide (GaAs) photovoltaic cells illuminated directly and by mirrors in a 2:1 concentration ratio.

Silicon cells, currently used in all solar powered spacecraft, have the advantages of an extensive manufacturing base, abundant resource materials, and lower cost per cell, as well as an R&D program in DOE aimed at major cost reduction for terrestrial cells. However, silicon cells in space suffer degradation from radiation effects and from high-operating temperatures, and hence would probably require periodic annealing of the array surface (possibly by laser or electron beam techniques) or the development of silicon cells less affected by ionizing radiation.

Gallium-aluminum arsenide photovoltaic cells have several advantages over silicon cells: low mass per unit area, resistance to thermal and radiation degradation, and higher efficiency. They have the disadvantages of relatively high cost, the limited production availability of gallium, and a smaller technology base than for silicon cells. Because of these latter characteristics, these cells would be used in a 2:1 concentration ratio in the reference system, trading the relatively expensive cells for less expensive lightweight reflectors to concentrate sunlight on the cells.

The structure that supports the solar cells would be an open-truss framework made of graphite-fiber reinforced thermoplastic composite (fig. 9). Because the solar array must be oriented toward the Sun and the transmitting antenna toward the Earth, a massive rotary joint is essential in order to provide the necessary mechanical coupling. Sliprings about 400 m in diameter would be used in conjunc-

Figure 11.—Major Reference System Program Elements



SOURCE: R. O. Piland, "SPS Cost Methodology and Sensitivities," *The Final Proceedings of the Solar Power Satellite Program Review*, DOE/NASA Conf-800491, July 1980.

tion with the rotary joint in order to transfer electric power from the array to the antenna.

POWER TRANSMISSION AND DELIVERY

The power transmission and delivery system for the reference system design is common to both photovoltaic options. It is composed of three major elements: the transmitting antenna, the rectenna, and the substation.

The selection of the microwave transmission frequency was based on tradeoffs between atmospheric attenuation and interactions with the ionosphere as well as the sizes of the antenna and rectenna. The optimal frequencies were found to be between 1.5 and 4 GHz. The reference frequency was selected to be 2.45 GHz, which lies in the center of the international Industrial, Scientific, and Medical (ISM) band of 2.4 to 2.5 GHz.

The size of the antenna is determined by the transmission frequency, the amount of heat it is feasible to dissipate at the antenna, the theoretical limits of ionospheric heating, and the maximum power densities chosen at ground level, i.e., at the rectenna.[7] For the reference system, these design considerations resulted in a l-km diameter antenna. It would be constructed of 7,220 subarrays each containing from four to thirty-six 70-kW klystron power amplifiers connected to slotted waveguides for transmitting power to Earth. Klystrons were chosen because their technology and operating characteristics at low power levels are well-known. However, they require a cooling system (probably heat pipes). Klystrons of 70-kW continuous power rating have not been built and tested at this frequency, so their characteristics are not known in detail.

Each of the more than 100,000 klystrons in the antenna must be properly adjusted or "phased" to provide a uniform power beam and to point it. This adjustment is especially critical at the very high, gross power level of the SPS beam. Were the antenna a totally rigid array of amplifiers precisely fixed in space, the adjustment could be accomplished once and for all just after the antenna is fabricated in space. However, because it would be desirable for the antenna to be relatively flexible it would be necessary to use an active system of phase control, a so-called "adaptive electronic control" in which a pilot beam, installed in the center of the rectenna and pointed toward the

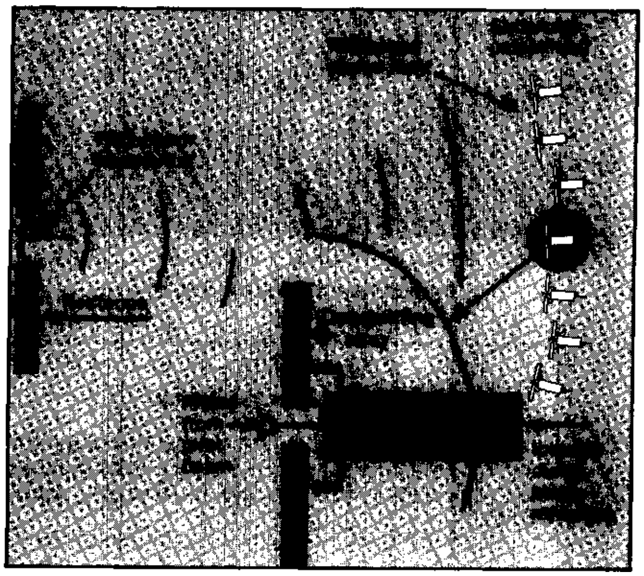
'Raytheon Corp., "Microwave Power Transmission System Studies," report No, ER75-4368, contract No NAS3-I 7835, December 1975.

satellite, establishes a phase reference or standard clock against which the individual klystrons compare and adjust their phases (fig. 12).[8]

An important safety feature inherent in this system is that loss of the pilot beam from the rectenna would eliminate all pointing and phase control. Without the pilot beam, the klystron subarrays would immediately lose synchronization with one another and al I focus would be lost, resulting in the spreading of the beam to very low power (0.003 mW/cm²). The transmission system would therefore require continual ground-based guidance to keep it operating as a coherent beam. By incorporating relatively well-known anti jamming techniques in the pilot-beam generator, deliberate or accidental diversion or misuse of the SPS beam could be prevented.

'William C Brown, "Solar Power Satellites Microwaves Deliver the Power, " *Spectrum,* **June 1979, pp 36-42.**

Figure 12.—The Retrodirective Concept



In the retrodirective-array concept, a pilot beam from the center of the rectenna establishes a phase front at the transmitting antenna. Central logic elements in each of the antenna's 7,220 subarrays compare the pilot beam's phase front with an internal reference, or clock phase. The phase difference is conjugated and used as a reference to control the phase of the outgoing signal. This concept enables the transmitted beam to be centered precisely on the rectenna and to have a high degree of phase uniformity. If this phase-control system fails, the beam would automatically be defocused, dropping the power density to 0.003 mW/cm², an intensity acceptable by current standards. This feature has been referred to as the "fail-safe" aspect of the microwave transmission system.

SOURCE: William C. Brown, "Solar Power Satellites: Microwaves Deliver the Power," *Spectrum,* June 1979, pp. 36-42.

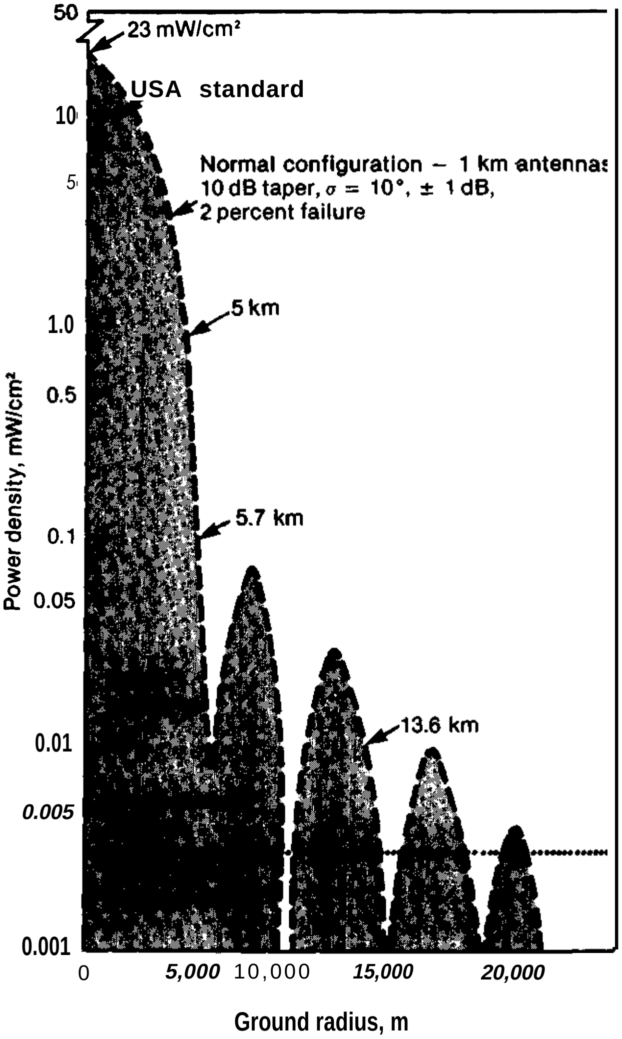
The parameters of the microwave beam are of critical importance in assessing the environmental impacts of the SPS. The peak power density at the transmitting antenna is calculated to be 21 kW/m2. By the time the beam reached the upper atmosphere it would have spread considerably and the intensity reduced to 23 mW/cm², a power limit that was set because theoretical studies suggested that at higher power densities, nonlinear instabilities could appear in the F layer of the ionosphere (200 to 300 km) as a result of the interactions between the beam and the electrically charged particles in this region. Recent experimental studies indicate that the limit in the lower ionosphere might be able to be set much higher, ' thereby making it possible to decrease the size of the antenna and/or rectenna significantly.

With these design constraints, a theoretical beam power distribution was conceived resulting in the radiation pattern at the rectenna shown in figure 13, on which are noted the present U.S. recommendations for public exposure (10 mW/cm²) and the current U.S.S.R. occupational guideline (0.01 mW/cm²).

The off-center peaks in figure 13 are called "sidelobes;" the level of intensity shown is a consequence of the 1-km antenna aperture (which is optimized to minimize orbital mass) and the projected cumulative antenna errors. The first sidelobe would have a peak intensity of 0.08 mW/cm², less than one-hundredth the current U.S. occupational exposure recommendation, about 8 km from the beam centerline; the intensity at the edge of the reference system rectenna (5 km from the beam centerline) would be 1 mW/cm²–one-tenth the U.S. occupational exposure guideline.

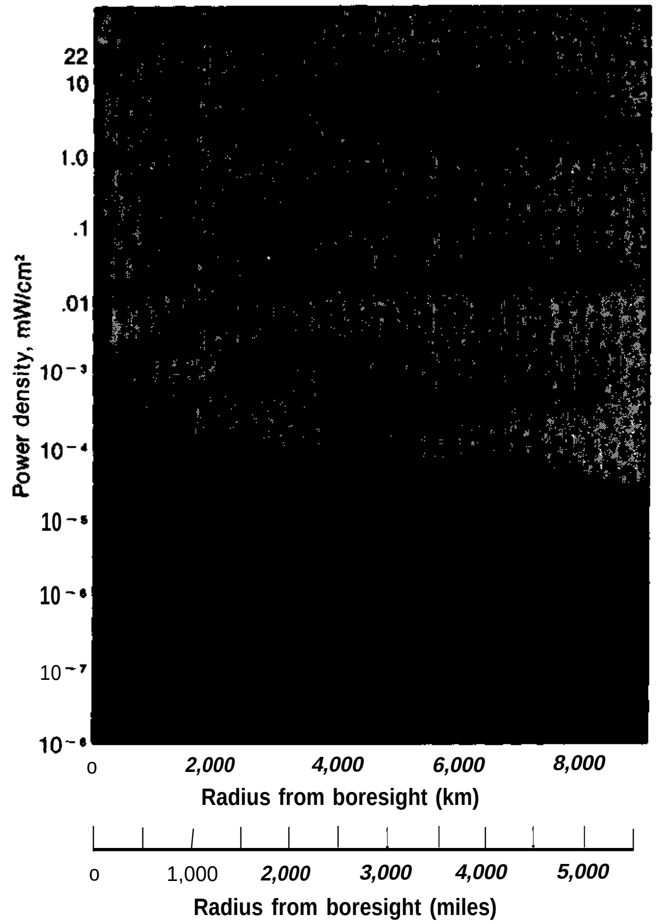
'W E Cordon, and L M Duncan, "SPS Impacts on the Upper Atmosphere," *Astronautics and Aeronautics, July/August* **1980**

Figure 13.—Power Density at Rectenna as a Function of Distance From the Beam Centerline



SOURCE: Department of Energy, "Satellite Power System Concept Development and Evaluation Program: Reference System Report," DOE report No. DOE/ER-0023, October 1978.

Figure 14.—Peak Power Density Levels as a Function of Range From Rectenna



Grating lobe spikes occur every 245 km for the 18-m subarrays used on simulations although only two grating lobes are shown. The SPS 10-m subarrays have grating lobes every 440 km.

SOURCE: Department of Energy, "Satellite Power System Concept Development and Evaluation Program: Reference System Report," DOE report No. DOE/ER-0023, October 1978.

In addition to the relatively strong sidelobes, the finite size of the antenna subarrays and their projected misalinements would produce much weaker "grating lobes, " which for the reference system would occur at 440-km intervals from the rectenna. The integrated intensity of these grating lobes, even for hundreds of operational SPSs, would be well below even the U.S.S.R. public-exposure guideline, as shown in figure 14.

The rectenna design is quite insensitive both to the angular incidence of the microwave beam (within 100, and to variations in phase or amplitude caused by the atmosphere. Hence, rectennas would be interchangeable; the same satellite could power different rectennas, as long as they were equipped with the appropriate pilot beam needed for phase control of the transmitting antenna. The reference rectenna would be composed of billions of dipole antennas placed above a transparent wire grid. The microwave energy received by each dipole would pass through a rectifier circuit that would convert it to dc power at high current and low voltage. Several more conversions would be necessary to condition the power for the grid. The received power would first be converted to ac and then transformed to high-voltage low-current 60-cycle ac power and then either fed into ac transmission lines for delivery to the users or reconverted to high-voltage dc for transmission, a relatively new transmission technology.

Estimates of overall rectenna conversion efficiency run from about 80 to 92 percent, and the extreme simplicity and repetitive-element construction of the electrical components would facilitate mass production at extremely low unit cost. Reliability of the rectenna should be extremely high, because each component would be ultrareliable and could operate redundantly. Hence replacement would be necessary only after a large number of individual failures.

None of the substation equipment involves technological advances beyond those that are projected through normal development by the electric utility industry. The major concern that has been expressed is the large scale of the minimum individual power unit. Current grid control systems are quite adequate to handle near-instantaneous switching of single power units as high as 1,300 MW. Single unit variations of 5,000 MW could present major control difficulties to the utilities as they currently operate[10 11] (see ch. 9 for a detailed description of utilities interface problems).

SPACE CONSTRUCTION

The mass and physical size of the space segment needed for an operational 5-GW satellite power station are larger by several orders of magnitude than any space system heretofore launched and therefore require careful consideration of the transportation options. The basis for all projected Earth-to-low-orbit transportation concepts is the current U.S. space shuttle, scheduled to become the operational mainstay of the U.S. (and much of the world's) space program.

Of the many possible shuttle derivatives and other new transportation prospects, 12 NASA selected four different types of vehicles to supply the four basic transportation functions:

- carrying cargo between Earth and low-Earth orbit (LEO),
- carrying personnel between Earth and LEO,
- transferring cargo between LEO and the geosynchronous orbit (CEO), and
- transferring personnel between LEO and CEO.

The designs of these four vehicles, called respectively, the heavy-lift launch vehicle (HLLV), the personnel launch vehicle (PLV), the cargo orbital transfer vehicle (COTV), and the personnel orbital transfer vehicle (POTV), are based on existing technology, although all would require considerable development before reaching operational status. [13 14 15 16]

Both the HLLV and the PLV would utilize fully reusable flyback boosters similar to those originally considered by NASA in early shuttle designs in the late 1960's. Both boosters would employ methane-oxygen rocket engines for (vertical) takeoff and airbreathing (turbofan) engines for flyback to base for horizontal landings. The HLLV orbiter would use oxygen-

[10] J. G. Bohn, J. W. Patmore, and H W Faininger, "Satellite Power Systems: Utility Impact Study," EPRI AP-1 548 TPS 79-752, September 1980.

[11] P J. Donalek, and J. L. Whysong, "Utility Interface Requirements for a Solar Power System, " Harza Engineering Co , DO E/E R-0032, September 1978

[12] Robert Salkeld, Donald W Patterson, and Jerry Grey (eds), 'Space Transportation Systems, 1980-2000, " VOI 2, AIAA Aerospace Assessment Series, A IAA, New York, 1978

[13] G Woodcock, "Solar Power Satellite System Definition Study, " Boeing Aerospace Co., Johnson Space Center contract No NAS9-1 5196, pt 1, report No D180-20689, June 1977; pt II, report No D180-22876, December 1977, pt I I 1, report No D180-24071, March 1978

[14] C Hanley, "Satellite Power System (SPS) Concept Definition," Rockwell International Corp., Marshall Space Flight Center, contract No NAS8-32475, report No SD78-AP-0023, April 1 '378

[15] Gordon R Woodcock, "Future Space Transportation Systems Analysis Study, " Johnson Space Center contract No. NAS9-1 4323, Boeing Aerospace Co. report No D1 80-20242-1 (three volumes), Dec. 31,1976

[16] Donald P. Hearth (Study Director), "A Forecast of Space Technology 1980-2000," NASA SP-387, January 1976.

hydrogen rockets essentially identical to those of the current space shuttle, and then glide back to base much like the shuttle does. Unlike the shuttle, it would be fully reusable; it would have no disposable external propellant tank.

The PLV orbiter would be very much like the current space shuttle, but would employ a passenger-carrying module in the payload bay. Like the shuttle, it would also use a disposable external propellant tank, but a somewhat smaller one. It could carry 75 passengers, plus the normal shuttle crew.

A fleet of COTV, all reusable, would make the round trip from LEO to CEO, carrying the cargo payloads up to CEO and returning empty to LEO for reuse. They would be propelled by efficient but slow electrostatic engines. Using low-thrust electric propulsion would require very long trip times, of the order of 4 to 6 months. The bases for selecting this propulsion option were essentially minimum cost and ready availability of the argon propellant and other materials. Such long trip times, although suitable for cargo, are clearly not acceptable for personnel, so a high-thrust propulsion approach was chosen for the POTV. The design utilizes a basic oxygen-hydrogen propulsion stage now undergoing research evaluation at NASA as part of its Advanced Space Engine program. It employs essentially the same level of "technology as that used in the current space shuttle main engine. It could carry up to 160 people from LEO to CEO and back, or 98 tonnes (480 man-months) of consumables from LEO to CEO.

Because it would be impractical to launch a full-sized power satellite by single launch vehicle, a strategy for constructing the satellite in Earth orbit would be necessary. The basic space construction strategy selected for the reference system is to launch all materials, components, and people to staging areas in LEO (fig. 15). The COTVs, because of their large solar arrays, would be assembled in LEO as well. The main construction base would be located in CEO, although not necessarily at the eventual geostationary-orbit location of the operational SPS. Hence the LEO staging area would serve as the transfer point for all materials and personnel both up to CEO and back down to Earth. Alternative strategies have been considered, some of which will be discussed later.

The principal factor that governs the cost and effectiveness of in-space construction is generally accepted to be the productivity of the construction crew and cost, and requirements for shielding. The replacement of some crew by automated equipment is therefore a major consideration in all construction strategies or scenarios, e.g., effort has already been devoted to automatic beam-building systems.[17] The use of teleoperators and robot manipulators for assembly of large structures has also been considered. The current growth of technology in these areas is extremely rapid,[18] and incorporation of such techniques would almost certainly benefit all aspects of SPS construction. Despite the wide range of construction options, estimated personnel requirements for them are approximately the same: 750 ± 200.[19]

GROUND-BASED CONSTRUCTION

Building the rectenna, although a very large and relatively unique structure, nevertheless would involve far fewer uncertainties than constructing the space segment. A detailed analysis[20] of both the basic structure and construction aspects concluded that the primary structural material should be galvanized or weathering steel rather than aluminum (which is more scarce and requires a higher energy cost to produce).

SYSTEM OPERATION

An active control system would be needed both to keep the satellite in the proper orbit

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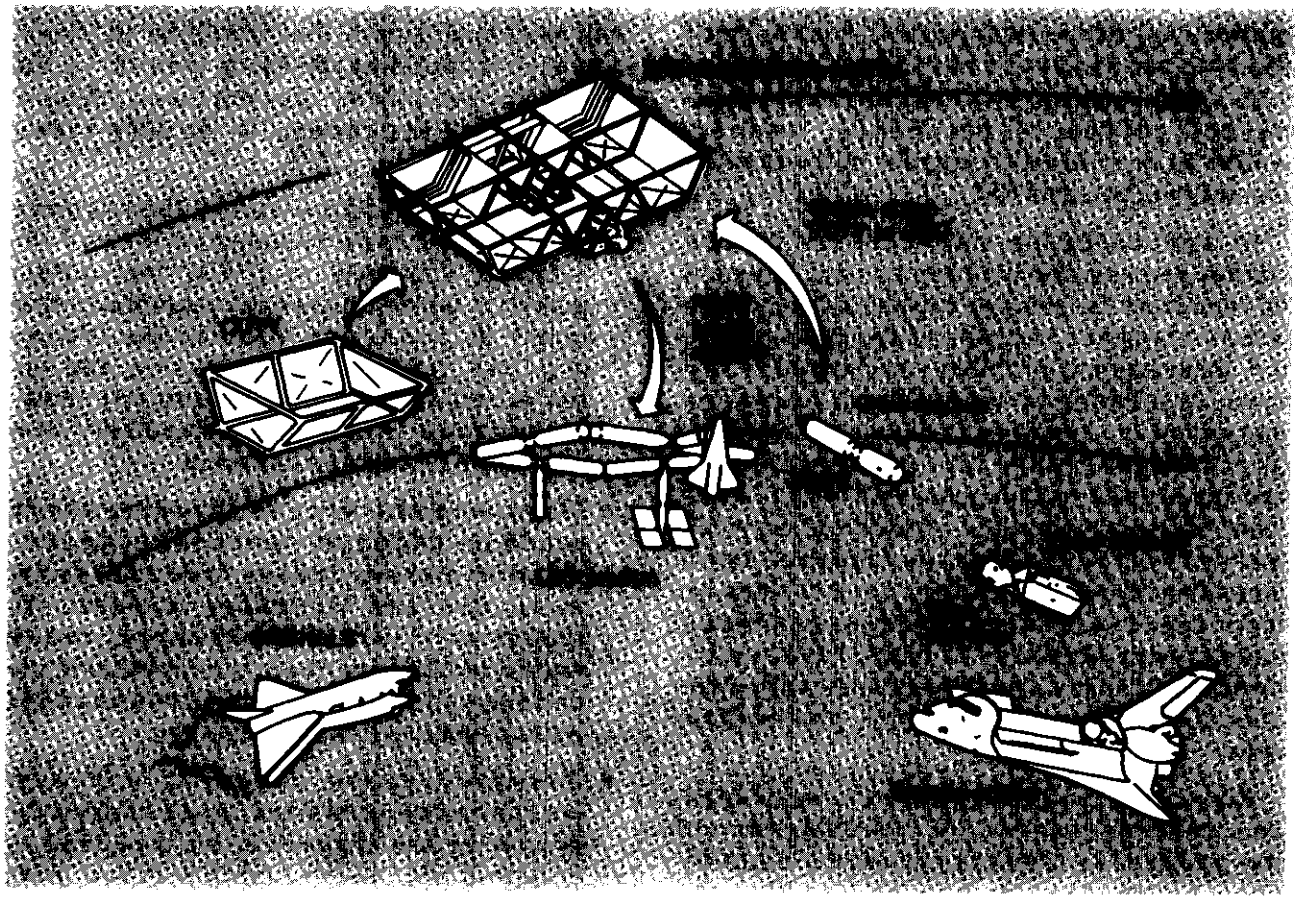
[17] Denis J Powell and Lee Brewing, "Automated Fabrication of Large Space Structures," *Astronautics* and *Aeronautics,* October 1978, pp 24-29

[18] Antal K Bejczy, "Advanced Teleoperators," *Astronautics* and *Aeronautics,* May 1979, pp. 20-31

[19] W H Wales, "SPS Program Review Transportation Perspective," in *The Final Proceedings of the Solar Power Satellite Program Review,* DOE/NASA Conf-800491, July 1980

[20] "Feasibility Study for Various Approaches to the Structural Design and Arrangement of the Ground Rectenna for the Proposed Satellite," NASA contract No. NAS-1 5280, Bovay Engineers, Inc, May 1977

Figure 15.—SPS Space Transportation Scenario



SOURCE: W. H. Wales, "SPS Program Review Transportation Perspective," in *The Final Proceedings of the Solar Power* Satellite *Proqram Review,* DOE/NASA Conf-800491, July 1980.

(stationed above the rectenna) and to maintain the solar array's orientation to the Sun. The mass of the necessary control system is estimated at 200 tonnes; its average electric power consumption would be 34 MW.

Because of its low coefficient of thermal expansion and relative stiffness, a graphite composite structural material was selected for the reference system in preference to the aluminum alloys so widely used in aerospace structures. Although a complex engineering problem and, furthermore, one not readily subject to testing at an adequate scale prior to deployment in space, it does not appear likely that dynamic stability would cause any major unexpected problems in either performance or costs, partly because of the predictability of the space environment as compared, for example, with the uncertain environment in which aircraft structures must be designed to operate, and partly because of the extensive body of applicable design, testing, and operational experience with high-performance aerospace structures. However, questions of dynamic instability resulting from low-probability occurrences such as major meteor strikes or aggressive military action would have to be evaluated.

Orientation of the transmitting antenna relative to that of the solar array would be maintained via the large rotary joint. Physical aiming of the antenna itself would be accom-

83-316 0 - 81 - 6

plished by gyroscopes, which would feed control signals to the mechanical-joint turntable so that it could follow the antenna pointing requirements. However, mechanical pointing of the antenna would not have to be performed with high accuracy, since the electronic phasing and pointing of the antenna subarrays would be insensitive to angular deflections of the antenna of upto100.

In addition to the equipment for satellite station keeping and attitude control, it would be necessary to provide routine maintenance of both the space and ground segments. Potential maintenance problems in the space segment, in addition to the expected routine replacement of components, include the effects of solar wind, cosmic rays, micrometeoroids, and impacts by station-generated debris. Aside from the solar wind and cosmic radiation effects on solar cells, which would require active annealing of the silicon cells, none of these effects would appear to introduce significant maintenance problems or costs, based on extensive past and current experience with operational satellites powered by photovoltaic cells.

Repair and replacement of the solar blankets and more than 100,000 70-kW klystrons in the transmitting antenna are estimated to require a crew of from 5 to 20 people at the geostationary orbit construction base,[21] along with the necessary transportation, support, and resupply (e. g., station-keeping propellant) services.

Maintenance requirements of the rectenna and substation are also primarily associated with repair and replacement of their billions of components. Although a certain degree of redundancy is built into the system, a maintenance crew would still be required to replace storm-damaged rectenna sections and routine failures of both rectenna and substation equipment.

Technical Uncertainties of the Reference System

Although most observers accept the basic scientific feasibility of the SPS system concept, there are many technical uncertainties associated with the reference system. This section identifies specific issues or problems in the reference system that would be of importance in formulating decisions concerning the research, evaluation, development, demonstration, and deployment of satellite power stat ions.

- Performance. A major issue in the reference system design is the tremendous scale of the satellite. The level of 5 GW (net output power) is based on scaling assumptions that could be subject to considerable change (e.g., the transmission frequency, the antenna and rectenna power densities); multiple rectennas served by a single satellite also constitute a potential variation.
- The overall efficiency of the entire system would be subject to considerable variation either up or down, and would be a key factor in all cost and technology tradeoffs. Although all system elements would involve known technology, there is considerable uncertainty about how their efficiencies might add up when assembled together.
- Powerplant lifetime, assumed to be 30 years for the reference system, could actually be greater or less depending on a number of economically interrelated factors (e. g., ease of replacement of damaged components, sudden technological advances in component efficiencies, etc.) This would affect all economic projections, even allowing for high-discount rates.
- The total mass in orbit, one of the critical parameters in assessing costs and launch-related environmental impacts, depends on a number of factors still subject to considerable variation. The power Collection/conversion system is an obvious factor; the reference system's two photovoltaic options are indicative of the significance of that tradeoff. The antenna mass is also important. Prospects for revising the reference-system's 100:1 ratio of rectenna-to-antenna area could have major impact on the overall system cost and performance. The 25-percent contingency factor is another major factor subject to revision if R&D mature.

[21] DOE, op cit

SPS would require an extensive program of research and testing of the numerous satellite and terrestrial components of the system before planning for a demonstration satellite could be completed. In addition, substantial improvements in components and overall technology would have to occur before the SPS could meet the performance specifications of the reference system. However, the current reference system does not constitute a preferred system. It is, perhaps, technically feasible but certainly not an optimum design. It was chosen by NASA/DOE as a model and a reference to be used in the assessment process. As such it has the inherent I imitation that as new information becomes available the design becomes progressively obsolete.

The following items summarize the major technical uncertainties for the reference system and suggest possible ways to alleviate them.

- Photovoltaic cells. The reference system specifies a silicon solar cell efficiency of 17-percent and a mass of 2 grams per peak watt (g/Wp). Current space-rated single crystal silicon cells operate at 12- to 16-percent efficiency. However, they are about nine times as massive (18 g/Wp) as called for in the reference system and they cost about $70/Wp (1980). The reference system assumes a cell cost of about $0.17/Wp. Although the issue of costs will be addressed in more detail in a separate section, it is clear that meeting all three goals for the silicon cell blanket would present manufacturers of current cell technology with an extremely difficult task. Normal advances in cell production techniques would readily result in the necessary efficiency increase. However, the burden of achieving a nine times reduction in weight along with a reduction in costs of a factor of 400 makes it highly unlikely that an SPS could be built using single crystal silicon cells.

  If efficiency-mass-cost goals were met, there would still be the problem of cell lifetime in space and the related problem of the feasibility of annealing the surface. Silicon cells are subject to serious degradation by high energy electrons and protons in the solar wind released by solar flares. One study" estimates that the accumulated particle damage would degrade the output from the cells by 30-percent during the 30-year nominal life of the satellite. The resulting damage could be repaired periodically by annealing the cells by either a laser or an electron beam. The beam would sweep across the surface of the cells and heat them briefly to several hundred degrees centigrade. Very little is known about either process in the laboratory and nothing at ail about how they would work in space or how much energy they would use to anneal the surface of the photovoltaic cells. However, experiments have shown that annealing by electron beam is much more efficient than laser annealing.[23] Because no long-term studies have been done, the suitability of silicon cells for extended duration space applications is in question; however, they have demonstrated excellent performance over a period of about 10 years in operating spacecraft.

  GaAs cells appear to be a more realistic candidate for a reference-type satellite, though they have received much less attention than the silicon cells. GaAs cells reach higher efficiencies and can operate at higher ambient temperatures than silicon cells. Laboratory models of GaAs cells have reached efficiencies as high as 18 percent.[24] Because of their currently higher unit cost, the GaAs array would probably require reflectors to concentrate the Sun's rays on the cells and thereby reduce the required cell area. Aluminized Kapton has been suggested as a reflective material because of its low thermal coefficient of expansion and low mass density.

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²*C R Woodcock, "SPS Silicon Reference System," *The Final Proceedings of the Solar Power Satellite Program Review*, DOE/NASA Conf-800491, July 1980,

"B E. Anspaugh, J. A Scott-Monck, R. G. Downing, D W. Moffett, and T. F Miyahira, "Effects of Electrons & Protons on Ultra Thin Silicon Solar Cells, " J PL contract No, NAS7-1OO.

²⁴Ibid

Here, again, whether Kapton and GaAs cells can maintain their integrity over the 30-year design lifetime of the satellite is unknown. Considerably more study would be needed to determine the feasibility of this option.

- Space charge and plasma effects. Because of the high voltages associated with operation of the klystrons, electrical charge buildup in the satellite components could cause arcing and subsequent failure of certain components.
- *Rotary joint/slip rings.* Although the basic technology of building a rotary joint and an associated slip ring (for electrical continuity) is well-known, considerable uncertainty surrounds their construction and operation on the scale of the reference satellite in a space environment. Because it would operate in a gravity-free environment, the design demands would be different than they are for terrestrial designs.
- Klystrons. Current klystrons last about 10 years, but these are tubes especially selected for their long life characteristics and they operate at much lower power levels than the 70 kW required of reference system klystrons. High-power klystrons do exist, but they operate in a pulsed mode, not continuously as the reference system klystrons would have to. The antenna's phased array control system would need considerable development and testing. Although pilot beams have been used in other applications, and the technology is therefore known, it is unclear whether the power beam would leave the ionosphere sufficiently unaffected to allow for undisturbed passage of the pilot control beam.

Although harmonics and other noise produced by the klystron or alternative transmitting device would seem unlikely to affect the natural environment adversely, they could cause radio frequency interference for communications systems (see the discussion of ch. 8). This problem might be severe and would need extensive study, but most experiments could be carried out in ground-based testing. Alternatives to the klystron may provide better noise and harmonic control (see section on alternatives below).

- *Space transportation.* The problems inherent in developing the capability to transport SPS components to LEO and CEO are those of extending a mature technology, i.e., there is sufficient understanding of the problems to be faced that there is little doubt that the appropriate vehicle could be developed. The most important question is whether the necessary massive loads could be transported for sufficiently low costs, i.e., would reusable vehicles prove economic? In this area, much can be learned from experience with the shuttle

In addition to economic concerns, there are additional technical questions relating to environmental effects that would require study. For instance, can the launch vehicles fly trajectories that would keep the effects of ionospheric contamination to a minimum? Would it be possible to substitute other technologies for the argon ion engine proposed for the reference system (see ch. 8).

- *Construction, operations, and maintenance.* There are unresolved questions about the productivity of humans and machines in the space environment. Some automated equipment has been built and tested on Earth, but considerable development would be needed to choose the best ratio between automated and human tasks.

Alternatives to the Reference System Subsystems

One of OTA's goals is to explore the possible alternatives to the reference system. Some options improve specific components of the reference system. Others would require significant redesign of the overall system. This is because the reference system is composed of a number of interlocking components, some of which depend heavily on the other elements of the system. Thus, a radical change in one component might require numerous other system changes in order to create the most efficient overall design.

A number of alternative subsystems and systems were considered in the process of electing the reference system design. Advances have been made in some components that were previously rejected. In addition, consideration of some of the above-mentioned technical uncertainties has engendered new designs that could alleviate these uncertainties or resolve some of the technical problems encountered in the reference system.

The following summary lists a number of subsystem options that could be considered as alternatives to the reference system. A more detailed discussion of each can be found in appendix A.

- *Solar thermal power conversion.* Either a Brayton- or Rankine-cycle engine offers higher efficiency energy conversion than photovoltaics. However, they currently suffer from limitations on the means for heat rejection.

  Thermionic, magnetohydrodynamic or wave energy exchanger technologies might eventually find use in combination with the Rankine or Brayton cycle.
- *Photovoltaic alternatives.* Materials other than silicon or gallium arsenide may eventually prove more viable for use in the SPS. Currently none of the other obvious options meet the projected standards for efficiency, low mass, materials availability, etc., that would be needed for satellite use. Different sorts of concentrator systems are also of interest, as is the possibility of using single cells or a combination of cells that respond to a wide portion of the solar spectrum. A possible approach would be to use a combination of al I these variations.
- *Alternative microwave power converters.* Several devices other than the klystron have been considered for converting electricity to microwaves and transmitting them to Earth including the magnetron, which offers the principal potential advantage of cost and low noise, and the solid-state amplifier whose reliability could be very high and mass low.
- Photoklystron. This device, which is still in the very early stages of study, both converts the sunlight directly to microwave power, and transmits it. If successful, it could replace both photovoltaic cell and amplifier.
- Offshore rectennas. For highly populated European and U.S. coastal areas, rectennas mounted in the shallow offshore seabeds offer some advantages over long transmission lines from suitable land-based rectennas.

THE SOLID-STATE SYSTEM

Two system approaches using solid-state devices have been considered for the SPS. The most direct of these simply replaces the kylstrons and slotted waveguides in the reference system by solid-state amplifiers and dipole antennas maintaining essentially the same basic configuration as that of the reference system (fig. 9); the second approach completely revises the satellite configuration by integrating the antenna and solar array in the Earth-facing "sandwich" configuration, using a movable Sun-facing mirror to illuminate the solar array (fig. 16). A number of alternative sandwich configurations have been explored but at the moment the configuration of figure 16 seems to be the best.[25]

Another related subsystem option uses the multibandgap photovoltaic cells discussed earlier, possibly in conjunction with selective filtering to reduce solar-cell temperatures. When such cells are utilized in the sandwich configuration of figure 16, they offer considerable potential mass reduction. A recent preliminary case study[26] compared sandwich-type systems such as that of figure 16 employing single-bandgap GaAs photocells similar to those of the reference system but having higher concentration ratios (CR) with optimized multibandgap photovoitaics. Such a configuration would result in an approximate W-percent increase in power delivered per kilogram.

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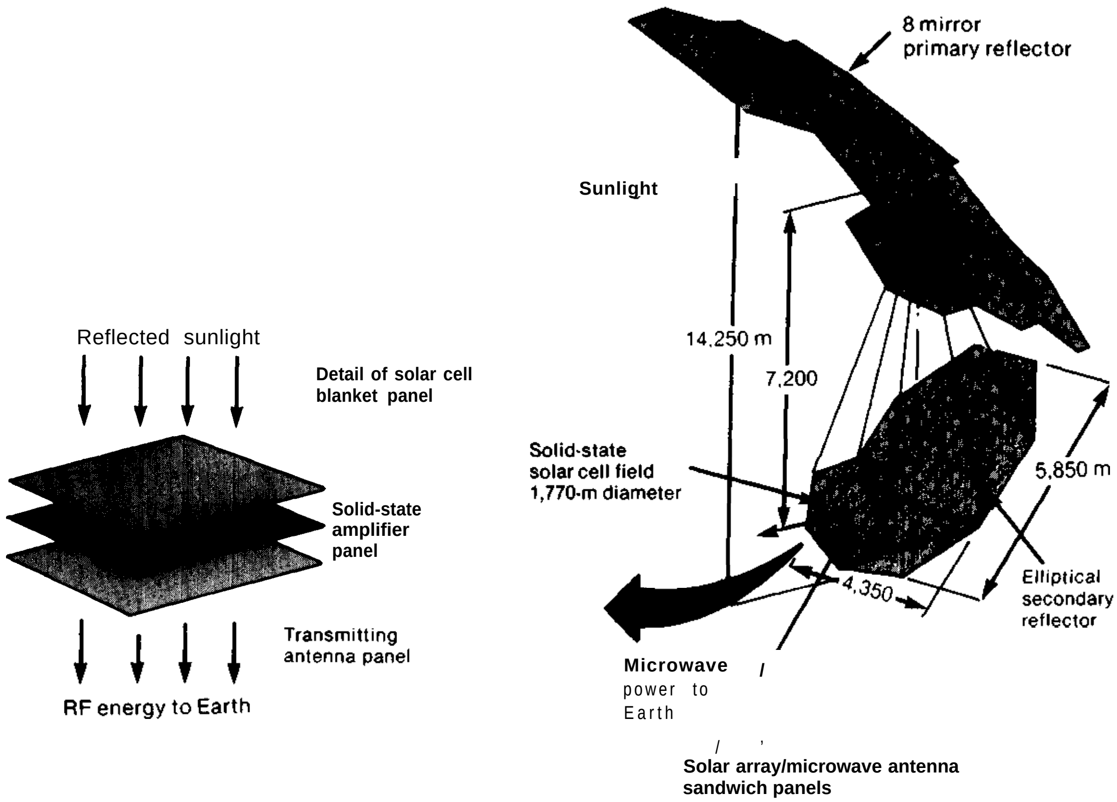
[25] G M Hanley, et al , "Satellite Power Systems (SPS) Concept Definition Study, " First performance Review, Rockwell International report No SSD79-01 63, NASA MSFC contract No NAS8-)2475, Oct 10, 1979

[26] Ibid

Figure 16.—The Solid-State Variant of the Reference System



SOURCE: G. M. Hanley, et al., *"Satellite Power Systems (SPS) Concept Definition Study,* "First Performance Review, Rockwell International report No. SSD-79-0163, NASA MSFC contract No. NAS-8-32475, Oct. 10, 1979.

LASER TRANSMISSION

Lasers constitute an alternative to microwave transmitters for the transmission of power over long distance.[27] They offer the fundamental advantage that at infrared wavelengths, energy can be transmitted and received by apertures over a hundred times smaller in diameter than the microwave beam. This obviously would reduce the size and mass of the space transmitter and the land-area requirement of the ground receiver. But perhaps even more important, the great reduction in aperture area would permit consideration of fundamentally different systems. For example:

- The use of low Sun-synchronous rather than high geostationary orbits for the massive space power conversion subsystem might be possible. (A Sun-synchronous orbit is a near-polar low orbit around the Earth that keeps the satellite in full sunlight all the time while the Earth rotates beneath it.) In this suggested system, the laser would beam its power up to low-mass laser mirror relays in geostationary orbit for reflection down to the Earth receiver, an arrangement that might considerably reduce the cost of transportation, since the bulk of the system mass is in LEO rather than in GEO. However, system complexity would be increased due to the need for relay satellites.

[27] Wayne S. Jones, and Maxwell W. Hunter, II, "Solar power Satellites: The Laser Option," *Astronautics* and *Aeronautics,* March 1979, pp. 59,67,

- Because the mass of the laser transmitters would not dominate the satellite, as does the reference-system microwave transmitter, laser satellites would not benefit nearly so much by large scale as the reference system satellites. The resulting smaller systems would improve the flexibility of terrestrial power demand matching, provide high degrees of redundancy, permit a smaller and therefore less costly system demonstration project, and might even preclude the need for ultimate development of an HLLV.
- The small size of the receiving station would make it possible to employ multiple locations close to the points of use, thereby simplifying the entire ground distribution and transmission system. It would also open up the possibility of repowering existing powerplants, regardless of their size, simply by replacing their steam generating units with laser-heated boilers and/or superheaters.

The most important technical disadvantages of laser-power transmission are the very low efficiencies of present laser-generation and power-conversion methods, low efficiency of laser transmission through clouds and moisture, and the relatively undeveloped status of laser power-system technology in general.

The laser system would consist of three distinct elements: the laser-generation subsystem, the laser-to-electric power-conversion subsystem, and the laser beam itself.

Laser Generators

Although the laser has become a well-known and widely utilized device in industry, the high-power continuous-wave (CW) laser generators needed for SPS are still in the advanced-technology or, in many cases, the early research phase.[28] However, the technology is improving dramatically as exemplified by the growth of laboratory-demonstrated conversion efficiencies (input power to laser beam) from about 1 to nearly 50 percent during the past decade.

Of all the currently operating CW lasers, only the electric discharge laser (EDL)[29] seems a feasible alternative for the SPS. The gas dynamic laser (CDL) suffers from very low efficiency if used in the closed cycles necessary for space (i.e., the gas supply must be circulated, cooled, and reused). Chemical lasers require a continuous propellant supply that makes them also unsuitable for long-term use in space.

High-power density at 50-percent conversion efficiency levels has been achieved for EDLs, but only in the open-cycle mode for short time periods. The closed-cycle systems needed for SPS have yet to be tested, even in the laboratory. In theory, they should achieve high efficiencies in that mode as well, but considerable improvement in the available technology would be required to reach the necessary goals.

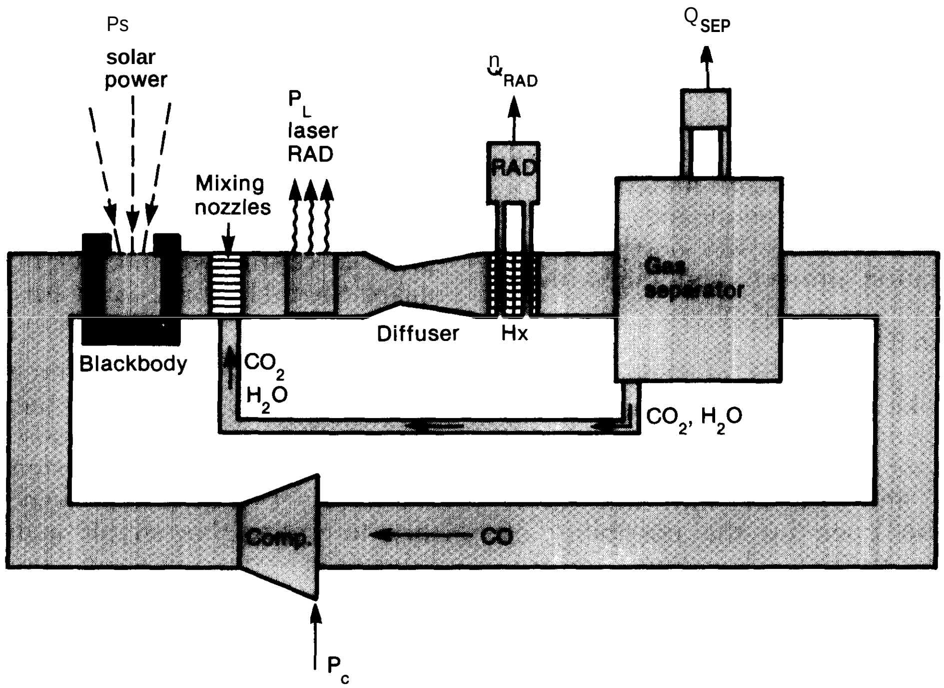
In addition to using improved designs of currently operating lasers, several advanced concepts have been suggested. Of these, the solar-pumped laser and the free electron laser (FEL) seem most promising for the long term.

- Solar-pumped lasers. Figure 17 illustrates the concept of a solar-pumped laser. The energy contained in sunlight directly excites a combination of gases confined between two mirrors, which subsequently "lase" and transmit the captured energy. It suffers the drawback that because only a part of the solar spectrum is useful in exciting any given lasant gas, its conversion efficiency is likely to be fairly low. However, elimination of the need for a separate electric power-generating system, and the consequent reduction in mass and complexity, could more than compensate for this drawback. Further, in comparison with other laser systems, the solar-pumped laser's efficiency need be only as good as the combined power-generating

[28] J Frank Coney bear, "The Use of Lasers for the Transmission of Power, " in *Progress in Astronautics, vol. 61,* A IAA, N Y , July 1978, pp. 279-310

[29] G W Kelch and W. E. Young, "Closed-Cycle Gasdynamic Laser Design Investigation, " Pratt & Whitney Aircraft, NASA Lewis Research Center report No CR-135530, Jan 1,1970.

Figure 17.—Indirect Optically Pumped CO/CO_2 Mixing Laser



SOURCE: R. Taussig, P. Cassady, and R. Klosterman, "Solar Driven Lasers for Power Satellite Applications," in *Final Proceedings of SPS Program Review,* Department of Energy, p. 267

system and laser generator of other laser systems (about 7.5-percent for a photovoltaic-powered carbon monoxide (CO) EDL[30]).

Although the information exists to determine the applicability of solar-pumped lasers to SPS, adequate studies have not been done. There is as yet little or no realistic basis for the mass, efficiency, and cost projections proposed by several authors.[31 32 33 34]

[30] R. E. Beverly, "Satellite Power Systems (SPS) Laser Studies Technical Report, Vol. 1, Laser Environmental Impact Study," Rockwell International SSD-80-0119-1, August 1980

[31] W. S. Jones, L. L. Morgan, J. B. Forsyth, and J Skratt, "Laser Power Conversion System Analysis: Final Report, Vol. I I," Lockheed Missiles and Space Co., report No LMSC-D673466, NASA report No. CR-1 59523, contract No NAS3-21 137, Mar 15, 1979

[32] Claud N Bain, "Potential of Laser for SPS Power Transmission, " report No R-1 861, PRC Energy Analysis Co , DOE contract No. EG-77-C-01-4024, September 1978

[33] John D. G. Rather, "New Candidate Lasers for Power Beaming and Discussion of Their Appl ications, " I bid., pp. 313-332.

[34] Daryl J. Monson, "Systems Efficiency and Specific Mass Estimates for Direct and Indirect Solar-Pumped Closed-Cycle High-Energy Lasers in Space," ref 105, pp 333-345

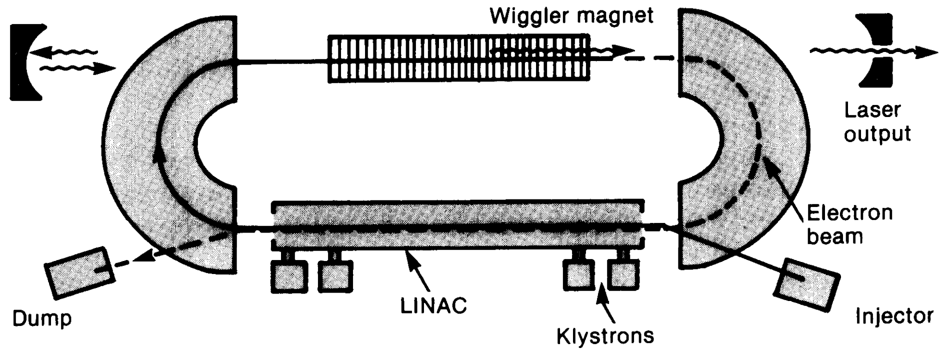
Free-Electron Lasers (FEL)

An FEL is powered by a beam of high-energy electrons oscillating in a magnetic field in such a way that they radiate in the forward direction (fig. 18). A number of pulses reinforce the stored light between the mirrors, generating a coherent laser beam. The high-energy density of the relativistic electron beam is theoretically capable of producing very high-power density lasers, and the emitted frequency is tunable simply by changing the electron energy.

Although efficiencies are theoretically projected to be quite high (around 50 percent for the combined FEL and storage ring[35]), it is not known whether such efficiencies could be reached in practice. In addition, the system mass per unit power output and the ability to

[35] John W Freeman, William B. Colson, and Sedgwick Simons, "New Methods for the Conversion of Solar Energy to R. F. and Laser Power, " in *Space Manufacturing III,* Jerry Grey and Christine Krop (eds) (New York AIAA, November 1979).

Figure 18.—The CATALAC Free Electron Laser Concepts



SOURCE: R. Taussig, P. Cassady, and R. Klosterman, "Solar Driven Lasers for Power Satellite Applications," in *Final Proceedings of SPS Program Review,* Department of Energy. p. 267

scale to the size and power levels of a laser SPS are impossible to predict reliably at this time.[36]

Laser Transmission

As in the case of microwave transmission, the fundamental parameter that governs much of laser transmission performance is the frequency (or wavelength). At ultraviolet or visible wavelengths, absorption losses in the atmosphere are higher than for infrared wavelengths. The wavelength also affects the efficiency of the laser power absorption and conversion equipment.

At the wavelengths of CO or CO, EDLs, (5 to 10 microns), the primary mechanism of beam attenuation is molecular absorption. Scattering by molecules or by aerosols in clear air is relatively unimportant. Attenuation of the beam by aerosols under hazy or cloudy conditions is quite significant and can completely block the beam if the clouds are thick enough. Although it is apparently possible to burn a hole through thin clouds,[37] the attenuation of energy is appreciable, and because clouds are seldom stationary, the laser would continually encounter new water droplets to vaporize.

Transmission of the laser beam through the atmosphere is also affected by a phenomenon called "thermal blooming;" i.e., heating of the atmosphere that causes it to act like a lens and distort the laser beam. Scientists are currently divided on the significance of this issue and opinions range from assertions that it is a major factor[38] to suggestions that it could be avoided altogether by selecting the transmitting wavelengths carefully.[39] Considerable classified research is now being carried out on this effect in connection with laser-weapons research. Some of this work might be applicable to SPS use, though in general the military lasers are pulsed, not CW systems. The difference could be critical and should be studied carefully.

With regard to laser optics, it is important to develop components capable of low-loss, high-power-density transmission and reflection of laser light.[40] It appears that adequate technology for SPS systems has a high probability of being available within the next 20 to 30 years, due primarily to advances being made in current military laser research and technology programs.

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[36] Beverly, op. cit.
[37] E. W. Walbridge, "Laser Satellite Power Systems, " Argonne National Laboratory report No AN L/ES-92

[38] Jones, et al , op cit
[39] Beverly, op. cit
[40] Bain, op cit

Transmission options for SPS lasers are essentially of two types: a narrow, highly concentrated beam or a wide, dispersed beam (fig. 19). Advantages of the narrow beam are the reduced land area needed and the small size of the ground power-conversion system; problems include potential environmental and safety impacts of the high-intensity beam, concerns over military uses, and the need for sophisticated high-temperature receivers and power-conversion equipment. Advantages of the dispersed beam are its less severe environmental impact, the possible use of low-performance optics, and simplicity of low-power-density receiving systems. Disadvantages include relatively high atmospheric dissipation, larger land area required and the large mass of Earth receptors. It is probably too early to make an informed selection between the two options, but the narrow-beam approach appears to offer the principal benefit compared to reference-system microwave transmission.

A final concern is the ability to point and control the beam to make sure it would always remain within the designated receiver area and to shut it off instantly should it stray. The adaptive-optics approach to beam control (e.g., phased-array) such as would be used for the microwave beam, appears adequate to provide the necessary pointing accuracy and to ensure safety, since any loss of phasing control would cause loss in coherence of the several lasers making up the beam, and each beam by itself would transmit far too little power to cause any problems. Adaptive optics systems are being studied for use in military directed energy weapons and look promising.[41] It should be emphasized that the overall system constraints might be quite different for the large CW lasers needed for SPS than for pulsed military examples.

Laser-Power Conversion at Earth

Several approaches are possible for converting high-energy-density laser radiation to useful electric power. The technology of laser energy converters is relatively new, but progress has been rapid. Laboratory models have achieved conversion efficiencies of 30 to- 40 percent and designers project eventual efficiencies of 75 percent for some versions. Table 6 summarizes the available technology and projects future potential efficiencies.[42]

The Laser-Based System

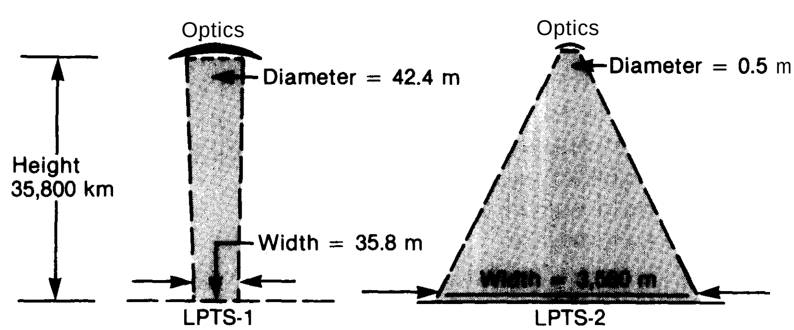
Lockheed[43] has generated one possible laser system (fig. 20) that utilizes power satellites in

[41] Claud N Bain, "Power From Space by Laser," in "High-Powered Lasers in Space," *Astronautics and Aeronautics*, vol. 17, March 1979, pp 28-40

[42] George Lee, "Status and Summary of Laser Energy Conversion," in *Progress in Astronautics*, vol 61 AIAA, N Y, July 1978 pp 549-565

[43] Jones, et al, op cit

Figure 19.—Optics and Beam Characteristics of Two Types of Laser Power Transmission System (LPTS) Concepts



SOURCE: Claud N. Bain, "Potential of Laser for SPS Power Transmission," report No. R-l WI, PRC Energy Analysis Co., DOE contract No. EG-77-C-01-4042, September 1978.

Table 6.—Projections for Laser Energy Converters in 1981-90

	Current	1981-90
Photovoltaics.	—30% efficiency —megawatt power levels —wavelengths below 1 micron	—45% efficiency —megawatt power levels —wavelengths below 1 micron
Heat engines	—Piston engine: Otto or diesel cycles —50% efficiency —1-10 k W —wavelengths near 10.6 microns	—Turbine —75% efficiency —megawatt power levels —wavelengths near 5 microns
Thermionics	—40% efficiency —1-10 kW —wavelengths near 10.6 microns	—50% efficiency —megawatt power levels —wavelengths near 5 or 10 microns
Photochemical cells	—Photoassisted dissociation of water —15Y0 efficiency —wavelengths near 0.4 microns	—Photoassisted dissociation of water —30% efficiency —wavelengths near 0.6 microns
Optical diodes	—Evaporated junction arrays —not ready to convert power	— Evaporated junction arrays —50% efficiency —megawatt power levels —respond to wavelengths from UV to over 10 microns

SOURCE: George Lee, "Status and Summary of Laser Energy Conversion," in *Progress ın Astronautics, vol. 61,* AIAA, N. Y., July 1978, pp. 549-565.

low Sun-synchronous orbit and relay satellites (laser mirrors) both in LEO and CEO. One geostationary relay serves each power satellite. Based on an analysis of five candidate systems in three power ranges, Lockheed selected a CO, EDL powered by a wave energy exchanger (EE) binary cycle and a similar binary cycle for ground power conversion.

The specific 500 MW system selected is diagramed in figure 21; hardware details of the power satellite appear in table 7, and the Overall system characteristics are summarized in table 8.

A major potential advantage of the laser system is that it could be demonstrated via a subscale 500-kW pilot program using the space shuttle to deliver the power and relay satellites into LEO orbits.

Other laser systems are possible. For example, Rockwell[44] has investigated a geosynchronous laser SPS powered by photovoltaic ceils and using 20 to 24 100-MW CO EDL lasers. The CO laser was chosen because it has greater overall efficiency and is lighter than a CO_2 laser.

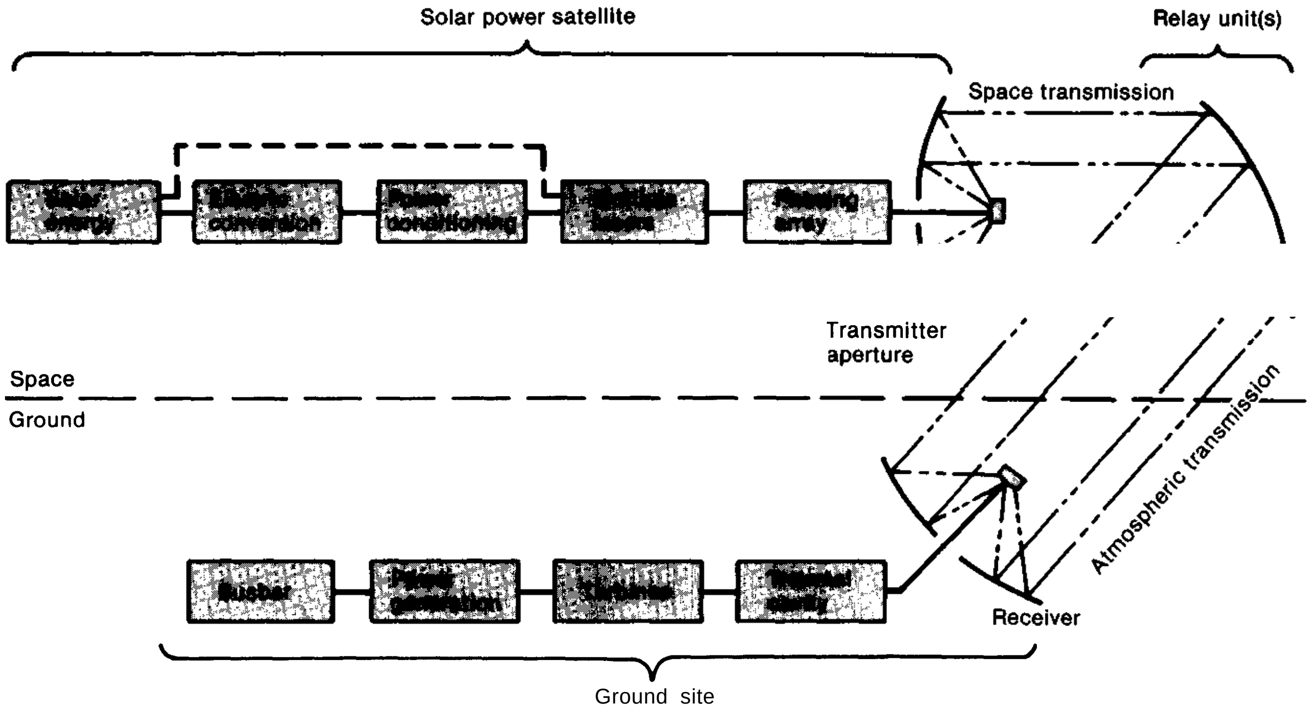
This study will use the LEO-based CO_2 laser system in its subsequent analysis because of the significant difference in space basing (i. e., LEO rather than CEO) which it presents compared to the reference system. Because of the significant uncertainties present in the laser systems concepts and the relative lack of technology base for laser devices, the optimum laser system would undoubtedly look rather different from any system so far devised.

A laser system that used photovoltaic arrays to collect and convert the Sun's energy would suffer from the fundamental difficulty that the overall efficiency of the system would be quite low compared to projected reference system efficiency .45 The major limiting factors are the projected efficiencies of the laser itself (50 percent for an EDL), the atmospheric transmission (84 to 97 percent), and the conversion efficiency of the terrestrial receptor (40 to 75 percent). When multiplied together with the higher efficiency of other system components, they result in an overall efficiency of 17 to 36 percent after photovoltaic conversion of sunlight to electricity to power the laser. When the efficiency of the solar cells (17 percent) is taken into account, the overall system efficiency falls to only 2.8 to 6 percent compared to the projected reference system efficiency of 7 percent. Although this decrease would con-

'*Beverly, op. cit.

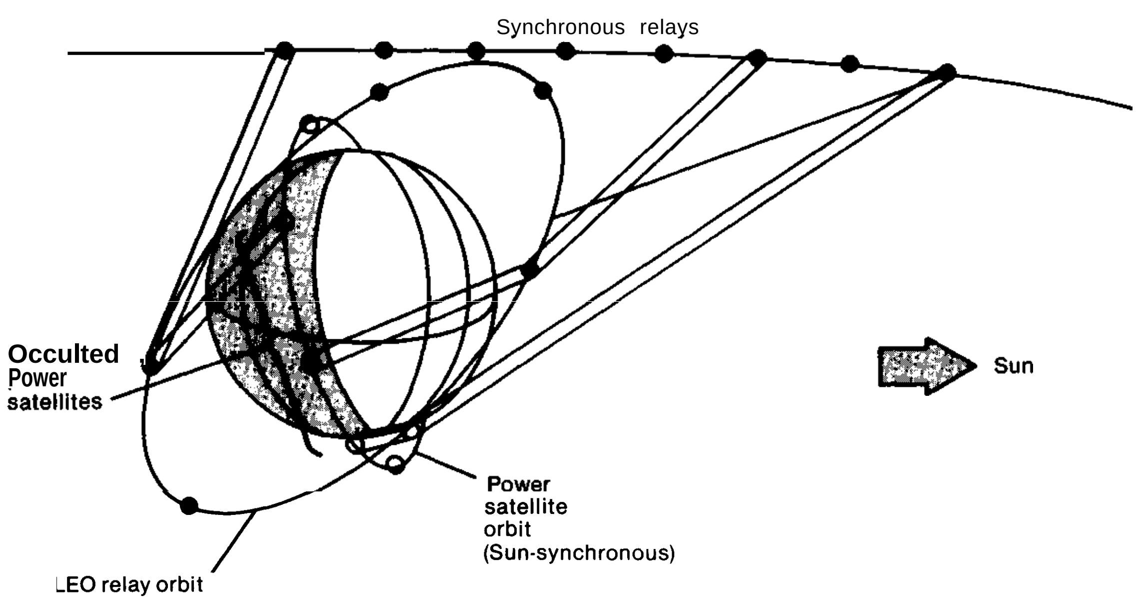
[45]DOE, op. cit.

Figure 20.—The Laser Concept (one possible version)



SOURCE: W. S. Jones, L. L. Morgan, J. B. Forsyth, and J. Skratt, "Laser Power Conversion System Analysis: Final Report, Vol. II," Lockheed Missiles and Space Co., report No. LMSC-D673466, NASA report No. CR-159523, contract No. NAS3-21 137, Mar. 15, 1979.

Figure 21 .—Components of the Laser Concept



SOURCE: W. S. Jones, L. L. Morgan, J. B. Forsyth, and J. Skratt, "Laser Power Conversion System Analysis: Final Report, Vol. 11," Lockheed Missiles and Space Co., report No. LMSC-D673466, NASA report No. CR-159523, contract No. NAS3-21 137, Mar. 15, 1979

Table 7.—500 MWe Space Laser Power System

	Collector	Solar cavity	EE/binary cycle	Power generation and conditioning	Laser	Spacecraft, structure, radiators, etc.	Transmitter aperture and optical train
Unit efficiency (%)	**85**	**86**	**73.5**	**93.1**	**23**	—	**98.7**
System efficiency (%)	**85**	**73.1**	**53.7**	***50.0***	***11.5***	—	11.4
Power in (MW)	7,913	6,726	5,784	4,251	3,958	—	910
Power out (MW)	6,726	5,784	4,251	3,958	910	—	899
Orbital weight (kg)	242,850	517,750	1,326,330	717,660	1,809,000	128,653 Spacecraft 4,108 Structure 94,433 Radiators 6,032 Stabilization 24,080	97,811 Telescope (2) 89,812 Beam reduction 5,379 Phasing array 1,539 Optical train 1,181

	Space transmission	Space relay	Atmospheric transmission	Ground receiver	Thermal cavity	Binary cycle	Electrical generation
Unit efficiency (%)	95	99	85	96	98	75.5	98
System efficiency (%)	10.8	10.7	9.1	8.7	8.5	6.5	6.3
Power in (MW)	899	854	845	718	690	676	510
Power out (MW)	854	845	718	690	676	510	500
Orbital weight (kg)	–	105,438 Transmitter 44,703 Receiver 46,729 Optical train 945 Spacecraft 5,900 Radiators 5,762 Structure 1,023 Miscellaneous 376	—	—	—	—	—

SOURCE: W. S. Jones, L. L., Morgan, J.B. Forsyth, and J. Skratt, "Laser Power Conversion System Analysis: Final Report, Vol. 11," Lockheed Missiles and Space Co., report No. LMSC-D673466, NASA report No CR-159523, contract No. NAS3-21 137, Mar 15, 1979.

Table 8.—Laser Power Station Specification

Solar power collected (MW)	7,913.0
Collector diameter(m)	2,710.0
Electrical power to laser(MW)	3,958.0
Laser power output (MW) (20 lasers at 45.5 MW each)	910.0
Transmitter, aperture diameter (m)	31.5
Secondary mirror diameter (o)	3.0
Transfer mirror size (m)	3.0 x 4.2
Mirror reflectivity (%)	99.85
Optics heat rejection (MW)	11.8
Radiator area (m^2)	2,656.7
Mirror operating temperature ("C)	200.0

SOURCE: W. S. Jones, L. L., Morgan, J. B. Forsyth, and J. Skratt, "Laser Power Conversion System Analysis: Final Report, Vol. 11," Lockheed Missiles and Space Co., report No. LMSC-D673466, NASA report No. CR-159523, contract No. NAS3-21137, Mar 15, 1979.

stitute a potential problem for the laser system, it must be emphasized that many other complex factors (e. g., the smaller terrestrial receivers, or lower mass in GEO), might compensate in complex ways for lower efficiency. When added up, the combination might make the laser system more acceptable overall than the microwave systems. 'b

"Abraham Hertzberg and Chan-Veng Lau, "A High-Temperature Rankine Binary Cycle for Ground and Space Solar Applications," m "Radiation Energy Conversion in Space," K W, Billman (cd,), *Progress in Astronautics and Aeronautics,* vol. 61 (New York, AIAA, July 1978), pp 172-185.

MIRROR REFLECTION

Instead of placing the solar energy conversion system in orbit as in the reference SPS, several authors have suggested using large orbiting mirrors to reflect sunlight on a 24-hour basis to ground-based solar-conversion systems.[47 48 49 50]

Typically, this option would use plane mirrors (fig. 22) in various nonintersecting low-altitude Earth orbits, each of which directs sunlight to the collectors of several ground-based solar-electric powerplants as it passes over them (the so-called "SOL ARE S" concept).

Each mirror would be composed of a thin film reflecting material stretched across a supporting structure made up of graphite-reinforced thermoplastic. As they pass within range of the terrestrial receiving station, the mirrors would acquire the Sun and the ground station nearly simultaneously. They would maintain pointing accuracy by means of built-in reaction wheels.

Two typical "limiting cases" have been identified from among several alternatives.[51] one would use a 1,196-km circular equatorial orbit (O ^{0} latitude) serving 16 equatorial ground stations each generating about 13 CW (baseload, with minimum storage) and another 6,384-km 40 '-inclination circular orbit serving four 375 GW ground stations at 300 latitude. Additional ground stations in each case (to accommodate demand growth) could be achieved simply by increasing the orbit altitude and mirror size, which increases the size of the illuminated ground circle and thereby permits the use of larger ground stations.[52] The orbiting mirrors themselves could probably be quite large (up to 50 km' each) with very low mass density[53] and still maintain their required optical surface flatness in the presence of disturbing forces.

A mirror system would offer the following potential advantages:

- The space segment would be simple and of low mass. It would consist only of planar reflective thin-film mirrors.
- It would minimize the need for large-scale space operations, since recent designs allow terrestrial fabrication and packaging with automatic deployment i n space.
- The system would be modular and highly redundant, i.e., there would be many identical mirrors capable of mass production.
- The mirrors would operate at low-orbit altitudes, thus not requiring the CEO transportation system of some other alternatives.
- It would eliminate the need for developing microwave- or laser-transmitting technology.
- The mirrors would reflect ordinary sunlight, thus eliminating many of the potential damaging environmental effects due to laser or microwave transmission.
- It could be used for a variety of terrestrial uses where enhanced 24-hour sunlight would be useful. SOLARES could increase the solar product fivefold over the same system operating on ambient sunlight.
- Demonstration would be very inexpensive compared to laser or microwave options.

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[47] Hermann Oberth, "Wege zur Raumschiffahrt, " Oldenburg-Verlag, Berlin, 1929; also see "Ways to Spaceflight, " NASA technical translation TT F-662

[48] Krafft A Ehricke (for example), "Cost Reductions in Energy Supply Through Space Operations, " paper IAF-A76-24, 27th *International Astronautical Congress,* Anaheim, Calif , Oct. 10-16, 1976.

[49] K. W. Billman, W. P Gilbreath, and S W Bowen, "Introductory Assessment of Orbiting Reflectors for Terrestrial Power Generation," NASA TMX-73,230, April 1977

[50] K. W. Billman, W. P. Gilbreath, and S W Bowen, "Orbiting Mirrors for Terrestrial Energy Supply, " in "Radiation Energy Conversion in Space," K. W. Billman (ed), *Progress in Astronautics* and Aeronautics Series, VOl 61 (New York Al AA, July 1978), pp 61-80

[51] K. W. Billman, W. P. Gil breath, and S W. Bowen, "Solar Energy Economics Revisited: The Promise and Challenge of Orbiting Reflector for World Energy Supply," DOE SPS Program Review, June 8,1979.

[52] K W Billman, "Space Orbiting Light Augmentation Reflector Energy System: A Look at Alternative Systems," SPS Program Review, June 1979.

[53] John M Hedgepeth, "Ultı ghtweight Structures for Space Power, " in "Radiation Energy Conversion in SpaceJ" K W, Billman (ed), *Progress in Astronautics* and *Aeronautics, vol. 61* (New York Al AA, July 1978), pp. 126-135.

Figure 22.–The Mirror Concept (SOLARES)

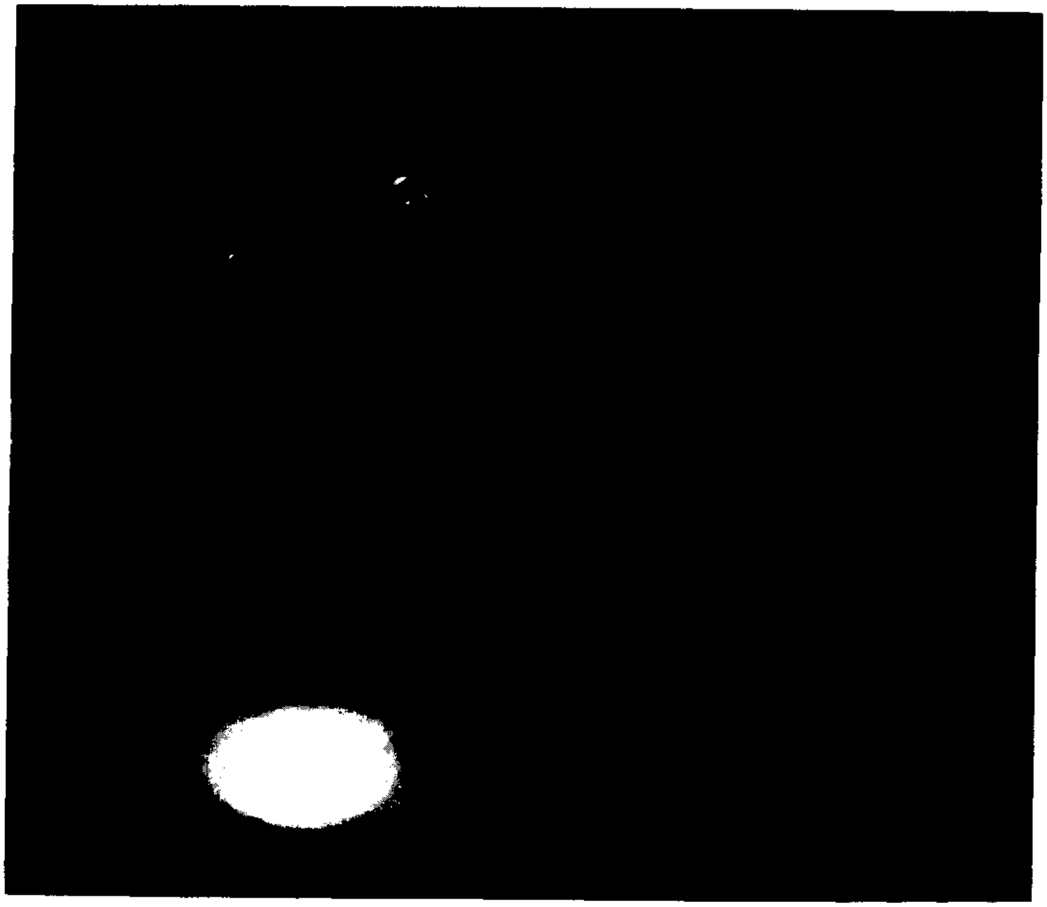
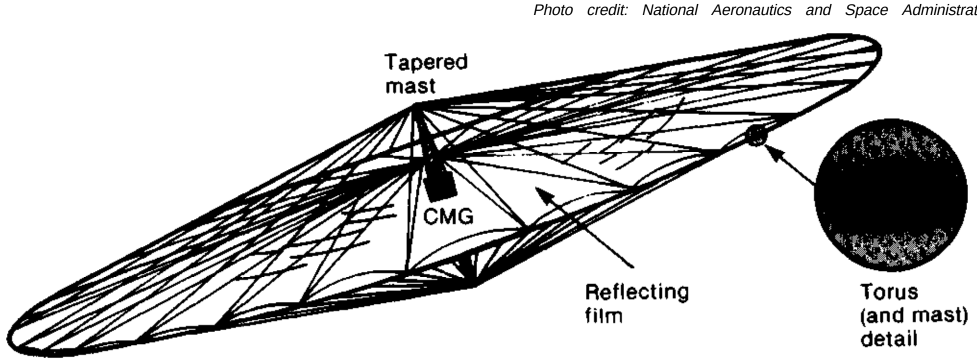


Photo credit: National Aeronautics and Space Administration



SOURCE: K. W. Bill man, "Space Orbiting Light Augmentation Reflector Energy System: A Look at Alternative Systems," SPS Program Review, June 1979.

On the other hand, mirror systems would possess the following potential disadvantages:

- They would require a large number of satellites each with individual attitude control. Maintenance might be expensive and difficult to accomplish.
- The mechanisms needed to keep the mirrors pointed accurately might be complicated.
- The mirrors might cause unwanted weather modifications around the ground stations (see below and ch. 8).

- Scattered light from the mirrors and the light beams in the atmosphere would interfere with astronomical research (see ch. 8).
- The large power production per site (10 to 135 GW) and necessary centralization of the electrical supply from them would not be attractive to the utilities (see ch. 9).
- The large area of the receiving sites (100 to 1,000 km²) would be likely to make land-based siting extremely difficult if not impossible from a sociopolitical standpoint (see ch. 9).

The Mirror System

The "baseline" Mark 1 SOLARES[54] design (table 9) would require a total mirror area of nearly 46,000 km². If each mirror were 50 km², about 916 of them would be necessary for a global power system that would produce a total of 810 GW from six individual sites, or about twice 1980 U.S. electric generation. It was chosen for comparative purposes because it demonstrates the potential for large scale energy output that might be achieved with mirrors. It is by no means the optimum SOLARES system. A low-orbit version (altitude 2,000 km) with 15 smaller ground stations (10,000 to 13,000 MW output) might be more feasible or desirable. One of the principal features of the SOLARES concept is that it could be used for any energy use where enhanced sunlight would be used to advantage. By using many more smaller mirrors, the mass per unit area could be minimized, and the total mass in orbit for the entire baseline system then becomes about 4X105 tonnes. Thus, the entire SOLARES baseline system would require only the same mass in space as eight 5,000 MW reference system satellites.

Several Earth-based energy production methods currently under development might be used in conjunction with orbital reflector systems: 1) photovoltaic arrays of varying sizes are projected for commercial deployment in the late 1980's, and 2) solar-thermal electric plants should become commercially feasible in selected locations about the same time, possibly also for "repowering" of existing coal- or oil-fired fossil-fuel plants with solar boilers. Much of the economic disadvantage of both types of solar-electric powerplants is associ-

[54] Billman, et al., "Solar Energy Economics Revisited. The Promise and Challenge of Orbiting Reflector for World Energy Supply, " op. cit

Table 9.—SOLARES Baseline System

configuration:
Space system
4,146km inclined orbit, 45,800km² total mirror area
Ground system
6 sites with DOE 1986 goal solar cells @ 15% efficiency
11 % overall system conversion efficiency, $\eta\alpha$-circle area = 1.168km2 each, 135 GWe each

Impact:
Total system would produce 3.24 times current U.S. consumption, total area = 84 x 84km² (52 x 52 mi²)

Baselined costs (in 1977 dollars)
Implementation schedule
5-year development, design, test, and evaluation (DDTE)
2-year manufacturing and transport fleet facilities preparation
6-year space and ground hardware construction
System complete about 1995

Direct costs estimate (billions of dollars)	
Facilities	$ 47.30
Hardware	885.65
Total direct	$932.95
Indirect costs estimate (billions of dollars)	
15% contingency on direct costs	$139.94
Design, development, test, and evaluation	43.80
Interest[a]:	
Facilities	23.58
Hardware	101.26
DDTE	41.01
Total indirect	$349.59
Total cost	$1,282.54
Indirect cost factor	1.38
Installed cost per rated output ($/kWe)[b]	1,508
Capacity factor(%)	95
1995 O&M costs:	
Fixed ($/kW-y)	3
Variable (mills/kWh)	2
Levelized capital cost (mills/kWh)[c]	27.2
Levelized O&M cost (mills/kWh)[d]	4.5
Levelized busbar energy cost (mills/kWh)[e]	31.6
Comparison baseload power systems (CIRCA 1995):	
Conventional coal/nuclear mix[f]	
Levelized busbar energy cost (mills/kWh)[e]	45
Ambient sunlight photovoltaic[f g]	
Levelized busbar energy cost (mills/kWh)	115

[a] 4% first year, 8% per annum until positive cash flow after Year 11.
[b] Includes all direct costs, 15% contingency, interest during implementation at 8% per annum.
[c] 15% fixed charge rate 30 years at 6% annual inflation.
[d] 30 years at 6% annual' inflation,
[e] 15% fixed charge rate.
[f] See text; these d. not include their historically extensive R&D costs that are Included, in SOLARES costing.
[g] Uses same terrestrial costing algorithm as SOLARES that results in indirect cost factor of 1.37.

SOURCE: K. W. Billman, W. P. Gilbreath, and S. W. Bowen, "Solar Energy Economics Revisited: The Promise and Challenge of Orbiting Reflector for World Energy Supply," DOE SPS Program Review, June 8, 1979.

ated with the energy storage needed to allow them to serve as intermediate or baseload plants. Should these plants prove to be even marginally successful, relieving their storage needs by keeping them I it for 24 hours a day by sunlight from orbiting reflectors would enhance the attractiveness of these terrestrial options.

The various benefits of a mirror system must be weighed against the percentage of time the ground-based energy production facilities would be obscured by clouds, smog, fog, and other atmospheric obstruct ions. However, there is some evidence" that the concentrated sunlight provided by the orbiting mirrors would tend to disperse water-based obscurations such as clouds and fog, as a consequence of the accelerated evaporation produced by the high-intensity solar radiation.

If the orbiting mirrors can disperse clouds of moisture around the SOLARES ground station, what effects may they have on the climate nearby? Large orbiting mirrors have been suggested for use in climate modification,[56] but their possible detrimental side effects have not been studied (see ch. 8). However, even if reflected sunlight could be shown to have a salutary effect on certain regions of the Earth, there is no reason to believe, without further study, that regions whose weather patterns could benefit from enhanced sunlight would necesssarily coincide with the SOLARES ground stations.

"Ibid

[56] I Bekey and J E Nagle, "Just Over the Horizon in Space," *Astronaut/es* and *Aeronautics*, May 1980.

SPACE TRANSPORTATION AND CONSTRUCTION ALTERNATIVES

Space transportation and construction (with the possible exception of SOLARES) are common to all the options. NASA contractors who developed the transportation, construction, and assembly plan for the reference system devoted considerable effort to the process of winnowing out a host of alternative approaches. Nevertheless, several other construction/assembly schemes have been proposed for various phases of SPS program development. If feasible, they would mostly serve the purpose of reducing costs by using technology developed for other programs or by reconfiguring the reference system scenario. Because transportation costs are a significant percentage of any systems cost (see section on costs below), it would be important to explore these alternatives fully.

Transportation

Transportation strategy in the early development phase and engineering verification is to use the shuttle or an upgraded shuttle to their maximum capacities. In these, as well as later demonstration and production phases, using shuttle size vehicles at high launch rates could be cheaper than developing and using larger launch vehicles (see section on costs). Perhaps the most obvious approach is to upgrade the shuttle-based space transportation system to perhaps five times the capability (i.e., total mass to space in a given time as represented by payload size, launch rate, and turn-around) of the present shuttle.[57]

The need to conduct relatively sizable experiments, and possibly prototype or demonstration projects in geostationary orbits rather than in low-Earth orbits, would pose a serious transportation problem. Current space-shuttle upper stages, or "orbital transfer vehicles, " are not capable of carrying large payloads to geostationary orbit and are not able to support any servicing operations there, since these units are not reusable.

Several innovative approaches have been suggested that circumvent the need for developing new vehicles. One such approach employ; an in-orbit propel ant processing facility

[57] Salkeld, et al., op. cit.

built into one of the shuttle's big "throwaway" propellant tanks to convert water into hydrogen and oxygen –the best propellants for high-performance rocket engines. The water required as the feedstock for this process would be carried into LEO as an "offload" on every space shuttle flight whose payload is less than the maximum shuttle capability. The hydrogen and oxygen, after being liquefied and stored in the propellant processing facility's tank, are then used as the propellants for a reusable low-thrust "space tug" whose principal component is also a leftover shuttle propellant tank. The tug, which replaces the cargo orbital transfer vehicle of the reference system, would carry SPS prototype or demonstration hardware up to CEO. Although such a system is rather completely defined,[58] considerable technology advancement and development would be required, e.g., for the in-orbit electrolysis and liquefaction plants, the space-tug-development, and the system logistics and integration. Cost estimates have not yet been released. Nevertheless, this concept represents an interesting suggestion for eliminating the development of a major new (or upgraded) launch vehicle just for an SPS demonstration, thereby reducing the "up-front" costs of any sizable SPS prototype or demonstration project.

Another scheme would use an electromagnetic propulsion device[59] called a "mass driver" to provide orbital transfer thrust instead of the chemical-rocket-powered space tug. The mass driver is simply a solar-powered linear electric motor, which derives its thrust by accelerating chunks of waste mass (e.g., chopped-up or powdered shuttle propellant tanks) into space at high exhaust velocities.[60 61] Since it uses electricity, its energy could come directly from the Sun via photoelectric conversion. This concept is far more ambitious than the in-space propellant processing scheme; furthermore, it depends on a device that, although tested extensively on Earth in experimental high-speed trains and in the laboratory, has yet to be demonstrated at the scale and acceleration levels required by the orbital transfer application. A modest research effort on this concept is currently being supported by NASA's Office of Aeronautics and Space Technology.

The production phase of the SPS program would present a number of opportunities for transportation alternatives that could not only reduce production costs, but could also mitigate environmental and other impacts. Because of the high proportion of total space segment construction costs (both nonrecurring and recurring) taken up by transportation, many of the proposed innovations center on alternatives to the family of four transportation vehicles selected for the reference system.

The most direct approach to transportation cost reduction would be to improve the HLLV, since it absorbs the bulk of transportation development and operations costs. The most likely technological alternative appears to be the use of fully reusable single-stage-to-orbit (SSTO) vehicles.[62] Very advanced winged SSTO vehicles that could reduce LEO payload delivery costs to the order of $1 5/km are projected as becoming practical in the last decade of this century, provided sufficient demand exists.[63]

For orbital transfer the personnel and cargo orbital transfer vehicles selected for the reference system probably represent the best available technology in the two principal options: chemical and electric propulsion.

Alternatives for routine high-mass payload hauling might include solar sails, laser propulsion, and various forms of electric propulsion other than the ion (electrostatic) rocket described for the reference system, e.g., elec-

[58] Central Dynamics Corp (Convair Division), "Utilization of Shuttle External Tank in Space, " unpublished presentation, June 1978.

[59] F. Chilton, B, H ibbs, H. Kolm, G K O'Neill, and J. Phil lips, "Electromagnetic Mass Drivers," in "Space-Based Manufacturing From Nonterrestrial Material s," G K C)'Neil I (cd.), *Progress in Astronautics and Aeronautics, vol. 57 (New* York AIAA, August 1977), pp. 37-61.

[60] Chilton, et al., "Mass-Driver Application s," ibid , PP. 63-94.

"Gerard K O'Neill, "The Low (Profile) Road to Space Manufacturing," *Astronautics & Aeronautics,* March 1978, pp. 24-32.

[62] Beverly Z. Henry and Charles H Eldred, "Advanced Technology and Future Earth-Orbit Transportation System s," in *Space Manufacturing* Facilities II, Jerry Grey (ed) (New York: Al AA, Sept 1, 1977), pp 43-51

[63] Ibid

tromagnetic (plasma) thrusters or the mass driver discussed above. None of these options has been studied in enough detail to make choices about them at the present time.

Space Construction

As currently designed, the space component of the reference system would be constructed in CEO. However, it may be more cost effective to build the necessary facilities and satellites in LEO and transport them to CEO fully constructed. Such a scenario would reduce the number of personnel needed in CEO as well as lower the total mass that must be transported there.

Introducing one of the LEO scenarios (i. e., laser or mirrors) would open up significant changes in the construction and transportation option for the SPS. Even a change in one major component of the reference system satellite could alter the ways in which the transportation and construction components are configured. For example, if the photovoltaic cells were to be replaced by solar thermal conversion systems, it would be attractive to construct satellites in LEO and transport them to CEO on their own power because they would suffer less from passage through the Van Allen radiation belts.

Of all the alternative options for SPS construction in the production phase, the prospective use of nonterrestrial materials is perhaps the most innovative and, ultimately, capable of the maximum potential return on investment.

The basic premise of the nonterrestrial materials option is that the cost, energy and materials requirements, and environmental impact of lifting the enormous cumulative masses needed to establish and operate a system of many satellite power stations off the Earth can be markedly reduced by utilizing first lunar materials, and eventually materials obtained from asteroids. The fundamental physical principle that supports this premise is that it takes over 20 times as much energy to launch an object to geostationary orbit from the Earth as it does from the Moon, and the situation for asteroidal materials could be even more favorable. The primary drawback is the high "up-front" cost of establishing the necessary mining base on the Moon and the space-based facility needed to construct and assemble the SPS. Hence, it is not likely that nonterrestrial materials would be used in the prototype, demonstration, or even the early phases of SPS production. However, if a commitment is made to produce a large-scale SPS system in CEO, the lunar materials supply option could well be less expensive than the Earth-launched option (including payback of the initial invest-merit).[64] It has been argued that by "bootstrapping" the operation (i. e., using nonterrestrial material right from the beginning, not only to build the SPS but to build all the necessary facilities as well), there is no need for any new launch-vehicle development (a major element in the "up-front" investment); i.e., the present space shuttle can provide all the Earth-launch space transportation needed to implement an operational multi-SPS network.[65]

Decisions on the nonterrestrial materials option clearly hinge on the results of current and projected SPS technology studies and experiments. Sufficient research on the two technological factors unique to nonterrestrial materials development—the mass driver (both for lunar materials transfer and for in-space propulsion) and lunar materials mining and processing capability—should be done so that a decision to proceed with either the Earth or nonterrestrial materials options could be properly made. Other study and research requirements for the nonterrestrial materials option include system analyses (including design of an SPS that maximizes the use of lunar materials), more intensive searches for appropriate Earth-approaching asteroids, and establishing capabilities for the host of space operational functions needed for other space programs.

As is clear from the preceding discussion, it is difficult to establish a priori alternatives to construction, assembly, and transportation,

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[64] David L Akin, "Optimization of Space Manufacturing Systerns, " in *Space Manufacturing III*, Jerry Grey and Christine Krop (eds) (New York. AIAA, November 1979)

[65] O'Neill, op cit

since each of the SPS alternative options would call for a different approach. General guidelines can be identified, minimizing transportation and construction costs during the evaluation, development, prototype, and demonstration phases by: 1) utilizing a phased, step-by-step approach (e. g., ground-based experiments, only then followed by dedicated space experiments); 2) maximizing use of the essentially developed space shuttle; 3) maximizing the common utilization of technology and development efforts by other programs having related requirements (e.g., large communications antennas and other large space structures, spacecraft power generation, control and transmission, etc.); and 4) developing new transportation vehicles and construction hardware only when economically necessary.

SPS COSTS

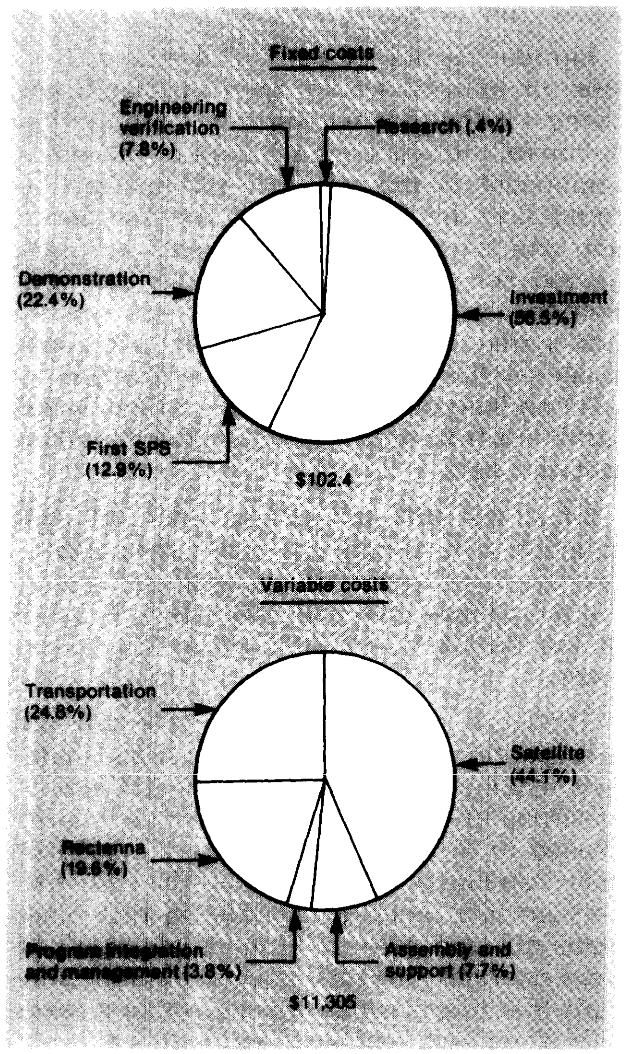
Although knowledge of the overall costs of an SPS program will be essential to making a decision about developing the SPS, current cost estimates are inadequate. Today's projections are based on extrapolations from current technology and in most cases assume major advances. Thus, the technical uncertainties of the concept are too great to provide a firm basis for economic analyses. Here, as in most other areas, it is only possible to develop the foundation for future analysis that would seek to reduce the current uncertainties.

Reference System Costs

The most detailed cost estimates have been made by NASA[66] for the reference system (fig. 23). According to these estimates, which are based on detailed hardware specifications and associated transportation and industrial infrestructure, achieving the first complete reference system satellite will require an investment of $102.4 billion over a 20-year period. Figure 24 illustrates one estimate[67] of how the costs could be allocated over time. Each additional copy of the satellite and associated terrestrial facilities would cost $11.3 billion. Expenses are divided into the following phases:

- *Research* — $370 million. This phase of SPS development (table 10) is by far the smallest, constituting less than 0.4 percent of the total SPS program. About half of these

Figure 23.—Reference System Costs (dollars in billions)[a]



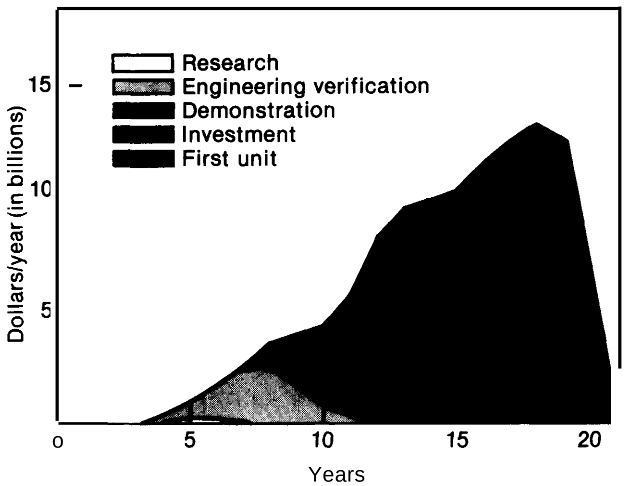
[a]NASA estimates—1977 dollars.

SOURCE: National Aeronautics and Space Administration

[66]Piland, op. cit.

[67]Woodcock, "Solar Power Satellite System Definition Study," op. cit.

Figure 24.— How Cost Could Be Allocated



SOURCE: National Aeronautics and Space Administration.

Table 10.—Research—$370 Million

	Millions of dollars	Percent of total
Power generation	$ 79	21
Power transmission	40	11
Structures and control	22	6
Space construction	25	7
Space transportation	20	5
System studies	19	5
Research flight test	165	45
	$370	

SOURCE: National Aeronautics and Space Administration.

costs are chargeable to the development of the transportation system.

- **Engineering–$8 billion.** This part of the program (table 11) contributes the complex engineering knowledge necessary for creating a useful space structure. The work includes developing an engineering test article in LEO, capable of generating 1 MW of power. It is the direct precursor to the demonstrator and provides the testing ground for constructing and using collector and transmitting subarrays, a rotary joint and satellite attitude control.
- *Demonstration –$23 billion.* This phase of the reference program (table 12) culminates in a 300-MW satellite and the associated rectenna and ground facilities to collect and disperse electrical power to the grid. The demonstrator requires a second generation shuttle and orbital transfer vehicle to provide the transportation capability to GEO.
- *Investment—$57.9 billion.* By far the largest percentage (57 percent) of the nonrecurring costs of the reference system are devoted to this phase (table 13). In addition to providing for the transportation and construction capabilities for the space component, it also includes the costs ($7.8 bill ion) for developing the terrestrial factories needed to produce satellite components.

Table 11 .—Engineering—$8 Billion

	Millions of dollars	Percent of total
SPS	$ 370	5
Test article hardware	210	3
LEO base (8 man)	2,400	30
Manned orbital transfer vehicle	1,200	15
Shuttle flights	870	11
Shuttle booster	2,900	36
Management and integration	61	1
Total	$8,000	

NOTE: Percentages do not total 100% due to rounding errors.
SOURCE: National Aeronautics and Space Administration.

Table 12.—Demonstration—$23 Billion

	Millions of dollars	Percent of total
Demonstrator:		
DDT&E	$2,700	12
Hardware	2,500	11
Pilot production facilities	400	2
Shuttle DDT&E and fleet	3,000	13
Construction:		
DDT&E	3,100	13
Hardware	3,000	13
Space operations (4 years operations, construct bases, and demonstrations)	2,800	12
Personnel orbital transfer vehicle (DDT&E and hardware)	1,700	7
Electric orbital transfer vehicle (DDT&E)	1,800	8
Demonstration rectenna	1,800	8
Management and integration	200	1
Total	$23,000	

SOURCE: National Aeronautics and Space Administration.

Table 13.—SPS Investment—$57.9 Billion

	Millions of dollars	Percent of total
Heavy lift launch vehicle	$16,600	29
Development.	$10,500 18%	
Fleet (6 boosters, 7 orbiters) ...	$ 6,100 11 %	
Electric orbital transfer Vehicle (21 x 284).	6,000	
Construction bases	17,200	30
Development.	$ 4,300 8 %	
Hardware and launch	$12,900 22%.	
SPS development	2,200	4
Ground-based factories (klystrons, solar cells, etc.)	7,800	13
Launch and recovery sites.	7,300	13
Program management and integration.	800	1
Total.	$57,900	

SOURCE: National Aeronautics and Space Administration.

Though these are the best estimates currently available, they suffer from an unavoidable lack of specific engineering details, as well as from insufficient manufacturing experience for most of the system components. Moreover, in some areas, (e. g., klystrons, slip ring, phase control) current technology is inadequate to define solutions to engineering problems. Thus, the estimates could eventually turn out to be high or low. The DOE SPS Cost Review[68] examined five different elements of the SPS reference design and concluded that the projected costs are "based on optimistic assessments of future technological and manufacturing capabilities. "

- Rectenna support construction. Projected costs were found to be low by a factor of 3 to 5. Automated production might reduce costs to a level more in keeping with the reference system estimates, but significant advances over today's methods would be needed.
- Graphite fiber-reinforced thermoplastic. Currently used for golf clubs, fishing rods, and for any other use where low weight and high stiffness are required, this is the recommended material for the satellite truss work. The proposed structures are insufficiently defined to specify the costs. Estimates of future costs for the materials alone vary by a factor of 30 ($40 to $1 ,250/kg).
- Photovoltaic cells. GaAs cell cost estimates are extremely optimistic given the current state of technology. Breakthroughs will be needed to reach the design goals for mass, efficiency, and costs. Silicon cell cost estimates are less optimistic but will still require significant simultaneous reductions in mass and cost and an increase in efficiency to achieve the SPS goal (2 g/W, $0.17/Wp, and 17-percent efficiency).
- Slip ring. It is not well enough defined to appraise the slip ring components or their operational capability.
- *Satellite electrical systems.* The degree of detail is insufficient to judge the credibility of the cost estimates of the subsystem.

Thus, the $102.4 billion estimate of "front end" costs and the $11.3 billion estimates for each satellite may be an optimistic estimate of SPS costs.

On the other hand, if unexpected breakthroughs were to occur in space transportation, rectenna or satellite technology, the costs of the reference system could be lower than now estimated. Since NASA estimates already assume some technological breakthroughs (e.g., in solar cell production, space construction, rectenna construction), they are more likely to be low than high. In either case, the estimates reflect a troublesome feature of the reference system —the high costs that are necessary to demonstrate the feasibility of the SPS (about $31 billion). A further $71 billion would be needed to build and use a single reference system satellite (investment of $57.9 billion and a first satellite costing $13.1 billion). Because the initial costs have a direct bearing on financing the project, they are more fully discussed in chapter 9.

A number of opportunities exist for reducing SPS development expenses. Some involve pursuing alternative concepts; others, revising the reference system. Because the reference system is by no means an optimal design, improvements could lead to significant cost reductions. Common to all potential systems

[68] J. H. Crowley and E J. Ziegler, "Satellite Power Systems (SPS) Cost Review," DOE/TIC-11190, May 1980

would be the division of SPS development into the phases outlined above: research, engineering verification, demonstration, and investment, with increasing commitment of resources in each successive phase. For microwave and laser systems, space transportation and construction would constitute a high percentage of the system costs in all phases. It is in these areas that there would be a high potential for reducing overall costs.

The precise costs of an SPS program would also depend strongly on the nature and scope of national and global interest in space. If commercial ventures in space grow at a strong enough rate (e. g., for telecommunications satellites, space manufacturing, etc.), the current shuttle and its related technology would be inadequate, and pressures would be strong for developing expanded space capabilities. The explosive growth of the domestic airline industry since the 1930's has been suggested as the appropriate model to use to investigate this eventuality. [69]

Much of the technology and experience needed for space construction (manned LEO and GEO bases, large-scale antennas, studies of space productivity, etc.) and space transportation (manned and unmanned orbital-transfer vehicles, shuttle boosters, HLLVS, etc.) of SPS would be developed for other programs as well. Of these, the SPS program should bear only its share. By charging only those costs that are unique to SPS to the SPS program, its front end costs would be reduced by a significant amount. Seen in this light, the massive space capability needed for mounting an SPS program would be less of an anomaly (given the future evolution of space technology), '" and SPS would need to shoulder fewer of the development costs for this capability.

There is also the possibility that a percentage of the investment phase could be shouldered by private investment, thereby reducing the burden to taxpayers. This would be all the more likely to happen in a milieu in which private investment in space is strong for other reasons. Under these combined circumstances, the total risk to the U.S. taxpayer would be substantially reduced.

One interesting option for reducing transportation costs of a CEO SPS would be to assemble the satellite in LEO and send it to CEO under its own power. This might be particularly applicable to the demonstration phase of the reference program, since it would avoid the need for premature investment in an expensive manned geosynchronous construction/assembly facility.

Whatever their potential savings, all of these possibilities could only be evaluated after the proper scale of a demonstration satellite had been determined. This decision, in turn, would depend on considerable terrestrial and space-based testing, some of which will take place in other space programs (see ch. 5).

Because the HLLV would be used later on in the production phase of the reference SPS absorbs the bulk of transportation costs, it is of considerable interest to find less expensive ways of transporting mass to space. Some of the alternative high-capacity transportation vehicles have been discussed earlier in this chapter. The heavy lift launch vehicles achieve their cost reductions by economies of scale. It has been suggested that smaller vehicles, perhaps only slightly larger than the current space shuttle, could be used instead of the much larger HLLV.[71] The smaller vehicles would use higher launch frequencies to achieve the same or better benefits. According to this proposal, the minimum-cost individual payload necessary to launch as many as five reference SPS satellites to orbit is about 50 tonnes (compared to the Shuttle's 30 tonnes). The prospects for employing routine airline-like launch practices opens a whole new approach to the logistics of major space manufacturing enterprises as well as providing potential cost reductions for SPS.

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[69] G. R. Woodcock, "Solar Power Satellites and the Evolution of Space Technology," *AIAA Annual Meeting,* May 1980.
[70] 1 bid.

"R. H Miller and D. L. Akin, "Logistics Costs of Solar Power Satellites," *Space Solar Power Review,* VOI 1, pp. 191-208,1980.

ALTERNATIVE SYSTEMS

Systems other than the reference system might be more or less costly, depending on factors such as the achievable efficiency, the mass in orbit, and the state of development of the alternative technologies that make up these systems. At present, these alternatives are much less defined and their costs accordingly even more uncertain than the reference system costs. The following discussion summarizes available cost data and the greatest cost uncertainties of the alternative systems.

The Solid-State System

- *The unit cost of the solid-state devices is unknown.* However, the semiconductor industry has considerable experience in producing large numbers of reliable solid-state components at low cost, and the learning curve for such production is well-known. In principle, it should be possible to make a realistic prediction of costs when the appropriate device or devices are well characterized.
- Solid-state efficiencies. Present efficiencies are much lower than for the klystron. Current research is aimed at increasing their operating efficiency (to reach at least 85 percent).
- Mass in space. Current estimates of the mass per kilowatt of delivered power[72] suggest that the mass in space would be higher than that of the reference system making the transportation costs higher as well.

Since many components of the solid-state system are shared with the reference system (e.g., the graphite fiber reinforced thermoplastic support structures, the photovoltaic arrays, the rectenna design, etc.), it would be possible to generate realistic relative costs if the above uncertainties are reduced.

The Laser System

The largest unknowns for the laser system are the efficiency, specific mass and the cost of the transmitting lasers themselves. This is because the technology of high-power CW lasers is in a relatively primitive state (current CW lasers achieve outputs of 20 kw or greater, operated in a so-called loop move, i.e., the lasant is recirculated). Space lasers for SPS would have to operate at much higher outputs (megawatts) and at higher efficiencies (i.e., 50 v. 20 percent) for current lasers. Concepts such as the solar pumped laser and the free electron laser are completely untried in a form that would be appropriate to SPS. Therefore their costs are even more difficult to ascertain. In general it can be said that the cost of the system would be tied to the overall efficiency of the system and the amount of mass in space, but considerable study and some development would be needed to make suitably reliable projections.

- *Transportation.* The laser systems that have been explored project higher mass in orbit than for the reference system, which may drive the cost of the laser system up. However, if a substantial portion of this mass is in LEO rather than in CEO, the overall transportation costs might not exceed the transportation costs of the reference system and could turn out to be lower.

- *Demonstration.* Because the laser system is intrinsically smaller it should be possible to mount a demonstration project for considerably less than for the reference system.

- *Terrestrial component.* The ground stations would have to have a certain amount of redundancy in order to accommodate laser transmission when cloudy weather obscures one or more receivers. The precise amount of redundancy would depend on the particular location and would include extra transmission lines as well as extra ground receivers.

[72]G. Hanley, "Satellite Power Systems (SPS) Concept Definition Study," vol. 1, Rockwell International SSD-8O-O1O8-I, October 1980.

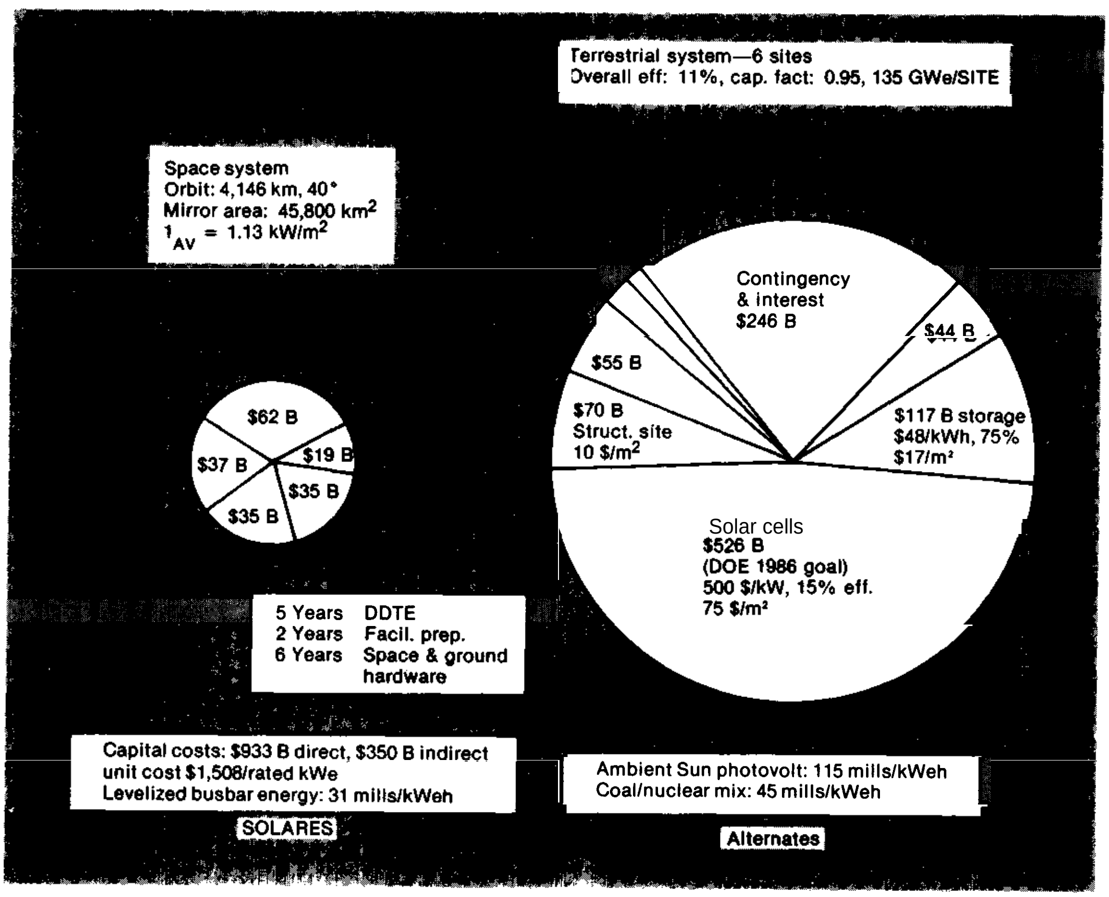
The Mirror System

Figure 25 summarizes mirror system cost estimates for the SOLARES baseline case[73] based on the DOE 1986 cost goals for photovoltaic cells. These "up front" cost estimates, which include contingency and interest on the borrowed money, lead to an estimated levelized busbar energy cost of 31 mills/kWehr compared to 1990 estimated costs of nuclear/coal mix of 45 mills/kWehr. In comparison, a strictly terrestrial system of photovoltaics producing the same overall output computed on identical assumptions would cost 115 mills/kWehr.

Since electricity production from the mirror system would depend heavily on the use of terrestrial solar photovoltaic or solar thermal systems, cost variations of either conversion system would have a strong effect on total system costs. Figure 26 summarizes the effect of varying several system parameters on the cost of electricity delivered to the busbar in the SOLARES system. The three most sensitive parameters are solar cell efficiency, solar cell cost per peak kilowatt and total space cost

[73] Billman, et al., "Solar Energy Economics Revisited: The Promise and Challenge of orbiting Reflector for World Energy Supply," op. cit.

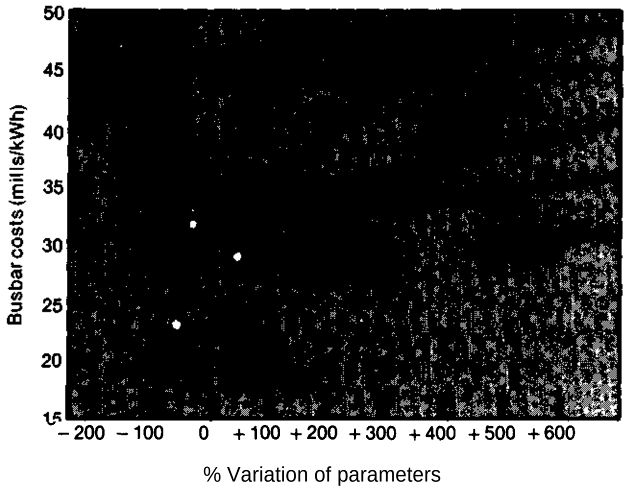
Figure 25.—Elements and Costs, in 1977 Dollars, for the Baseline (photovoltaic conversion, 4,146 km, inclined orbit) SOLARES System



NOTE: Total costs are proportional to the areas of the circles. Interest and contingency constitute 33 percent of the total SOLARES costs.

SOURCE: K. W. Billman, W. P. Gilbreath, and S. W. Bowen, "Space Reflector Technology and Its System Implications" AIAA paper 79-0545, AIAA 15th Annual Meeting and Technical Display, 1979.

Figure 26.—Sensitivity of the SOLARES Mirror System to Variations in System Parameters



SOURCE: Ken Billman, W. P. Gilbreath, and S. W. Bower, "Space Reflector Technology and Its System Implications" AIAA paper 79-0545 AIAA 15th Annual Meeting and Technical Display, 1979,

(transport, construction, mirrors in space). A cost over-run of about 2 times (to $1,000/pk kWe) could be tolerated before a busbar cost of 45 milis/kWehr would be reached. Similarly, a space system total cost over-run of a factor of 4.25 could be tolerated. Finally, because of the projected high energy production per unit of mirror mass in space, a twenty-three-fold increase in space transport cost (or $1 ,380/kg) would still result in a production cost of 45 mills/kWehr. For comparison, the charge for transporting mass to space by means of the space shuttle is estimated to be between $84 and $154 (1975 dollars). "

[74] National Aeronautics and Space Administration, "Space Transportation Reimbursement Guide," JSC-11-802, May 1980