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Survey and Documentation of Emerging Technologies for the Satellite Power System (SPS)

April 1981

Prepared for:
U.S. Department of Energy
Office of Energy Research
Solar Power Satellite Projects Division

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DOE/NASA
Satellite Power System
Concept Development
and
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FOREWORD

This report, prepared under the auspices of Argonne National Laboratory by Peter Glaser and Phillip Chapman of A. D. Little, Inc. for the Department of Energy, discusses technologies that are currently emerging and which could be used to further the development of the satellite power system (SPS) energy concept. The concept was studied by the Department of Energy and NASA during a three-year Concept Development and Evaluation Program (CDEP). The energy system considered during CDEP as a common basis for all evaluations was a "Reference System" constituted principally from technologies that were available in the early to mid-1970's. The newly-emerging technologies identified in this report suggest that newer engineering methods, materials and design approaches could be applied to the Reference System and the CDEP construction and operational scenario to achieve desirable improvements in the SPS energy concept.

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Concluded)

LIST OF FIGURES

LIST OF TABLES

1.0 EXECUTIVE SUMMARY

1.1 Purpose and Scope

The purpose of this study is to survey emerging technologies and new concepts which may offer advantages over those selected for the SPS Reference System.

A brief historical overview of the genesis of the Solar Power Satellite (SPS) concept is presented leading to a discussion of the assumptions and guidelines which were originally established and which led to development of the SPS Reference System design concept. Some of these guidelines are applicable to almost any SPS design, but others could be changed, leading to new and perhaps preferable systems. Moreover, while some of the guidelines are based on solid data, some are little more than arbitrary assumptions which were adopted only to proceed with a concrete point design which then could be assessed in the DOE/NASA Concept Development and Evaluation Program.

In order to stimulate new SPS concepts and to facilitate comparative assessment of emerging SPS technologies, one useful approach is to break the overall system into functional parts. The system functions which must be performed by any SPS concept and the interrelations between them are discussed and a systematic framework is presented for assessment of the wide variety of system concepts and subsystem technologies which have been proposed. About 80 alternative SPS technologies are reviewed.

1.2 Conclusions

The conclusions drawn from this survey of the emerging technologies for the SPS are:

- There exist a variety of technological alternatives for the SPS concept. Some of the options considered will undoubtedly prove impractical, but it is highly probable that others could significantly improve the feasibility, increase performance, or lower the costs of the system.

- The SPS does not depend critically on any specific technology. This increases confidence that the system will prove technically feasible.

- Further work will be required to define the optimal SPS design concept, to develop the requisite technologies, and to establish reliable cost estimates.

- Trade-offs will be required between various concepts which reduce costs (e.g., front-end investment costs and those which reduce the costs of construction or operation of the SPS when the capacity buildup is well under way).

- It is possible to distinguish between concepts which offer marginal improvements or which are of dubious feasibility and those with a high potential payoff.

2.0 HISTORICAL OVERVIEW

2.1 Background

The potential of solar energy as a source of power has been recognized and evaluated for more than 100 years. As the world's energy needs grew and as a result of the industrial revolution, the efforts to harness solar energy accelerated during the last half of the 19th Century and the beginning of the 20th Century. These efforts subsided with the successful development of energy economies based, at first, on coal; and, subsequently, on the use of petroleum fuels. In the 1950's, fossil fuels seemed plentiful and nuclear energy received considerable attention as a potential major alternative. But even then, there was interest in solar energy utilization as demonstrated at the First World Symposium on Solar Energy, Phoenix, Arizona, in 1955, culminating with the United Nations Conference on New Sources of Energy, Rome, Italy, in 1961.

The effects of the exponential growth of energy consumption in the industrialized nations and the global population explosion, which would place increasing demands on available resources were just beginning to be recognized in the 1960's. In 1962, Hubbert(1) indicated that the world's fossil fuel resources were finite, and that on a time scale of recent human history their availability would be only an ephemeral event lasting perhaps a few centuries. In 1965, Gaucher(2) projected that energy consumption in the United States, shortly after the year 2000, would create a gap which could be filled by solar energy or, perhaps, fusion. Subsequent projections of energy consumption by the United States, other industrialized nations and the developing nations, indicated that soon after the year 2000 solar energy utilization would be essential as part of a transition from non-renewable to renewable energy resources.

2.2 SPS Concept Assumptions and Objectives

Technologies which could be used to convert solar energy into useful heat and power fall into two broad categories: (1) terrestrial solar energy conversion, and (2) solar energy conversion in space for use on Earth. The solar power satellite (SPS) concept, which was conceived to accomplish the latter purpose, was based on the assumption that:

- No one energy source or energy conversion method will, by itself, meet all future energy demands on a global scale.

- The search for new sources of non-renewable energy sources can only put off the day of their ultimate exhaustion.

- A spectrum of appropriate solar technologies will be developed and utilized to their optimum capacity whether based on distributed or centralized technologies, consistent with economic, environmental and societal criteria.

- The SPS will be integrated with other solar technologies so as to maximize the benefits of solar energy on a global scale.

The following objectives guided the development of the SPS concept:

- To be of global benefit;

- To conserve scarce resources;

- To be economically competitive with alternative power-generation methods;

- To be environmentally acceptable; and

- To be acceptable to the nations of the world.

Key issues dealing with the technical, economic and environmental aspects of the SPS concept were beginning to be addressed in studies performed in 1973(3). A review of the concept and an initial comparison with alternative energy systems were conducted by an ERDA Task Group in 1976. The Task Group Report(4) concluded that there was insufficient data available at that time for program decisions and that additional study was required. This led to the initiation in 1977 of a three-year joint DOE/NASA "SPS Concept Development and Evaluation Program."(5)

3.0 ASSUMPTIONS AND GUIDELINES FOR THE SPS CONCEPT

3.1 General Guidelines

The SPS is potentially a major new source of energy and its development would require a significant commitment of national and international resources. Decisions regarding directions for the SPS program have been based on a set of principles, goals and value judgements. Not all of these assumptions (here called General Guidelines) have been spelled out clearly, but instead are implicit in approaches to systems design.

Many of these guidelines, listed in Table 3.1 and briefly discussed below, are axiomatic.

3.2 Technical Assumptions

In principle maximum utilization of solar energy could be made by an SPS in an orbit closer to the Sun than that of the Earth. However, because of practical limitations on power transmission it was assumed that the SPS would be placed in a geosynchronous Earth orbit where solar energy is available 24 hours a day during most of the year, and where effective use could be made of solar energy conversion technologies; e.g., photovoltaic, thermal electric, and others which may be developed in the future.

The following guidelines were established for SPS technologies:

- The transmission of power from the SPS to the receiving antenna on Earth should allow all-weather transmission so that full use can be made of the nearly continuous availability of solar radiation in geosynchronous orbit, creating a baseload power plant.

- An Electromagnetic beam link should be developed to transmit power from the SPS through the ionosphere and atmosphere to the receiving antenna on Earth with minimum interface and absorption.

Table 3.1

GENERAL SPS GUIDELINES

- Basic Assumption
  - Technological solutions are an acceptable approach to the energy problem
- Energy Impacts
  - Capable of major contribution to world energy supply
  - Usable by developed and developing nations, with minimal geographic and climatic restrictions
- Unit Power Output
  - Compatible with present utility structures and national power needs
- Economic Impacts
  - Within financing capabilities (government/private)
  - Competitive with alternative energy sources (external costs included)
- Impact on Resources
  - Minimum use of scarce resources
  - Favorable energy payback period
- Environmental Impacts
  - Reduced environmental insult to Earth
  - Minimum impact on upper atmosphere/ionosphere
  - Minimum EMI with terrestrial and space systems
  - Acceptable uses of land
- Societal Effects
  - Stimulus to world economic growth
  - No exacerbation of international conflicts
  - Improvement in the human prospect
- Public Acceptability
  - Participatory technology

- The beam transmission system should consist of a transmitter which is actively controlled to direct the beam precisely to the receiver on Earth.

- The receiver should intercept, collect, and convert the beam into direct current with very high efficiency and interface with a utility power transmission network.

- No active cooling system should be used and waste heat pollution should be reduced to a minimum.

3.3. Energy Supply

The SPS is intended to be a viable baseload power generation system, which must be capable of supplying a significant fraction of future power requirements utilizing a number of satellites orbiting the Earth.

3.4 Unit Power Output

In considering any new power-generation technology, an important issue is that of the output of individual plants. The largest presently-planned nuclear plants have an output of about 1.4 GW; the largest "nuclear park" (i.e., multiple reactor installation) now in development is the Hartsville complex of the Tennessee Valley Authority (TVA), which will have a total output of just over 5 GW. The output of conventional and nuclear plants may continue to increase (at least in the United States and other advanced countries), either through increasing unit size or agglomeration of several plants in power parks, so as to take advantage of continued economies of scale. Based on reliability considerations, it might be assumed that unit power output can be increased in rough proportion to the total load on a given utility power pool.

Even if the SPS proves reliable and the higher estimates of capacity growth prove valid, the use of large size SPS's (3-5 GW) could introduce potential difficulties such as: (a) integration in the utility grid; (b) need for large ground receiver sites; (c) usefulness to smaller nations; and (d) cost or capital requirement needs.

Therefore, it may be highly desirable for the SPS design to be sufficiently flexible to permit unit outputs in the 1-GW range or lower.

3.5 Economic Impact

The economic decisions about buying power from the SPS are likely to be made primarily on the basis of the delivered price. At present, it is not clear to what degree societal costs and benefits will impact the SPS. As a general guideline, the SPS whould be capable of delivering power at a price competitive with other future energy production methods and of providing economic benefits (i.e., economic growth stimulation, technological spin-off).

3.6 Impact on Resources

A guideline which was adopted in the early feasibility studies of the SPS was that the required materials would be selected from those which are abundant on Earth. This may be modified if the SPS is to be produced at a rate such that the use of extra terrestrial resources can be justified on economic grounds.

Even if abundant materials are used, a major expansion of manufacturing capacity may be required to provide some SPS components or subsystems (e.g., silicon solar cells, graphite fiber composite structures, dipole rectifiers, etc.). Availability of materials and industrial capacity considerations, in addition to technical performance parameters, should be taken into account in the establishment of design requirements. Similar comments apply to deployment scenarios, for example, a gradual increase in the rate of buildup of capacity (as opposed to the fixed level addition of 10 GW per year) could ease development of the necessary industrial infrastructure.

The energy required for construction, deployment and orbital assembly of the SPS and the mix of energy resources to meet this requirement must be consistent with the objective that the SPS be economically competitive with future alternative power generation methods.

SPS energy payback should be in the range of a few years and the net energy ratio should be positive. Specific design parameters for SPS subsystems (e.g., thickness of solar cells, cell radiation exposure recovery, and substitution of steel for aluminum in the receiving antenna support structure) should be chosen to reduce energy consumption during manufacture and deployment.

3.7 Environmental Impacts

The fundamental environmental guideline for SPS is that adverse effects should be minimized. However, all human activities - especially energy supply projects - will have some environmental impacts.

A number of areas of potential environmental concern have been identified in connection with the SPS. Several of these effects are not well understood and some may have a long-term consequences and, therefore, require analysis and solution. These are:

- Long-term, low-level microwave exposure effects on health and ecology.
- Microwave heating of the ionosphere resulting from microwave beam absorption.
- Effects of rocket engine effluents on the atmosphere.
- Increased ion density in the magnetosphere resulting from ion engine effluents.
- Electromagnetic interference with terrestrial and space electronic and electrical equipment and radio astronomy.

- Environmental effects resulting from the extraction, processing and fabrication of SPS and space vehicle materials, components and facilities.
- Interference with optical astronomy by solar radiation reflected from the SPS.
- Meteorological and climatic effects near rectenna and launch sites.

4.0 SYSTEM FUNCTIONS AND ALTERNATIVE TECHNOLOGIES FOR THE SPS

4.1 System Functions and Assessment Methodology

In considering a methodology for an ongoing comparative assessment of emerging new technologies for the SPS, a number of difficulties immediately arise. The SPS is presently a very fertile field for innovation and many of the proposed novel concepts involve quite subtle advantages and disadvantages which may not be apparent without detailed analysis. Moreover, a change made in a particular subsystem often propagates throughout the system so that the consequences of the new technology cannot be evaluated without what amounts to a complete system design study. During the R&D phase, before commitment to a final recommended design, it will be important to have available a systematic and routine technique for examining the impact of changes at the subsystem level.

One useful approach to this problem is to consider the functions which must be performed in an operational SPS, instead of concentrating on specific engineering solutions. Table 4.1 shows the primary functions for any SPS, although it should be noted that these functions may overlap in some concepts. In addition, there are a variety of secondary functions, listed in Table 4.2, which must be carried out in order to make the system practical. In general, changes in the technical approach to primary functions will have a major effect on the configuration, performance, and cost of the system; changes in the technologies employed to meet secondary functions may or may not have only a minor impact.

A complementary technique for assessment is to display the interrelationships between alternative subsystems for meeting the functional requirements. Figure 4.1 shows some of the alternatives which have been proposed in a form which may clarify the design choices. Any path through this diagram, from the general guidelines to the utility busbar, represents a conceivable SPS system. Paths which terminate represent technologies which are considered infeasible. For completeness, nuclear power alternatives have been included in the Figure, but are not considered further.

TABLE 4.1

SPS PRIMARY SYSTEM FUNCTIONS

- Collection of Solar Energy in Space
- Conversion to Intermediate Form of Energy
- Transmission of Energy to Earth
- Reception and Conversion to Usable Energy on Earth

Table 4.2

SPS SECONDARY SYSTEM FUNCTIONS

- Space Transportation
  - Earth to LEO
  - LEO to GEO
- Station-keeping and Attitude Control
- Fabrication and Assembly in Space
- Power Beam Phase Control
- Satellite Maintenance
- Receiver Maintenance
- Power Conditioning and Distribution Aboard Satellite
- Power Conditioning and Distribution at Receiver
- Satellite Thermal Control
- Ancillary Functions of Rectenna Reservation

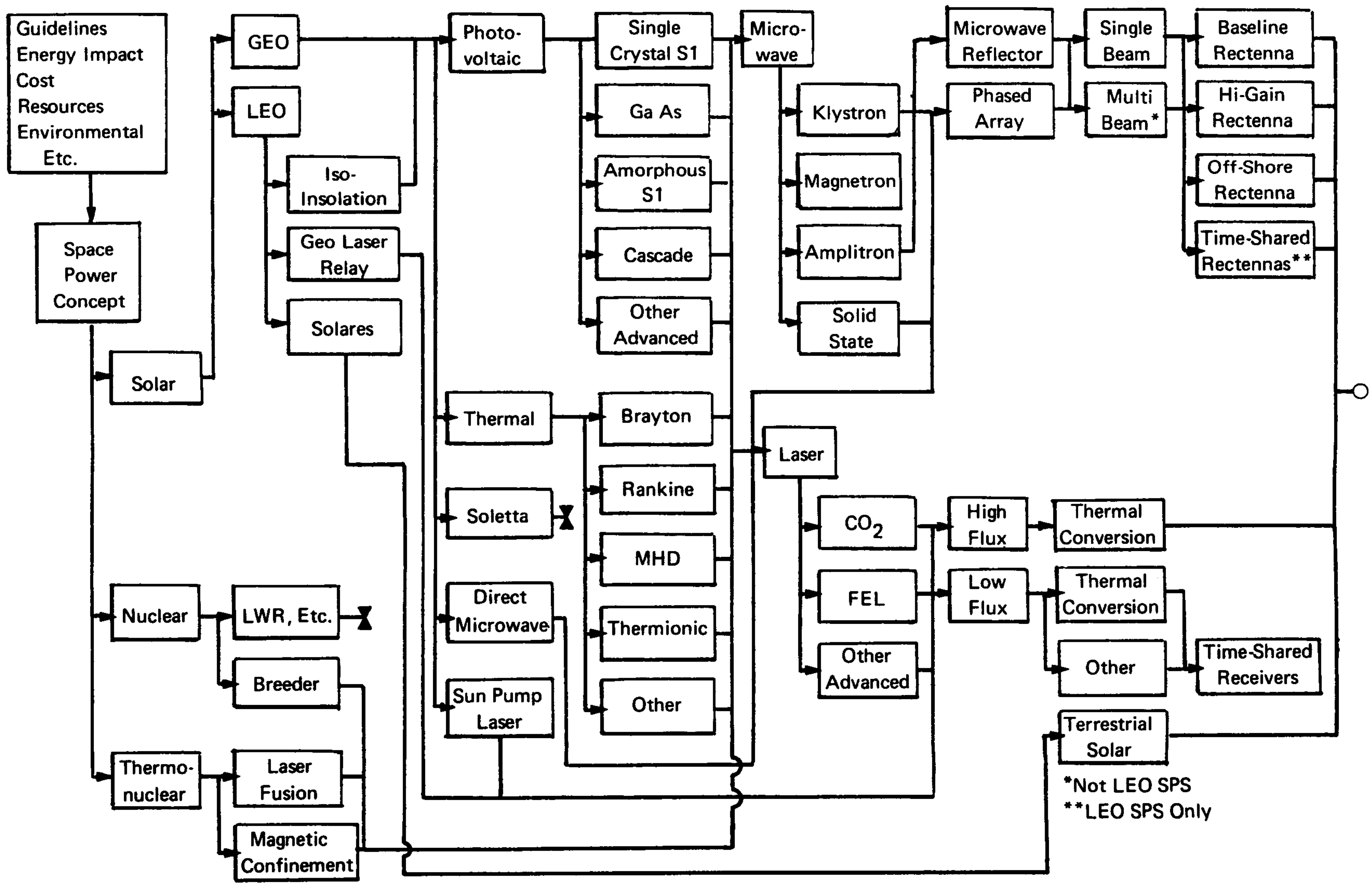


FIGURE 4.1 TECHNOLOGY ALTERNATIVES FOR SPACE POWER SYSTEMS

A further difficulty is that many of the costs and benefits of proposed new systems are of an intangible kind, expressible only in incommensurable units. As an example, consider the laser power transmission system (LPTS), as compared with the microwave power transmission system (MPTS). The LPTS allows changes in the optimum SPS power output; may reduce land-use problems but may require extensive long-distance power-pool interties to avoid weather outages; and perhaps increases the probability that the SPS will be perceived as a weapon. The relative importance to be assigned to these advantages and disadvantages is inescapably a matter of judgment, and any given assessment of the LPTS on these bases may thus be acceptable only to those who share a common value system.

It may be possible to overcome these difficulties, at least to a useful extent, by a two-stage process which explicitly recognizes that the primary requirement is not now to provide a definitive and reliable assessment of each proposed technology, but to specify a subset of concepts which offer the greatest potential. The surviving concepts may then be subjected to more detailed analysis, as resources permit, perhaps leading eventually to modifications in the SPS reference system. In the first stage of this process, it is essential to use a systematic screening designed to give a preliminary evaluation of technical and economic feasibility so that proposed technologies may be compared as nearly as possible on a common basis.

The assessment methodology which is proposed here and which has been used as far as resources permit in the later discussions of specific emerging technologies consists of three parallel approaches:

1. Assessment of the technology in relation to the system functions in the SPS;

2. Examination of the relationship between a proposed new subsystem and the other components of the SPS; and

3. A preliminary screening process to provide a preliminary assessment of technical and economic feasibility as a first step in determining research priorities.

4.2 Primary System Functions

4.2.1 Collection of Solar Energy in Space

The primary solar collector in the SPS can take a variety of different forms, including at least the following:

- An array of photovoltaic cells, with or without concentration.
- A mirror system which concentrates sunlight to heat a working fluid in a thermal conversion system.
- A mirror system to drive thermionic conversion devices, photo-klystrons, a sun-pumped laser, etc.

In most but not all cases, the unit power output of the system is determined by diffraction and cost minimization (Appendix A), and the size of the solar collector is then fixed by the efficiency of the overall energy conversion and transmission chain.

4.2.2 Conversion to an Intermediate Form of Energy

With the exception of soletta systems (which directly reflect sunlight to a receiving site on Earth), most SPS concepts require conversion of solar energy to one or more intermediate forms before transmission to Earth. For example, a thermal conversion system may use solar radiation to store enthalpy in a working fluid, which is then converted to electricity by MHD devices, turbomachinery, etc., in order to operate microwave conversion devices. Photovoltaic systems generate electricity directly, which is then used to obtain a power beam. Some direct conversion schemes also exist, such as the photoklystron and the sun-pumped laser, in which any intermediate form of energy is contained within devices which take sunlight and create a power beam without separate power conditioning and distribution.

4.2.3 Transmission of Energy to Earth

There are at least five conceivable ways to transfer energy from a satellite to the surface of the Earth:

- Microwave Power Beam
  This system, which is used in the SPS Reference System is described in Appendix A, and has the advantage that the technology is relatively well understood and it offers the possibility of a high transmission efficiency (in excess of 60 percent, from DC in the satellite to DC at the utility bus). Other factors being unchanged, the MPTS gives the smallest solar array for a given power output, reducing array capital costs. If the SPS is in GEO, however, the unit power output tends to be higher than with other approaches, which implies a high front-end cost before the first system is operational and which could impede market penetration (Section II.1.3). Uncertainties regarding the long-term effects on terrestrial biota of low-level microwaves must be resolved before this system can be declared practical.

- Laser Power Beam
  Because diffraction is much less important at visible or infrared frequencies, the LPTS offers the capability of building the SPS in GEO with a unit power output at any level above about 10 MW (Appendix B). However, the efficiency of the transmission system is likely to be considerably less than in the case of the MPTS, so that the cost per kilowatt may be higher. If the flux density at the receiver is high enough, the laser beam will burn through clouds, but

such a beam poses hazards to birds and airplanes and could conceivably be used for military purposes. The beam flux density can be reduced to any reasonable level (if necessary, using concentration at the receiver) so that the beam could be environmentally safe, but in this case it is necessary to have a geographically dispersed network of receivers, with more receivers than satellites—the beams are then directed to whichever receivers are not cloud covered, the power being delivered to load centers by terrestrial transmission systems interconnecting the receivers. The laser SPS is one of the most significant alternative technologies to the SPS reference system and is discussed in Section 5.3.6.

- Re-directed Sunlight

  Mirrors in orbit could direct solar radiation to a fixed point on Earth, providing nearly continuous insolation for a terrestrial solar energy conversion facility. If a mirror is in GEO, however, the finite angular diameter of the Sun results in a minimum diameter of the image on Earth of about 300 km. In order to provide insolation equal to that at high noon, the orbital mirror would have to be at least 300 km in diameter. If solar radiation received over such a large image area were converted to electricity with an efficiency of 15 percent, the power output would be in excess of 10,000 GW. Soletta systems may therefore be of practical significance only in low orbits (Section 5.3.5).

- The Orbital Tower

  An ambitious concept has been proposed in which a cable is suspended from a large satellite in GEO, reaching all the way to the ground. In principle, tapering of the cable would allow this cable to be built from existing materials, but the ratio of the diameter in GEO to that at ground level is an exponential function of the density-to-strength ratio of the cable material. Much stronger materials than are now available would be needed to make this concept practical. If the orbital tower could be built, launch to GEO or escape would require only an elevator which climbed the cable (with high specific impulse thrusters in GEO to maintain the orbital angular momentum and energy), greatly reducing costs. Power from a solar array in GEO could be transmitted to Earth along a superconducting transmission line attached to the cable, assuming terrestrial distribution difficulties could be resolved.

- Stored Energy

  If a means could be found for storing large amounts of energy in a system of sufficiently low mass, and if the energy could be readily withdrawn from storage in a form suitable for use on Earth, it would be feasible to store energy from solar conversion in orbit and physically transport the storage devices to Earth. As a fanciful example, it would not violate physical law to use the power output of the SPS to manufacture antiprotons and positrons in GEO, shipping the energy to the ground in the form of an anti-hydrogen plasma in a magnetic bottle. The technical difficulties impeding development of such an approach would be immense. An effective and economical means for storing energy on a large scale would of course greatly improve the effectiveness of terrestrial solar systems for baseload power generation. It has however been suggested that the long-range future for space solar power might involve arrays in solar orbit at a fraction of an astronomical unit (where the insolation flux density is much higher than in the vicinity of the Earth), with anti-matter energy storage as a means of shipping energy to wherever it might be needed.

4.2.4 Reception and Conversion to Useable Energy on Earth

The technique used for converting beamed energy to a useful form on Earth depends on the nature of the power transmission system. Neglecting the last two energy transmission systems as too advanced for practical consideration, the possibilities are as follows:

- MPTS

  Microwaves can be converted to electricity with high efficiency, using one of the variants of the SPS rectenna principle. If desired, the power generated could be used to create a synthetic fuel (e.g., hydrogen), to be used in mobile applications or to reduce terrestrial transmission costs. Whether or not synthetic fuels would be an economically feasible adjunct to electric power production from the SPS depends on the cost of power produced (compared to other, terrestrial sources of energy), and on the efficiency of conversion to the fuel energy to its end-use form. If the SPS became the system of choice for power generation, production of fuels might conceivably be viable as a load-leveling technique.

- LPTS

  A wider variety of conversion techniques are conceptually feasible with laser power transmission. Laser radiation may be converted to electricity by thermal or photovoltaic means, or by an infrared rectenna (i.e., an array of dipoles and rectifiers scaled to the wavelength of the laser radiation). The laser radiation may be concentrated and used directly as a source of heat, for industrial processes and other applications. It may also be possible to use laser radiation directly in chemical processing, including production of fuels, and to power aircraft.

- Solettas

  These systems could be combined with any of the conversion techniques presently under consideration for terrestrial solar energy conversion systems.

4.3 Secondary System Functions

The secondary functions which must be carried out to support or supplement the primary functions discussed above are listed in Table 4.2. This Section discusses those functions for which significant alternatives to the SPS reference system technology exist or have been proposed.

4.3.1 Space Transportation

The specific cost of transportation to LEO in the STS (space shuttle), at full utilization, is projected to be $850/kg of payload. To be economically viable, the SPS needs a launch cost below $50/kg. The keys to this reduction are (i) fully reusable vehicles, and (ii) the greatly increased traffic to orbit implied by the SPS. A buildup rate of 10 GWe per year would require an annual throughput of cargo of the order of 100,000 metric tons. The frequency of launches depends on the payload of individual launch vehicles, but it would allow efficient utilization of launch facilities and require a sufficiently large fleet of vehicles to permit substantial economies in their manufacture. It is probable that acceptable launch costs can be achieved without radically new technology, using commercial airline operations as an analogy.

It is highly desirable to minimize space transportation costs, not only because of direct effect on overall SPS costs (which represents ~ 33 percent of the total cost), but because cheap transportation would permit heavier and cheaper satellite systems.

The SPS reference system assumes use of the Heavy-Lift Launch Vehicle (HLLV), a two-stage vehicle with a net payload of 424 tons and a design life of 300 flights. The estimated launch cost with this vehicle is about $30/kg (1979 dollars). Large vehicles of this type may achieve economies of scale (specifically, the payload fraction increases with the size), but there are indications that, when tooling for vehicle construction, launch operations, etc., are taken fully into account, the cost-optimum vehicle may be considerably smaller.

In addition to cargo launches, the SPS would require Personnel Launch Vehicles (PLV's), Cargo Orbital Transfer Vehicles (COTV's) and Personnel Orbital Transfer Vehicles (POTV's) to LEO and GEO and between LEO and GEO.

The PLV is derived from the STS (using a flyback booster); the major modification to the orbiter is a cylindrical enclosure in the cargo bay with accommodations and life support for 80 passengers. The resulting cost is $150,000/passenger, a figure which might be reduced if a dedicated PLV were designed, or if the HLLV were man-rated.

The baseline COTV is a large solar-electric vehicle, with a net payload of 3600 metric tons. The transportation cost between LEO and GEO with this vehicle is about $19/kg, including the cost of bringing up propellants to LEO in the HLLV. Because of the low thrust levels employed, the trip time is 180 days, which represents a significant delay in the construction schedule for each SPS. Rapid transportation to GEO could reduce the total cost of each SPS by up to 5 percent, because of the reduction in the interest charges on capital invested.

The POTV is a chemical-propulsion vehicle (LO_2/LH_2), which carries 80 passengers between LEO and GEO (or return). Propellants for return are normally stockpiled in GEO, using the COTV, but the vehicle is capable of a round trip with on-board propellants, at reduced payload. The trip time is 11 to 23 hours, depending on orbital phasing, and the cost estimate is $19,000/passenger. The POTV can also be used for high-priority cargo, carrying 16 tons at a cost of $96/kg.

It is clear that the transportation system has not yet been optimized, even in the context of the SPS reference system. Significant cost reductions may be feasible with more efficient designs, using known technology. Moreover, there are a variety of alternative technologies, discussed in Section 5.6, which, if successfully developed, could allow even greater economies.

4.3.2 Station-Keeping and Attitude Control

The principal orbital perturbations affecting the SPS are:

i) Solar radiation pressure, which creates an eccentricity in the orbit. The velocity increment required to overcome this effect is of the order of 200 m/s per year, depending on the total insolation received and the mass of the satellite. If uncorrected, the eccentricity produces a periodic change (about 1 percent) in the range to the rectenna and a small variation in the angular velocity of the spacetenna. These effects may be tolerable.

ii) Lunar and solar gravity gradients, which cause the inclination of the orbit to grow slowly, averaging 0.5°/year. Correcting this requires a velocity increment of about 50 m/s year.

iii) Ellipticity of the Earth (in equatorial section). This creates stable positions in GEO at 60° longitude and 120°W. At other longitudes, this perturbation must be overcome to prevent drift of the satellites, but the velocity increment needed is very small, less than 1 m/s per year.

iv) Radiation reaction from the power beam. Being nominally along the local vertical, this acts like a very slight reduction of the gravitational force. The effect on the orbital angular velocity may be offset by a small reduction (less than 100 m) in the orbital altitude.

The nominal attitude of the SPS solar array is perpendicular to the orbital plane (POP). This is a position of (unstable) equilibrium under gravity- gradient torques, minimizing the required control torques. The penalty paid is a reduction of up to 9 percent in the power output (at the solstices), because of cosine effects due to not following the sun in declination, but (for the SPS reference system) oversizing the array is cheaper than providing additional propellants for control thrusters. Additional torques, generally small, are produced by solar radiation pressure and microwave recoil (if these forces do not act through the center of mass) and by any variations in the angular velocity of the spacetenna.

Conceptual SPS designs exist (see Section 5.3) which are stable or neutral under gravity-gradient torques. In some designs (e.g., high concentration systems), it may be necessary to track the sun in declination.

If the decision is made to use thrusters to overcome the orbital perturbation due to solar radiation pressure, they can be located at appropriate positions on the solar array. Attitude control can then be achieved by modulating the individual thrust levels, at little additional cost. Care should be taken to locate the thrusters at nodes of the major structural mode of the array, to avoid exciting oscillations. If some of the thrusters for station-keeping are appropriately located on the array, active damping of structural modes may be feasible.

Momentum wheels can be used for attitude control (at least against cyclic disturbances), but cannot provide station-keeping. It is therefore probable that these functions will be performed by high-specific-impulse thrusters in most SPS designs. There is a trade-off between the capital cost of additional solar array to power the thrusters (which increases with specific impulse) and the annual cost of supplying propellant (which decreases with specific impulse). It appears that the optimum I_{sp} may be of order 10,000 seconds, but will differ for different system concepts.

Solar power for electric thrusters is not available during equinoctial eclipses. There are three options available for use during these times: (a) allowing the satellite to drift slowly in attitude and orbital position during an eclipse; (b) providing electrical energy storage; and (c) using chemical thrusters. Because eclipses are rare and brief, the last option does not exact a serious penalty in propellant usage, but it incurs additional capital cost for the thrusters, tankage, etc. It has the advantage, however, that the chemical thrusters may be used for emergency control in the event of a system failure.

4.3.3 Fabrication and Assembly in Space

There are basically three options regarding the assembly strategy for the SPS:

i) The construction facility could be located in GEO, using components ferried up from Earth or from a supply depot in LEO. The principal penalties are the additional capital cost of establishing the facility in high orbit, and the fact that assembly workers may require shielding against cosmic radiation. Some transportation alternatives require GEO assembly because of limited individual payloads.

ii) The construction facility could be in LEO, with entire satellites or major sub-assemblies ferried to GEO. If the solar array is used to power ion engines for this type of transfer, the resulting slow passage through the Van Allen Belts may result in solar cell damage.

iii) The construction facility could be located in an orbit of intermediate altitude, above the radiation belts.

There may be an advantage to locating any LEO facilities in equatorial orbit (especially if equatorial launch facilities are available), so that they do not pass through the South Atlantic anomaly, providing a benign radiation environment.

The assembly technique employed would depend on the design of the system—for example, it would be very different for a thermal conversion system than for a photovoltaic system.

A major issue which has yet to be fully resolved is the degree of fabrication in space, as opposed to terrestrial factories. To provide high-packing density during launch, it is probable a space beam-builder could be used to create the basic structure, starting with rolls of aluminum foil or carbon-composite components. However, it may also be desirable to fabricate photovoltaic cells in space, avoiding launch of fragile components and perhaps taking advantage of the space environment to produce higher performance and lower cost cells.

4.3.4 Power Beam Phase Control

The MPTS employs an active retrodirective array (ARA) in which a pilot transmitter at the center of the rectenna controls the phase of the wavefronts leaving the spacetenna. The principle is as follows: If the phase of the signal leaving each transmitter element is the conjugate of the phase of the pilot signal at that point (i.e., if it is advanced in phase, relative to the pilot signal, by twice the transit phase delay from the pilot to that point), then the signals from all the transmitter elements will be in phase when they arrive at the pilot—in other words, the beam will be directed accurately towards the pilot. The transit lags may be measured with respect to a common phase reference at each transmitter element. The need to provide an accurately constant phase reference across the 1 km diameter of the spacetenna may be avoided by central phasing—i.e., by transmitting the pilot signal received at each transmitter element to a central point, where phase conjugation is carried out. In such a system, it is not necessary for the spacetenna to be rigid, as long as the relative movement of the elements is not too rapid.

The ARA is a closed-loop system which has clear advantages in terms of tracking accuracy over self-contained phase-control techniques. An additional major advantage is that the power beam cannot be formed in the absence of the pilot signal—if the pilot fails, the transmitter phases become random, spreading the beam over 2π steradians and reducing the ground flux density to communication signal levels. It is thus a fail-safe system, and it is impossible to point the beam at targets other than the pilot. The fears which have been expressed that the beam might escape control and randomly expose the population to unacceptable microwave fluxes are therefore illusory. Moreover, it is easy to provide safeguards against attempts (e.g., by terrorist groups) to take over the beam by setting up a pilot transmitter in a target area such as a city. The rectenna pilot signal may be encrypted so that signals from other pilots are ignored; and, even if the code is broken, a dead-man switch can be used to deactivate the transmitter if power is not received at the designated rectenna.

It is highly desirable to preserve the advantages of the ARA if some other type of power beam is used. For example, there may be advantages to using a microwave reflector to provide the needed spacetenna aperture (Section 5.5.1.2), but application of the ARA principle to such a system has not yet been studied in detail. Adaptive optic techniques may in principle be used to maintain a desired geometric figure of the reflector, and the contour could be adjusted to compensate for phase errors in the ionosphere, etc., by measurement of the flux received at the rectenna; but the response time for such a system would be determined by the round-trip speed of light time to GEO (0.24 sec), whereas in a true ARA the response time is fixed by the dimensions of the spacetenna. However (at least for a 5 GWe SPS at 2.45 GHz), it is unlikely that the feed to the reflector would be a point source at the focus. The angular diameter of the rectenna as seen from the satellite is about 0.27 milliradian, so that, if the focal length of the reflector is 2 km, the feed diameter would have to be less than 0.5 meter in order for it to act as a point source. The resulting flux at the feed would be about 30 GW/m^2. It seems probable that the feed would be a larger array, closer to the reflector, emitting an approximately spherical wavefront, centered on the focus. It may be possible to use ARA techniques to control the phase of the signal from such a feed array. Design of a system with an appropriate combination of feed phase control and reflector figure control, permitting adequate thermal dissipation at the feed, and providing the desired power taper across the output aperture, is a challenging area for research.

In the LPTS (Section 5.3.6), the most straightforward approach to phase control may be to use an adaptive reflector for the output optics, with a small laser at the receiver for boresighting. If multiple lasing cavities are used, controlled by a common master oscillator, intracavity phase control may be feasible to provide an optical phased array. ARA techniques are in principle applicable to such a system, but the specific technology for phase conjugation, etc., at optical wavelengths has not been developed. The required pointing accuracy is about 0.5 microradian (0.1 arc seconds), a level attainable using an interferometer to detect the direction to the boresighting laser. As discussed in Appendix B, it may not be necessary for the beam to be precisely diffraction-limited, which suggests that on-board figure control to preserve beam quality could be acceptable. However, this approach would allow the beam to be directed to targets other than the receiver, increasing the possibility that the system could be perceived as serving military purposes.

4.3.5 Satellite Maintenance

Maintenance requirements for the SPS have not yet been considered in detail, although it is clear that the primary tasks would be replacement of failed photovoltaic cells and microwave conversion devices. Localized areas of the solar array may be electrically isolated for maintenance, but the maintenance strategy will affect design. How many cell failures in a given panel should be tolerated before replacement? Should individual cells, series strings, or complete panels be replaced? To avoid connection problems, the minimum replacement module would probably be at the panel level, with refurbishment of panels in an on-board repair facility offering a shirt-sleeve environment.

Spacetenna maintenance is complicated by the need to protect workers from high microwave flux levels and perhaps from x-rays generated by high-voltage conversion devices. It is highly desirable to carry out needed maintenance without system shutdown, and the spacetenna should be designed with this in mind. Individual subarrays may be disconnected without significantly affecting the power beam, and maintenance will almost certainly employ workers in modules equipped with remote manipulators (rather than in conventional spacesuits). The modules may be shielded against microwaves, but care would be needed to avoid electrical hazards.

Maintenance requirements and techniques depend strongly on the system concept and will require study for each alternative being seriously considered.

If single-crystal solar cells are used, an important maintenance task will be thermal annealing to repair radiation damage. Annealing will be needed mostly around the maximum of the solar cycles (i.e., every eleven years), when the frequency may be once per year. For this purpose, the cells should be heated briefly to about 500°C. It is presently proposed[6] to use an array of CO_2 lasers with a total output of 150 kW for this purpose, mounted on a gantry which moves slowly over the solar array. An alternative which may be of interest would be to use a set of cylindrical lenses, travelling over the array, to heat the cells with concentrated solar radiation.

One of the advantages of gallium arsenide solar cells with solar concentration, as in the alternate SRS (Appendix A) is that periodic annealing is unnecessary.

4.3.6 Ancillary Functions at Rectenna Site

The rectenna could be designed to be as much as 80 percent transparent to sunlight, which suggests that the rectenna reservation could be used for ancillary purposes without undue interference with its primary function. This possibility could impact rectenna design. For example, if the rectenna were constructed sufficiently far above the ground, and if the area beneath it were shielded from microwaves, it would be feasible to use the land area for growing crops, grazing cattle, etc. With integrated design, the rectenna structure could support greenhouses, permitting intensive agriculture. This possibility may be of particular interest in desert areas and for rectennas at fairly high latitudes, where the growing season could be significantly extended.

Ancillary uses would be especially important if offshore sites were chosen for rectennas. A rectenna island could provide the basic support structure for a variety of marine systems, including deepwater ports, industry, fisheries and mariculture, and perhaps wave energy conversion systems. The revenues obtainable from these secondary uses may amount to several hundred million dollars per year, and may improve the acceptability of offshore rectennas. Detailed studies are however needed of the design impact (and especially the capital cost implications) of such uses, in order to determine which of them could be economically justified.

5. A SURVEY OF EMERGING SPS TECHNOLOGIES

5.1 Assessment Criteria

Because of the large number of alternative technologies which have already been proposed for the SPS, any survey of the field requires a systematic methodology. The methodology used in this study first sorted the various concepts into groups according to the SPS system function which they are intended to perform. The next step considered, where this was appropriate, the relationship of the new technology to the rest of the SPS, in order to gain understanding of the consequences if it were adopted. Finally, each concept was screened in relation to questions listed below to permit a preliminary indication of which technologies may offer the greatest potential for improving the performance or reducing the cost of the SPS, together with a tentative assignment of research priorities. The order of the questions is significant: concepts for which negative answers were obtained to early questions were likely to be assigned lower priority than those which survived until later in the screening process.

The present study should be regarded only as a preliminary survey intended to guide the more detailed analysis which is necessary before realistic research planning can be undertaken. The process used here inevitably involves an exercise of judgment, partly because, in many cases, insufficient information is available for truly objective evaluation at present, and partly because a much more detailed assessment is needed before drawing firm conclusions.

At the present stage of the assessment of emerging SPS technologies, a desirable approach is to err on the side of an optimistic appraisal of proposed concepts, since it is more important to avoid the mistaken downgrading of creative ideas than it is to eliminate impractical proposals. For this reason, and to provide as much completeness as possible, a number of concepts were included in this survey which are not now regarded as realistic possibilities within the time frame of interest to the SPS.

The questions used for preliminary screening were as follows:

- Does the concept violate known physical laws? As far as is known, no proposals were included in this survey which violate this test. It is worth including as a first question, however, because quite subtle errors can occur and have occurred in this field.

- Is it technically feasible? Does it require materials, processes, or devices which, while not prohibited by known physical laws, do not now exist and will not become available with foreseeable improvements in the state-of-the-art? An example of a concept which fails this test is the use of antimatter energy storage, mentioned in Section 4.2.3.

- Can it be built within reasonable technical and economic constraints? An example which does not pass this test because of the scale of the required undertaking is the orbital tower.

- What is the technical risk? What is the state of technology readiness? For example, organic semiconductors may, in the future, permit production of low-cost photovoltaic cells, but, although the potential is clear, there is no way to predict when or if successful devices might be available.

- Is it significant? Can it be shown that the new concept, if successfully developed, would represent a first order improvement in the SPS? What would be the impact on system design? Is there a reasonable way to integrate it with other subsystems, or would it require radical innovation in other areas?

- What is the cost impact? What are the magnitude and timing of the required RDT&E and capital costs? What is the effect on operational costs? What industrial infrastructure would be required? The use of extraterrestrial resources for construction of the SPS is an example of a technology which might reduce unit costs, but at a significantly higher front-end cost than in the case of the SPS reference system.

- What is the cost risk? How certain are cost projections related to the new concept?

- What is the impact on external costs and benefits? How would the new concept affect utility integration of the system? What is the probable environmental impact? Would it change the international acceptability of the SPS? What are the military implications, if any? Does it affect the societal issues surrounding the SPS? Would it simplify or exacerbate institutional problems which may be encountered?

For future reference, these questions are listed briefly in Table 5.1.

TABLE 5.1

ASSESSMENT CRITERIA FOR ALTERNATIVE TECHNOLOGIES

- Is it Scientifically Feasible?

- Is it Technically Feasible?

- Can it be Built Within Technical and Economic Constraints?

- What is the Technical Risk?

- Is it a Significant Improvement?

- What is the Cost Impact?
  - Required front-end investment (RDT&E)
  - Industrial infrastructure requirements
  - Capital costs
  - Operational costs

- What is the Cost Risk?

- What is the Impact on External Costs and Benefits?
  - Utility integration
  - Environmental impact
  - International acceptability
  - Military implications
  - Societal issues
  - Institutional issues

5.2 Alternative System Concepts

5.2.1 Thermal Conversion

Thermal conversion (primarily Brayton cycle) received early emphasis (1) in studies of the SPS. In this concept, parabolic concentrators direct high-flux solar radiation to a cavity absorber, where a working fluid (helium) is heated to drive fairly conventional turbomachinery, with recuperation to improve efficiency before returning the helium to the absorber. The overall efficiency is slightly higher than in the SPS reference system, but the difference in collector area is negligible. Although the mass per unit area of the concentrators may be less than that of a photovoltaic array, the requirement for space radiators to dump waste heat means that the total mass per unit output is comparable to that of the SPS reference system. The thermal conversion system is definitely more complex than the SPS reference system, in terms of construction, operation and maintenance, and the high concentration employed requires precise orientation relative to the line of sight to the Sun. For these reasons, photovoltaic conversion is now preferred. However, there are a wide variety of options for thermal conversion (see Section 5.3.1), and further work may lead to improvements in performance or cost. Moreover, many thermal conversion concepts employ technologies which are adapted from terrestrial systems with which there is extensive experience: the cost figures are therefore generally more reliable than in the case of photovoltaic conversion, where economic competitiveness depends on extrapolation of photovoltaic system cost trends by more than an order of magnitude (in other words, the cost risk is less). Further system studies of thermal systems are thus strongly recommended, not only because they could lead to an improved SPS, but because they can serve the useful immediate function of providing an upper bound to projected costs.

5.2.2 LEO SPS with GEO Relay

The oblateness of the Earth produces a rotation of the line of nodes of a satellite orbit at a rate which depends on the orbit altitude and inclination. In particular, there is a family of (retrograde) orbits for which the precession amounts to one revolution about the polar axis per year, so that the right ascension of the normal to the orbit maintains a fixed relationship to that of the Sun. If the orbit inclination is between 100° and 110° (with corresponding altitudes between 1500 and 2500 km), and if launch occurs near local sunset or sunrise, the satellite can be continuously in sunlight throughout the year, never passing into the shadow of the Earth; these are the "iso-insolation" orbits. A solar array in such an orbit is thus capable of providing baseload power. In the present concept, studies primarily by Lockheed,(2) a power beam transfers the energy to a fixed receiving site on Earth via a relay in GEO. Either a microwave beam or a laser can be used, although the latter is preferred because it permits a smaller and perhaps simpler GEO relay satellite.

The primary motivation for this system is that it reduces the mass to be shipped to GEO (since the relay is much lighter than the power satellite itself). At least two relays are required to avoid occultation of the beam by the Earth (although these can be shared by two power satellites if there are two receiving sites, well separated in longitude). Beam steering is more complex, and the system doubles the number of power beams (compared to the SPS reference system) traversing the space between LEO and GEO, increasing the probability of encounters between beams and other satellites. Whether or not this system can be competitive depends in large part on the cost of transportation between LEO and GEO, and it should be noted that there are a number of options for reducing this cost (Section 5.6.2).

5.2.3 Gravity-Gradient Stabilized SPS

The nominal attitude of the SPS reference system solar array is perpendicular to the orbital plane (POP). This is a position of unstable equilibrium under gravity-gradient torques, minimizing attitude control problems, but an area penalty (9 percent) is incurred due to cosine effects, as the array does not track the Sun in declination. In addition, the spacetenna must rotate once per day about a single axis in order to track the rectenna, requiring sliprings to transmit power. The gravity-gradient stabilized SPS is intended to overcome these problems. There are several variants[3] of the design, but, in the concept which is probably preferred, the satellite has a long axis which is nominally along the local vertical, with a fixed spacetenna at the bottom. Relatively small photovoltaic arrays are attached at intervals along the vertical axis, rotating about horizontal axes each day as the satellite moves in its orbit so as to remain perpendicular to the sun line. Libration in roll or pitch, or an inclined GEO (or some combination of these) is required to avoid shadowing of one array by another near local noon and midnight. It is proposed to convert solar energy locally (i.e., at the arrays) to microwaves, using a solid state conversion system (called LITOMIC). The central spine of the satellite contains a high-power waveguide into which the output of each array is fed. Power distribution thus uses microwaves rather than electricity.

One possible difficulty with this approach[4] is the high power level (up to 8.8 GW) in the central waveguide. If imperfections exist or develop, a great deal of energy can be dumped into a defect, perhaps leading to catastrophic failure.

This system appears to be a rather complex solution to relatively simple problems (some of which may be solved in other ways: see Section 5.2.9). It is not clear at present that it offers advantages over the SPS reference system in terms of cost, complexity, performance or reliability.

5.2.4 Integrated Solar-to-Microwave Conversion

In this concept (the "Sandwich"),[5] photovoltaic cells are attached directly to the back of a solid-state spacetenna, which is oriented permanently towards the Earth. The photoklystron (Section 5.3.3.1) might also be used for power conversion. A mirror system employing two reflections and affording some concentration (and perhaps spectral filtering to minimize thermal loads at the solar cells) is used to direct sunlight to the photovoltaic array; one of the mirrors must rotate (about an axis normal to the GEO plane) to compensate for orbital motion.

The direct connection between solar cells and microwave devices greatly simplifies power distribution. The rotating joint is part of the light collection system rather than the electric power distribution system, so that no sliprings are required (as presently conceived, the joint is very large in diameter, but improved mirror designs may overcome this problem). Little penalty is incurred in using a large spacetenna, the size of the solar array: this reduces flux densities and thermal dissipation to levels which can be handled by solid-state devices, may allow operation at high Fresnel numbers (thereby improving the flux density distribution at the rectenna), and may permit considerably lower unit power output than the SPS reference system.

5.2.5 Solares

As noted in Section 4.2.3, it appears to be impractical to use a mirror in GEO to provide continuous and/or intensified insolation at a ground site, because of the large scale of such a system, determined by the orbit attitude and the angular diameter of the sun. Solares[6] uses a large number of smaller mirrors (area <1 km^2) in orbits ranging in altitude up to several thousand kilometers to provide fairly constant illumination to a number of ground sites, where conventional terrestrial solar energy conversion systems generate electricity or other forms of energy. When fully operational, the system would still be an impressive undertaking: for example, up to 80,000 mirrors might be required (for a total mirror area of 63,000 km^2), to provide a total of 980 GWe at five sites; this is comparable to current world consumption of electricity. These figures imply a ratio of collector area to power output which is an order of magnitude larger than for the SPS reference system, the principal reason being that the mirrors have a low duty cycle, being eclipsed by the Earth on each orbit and spending much of each orbit over areas (e.g., oceans), where there are no ground sites. However, the mirrors are simple, lightweight devices, and the total cost of the mirror system is projected to be only about 50 percent of the total capital cost of this example system, which is estimated as $496 billion (or $506/kWe). If this cost were substantiated by more detailed analysis, Solares would be highly competitive with existing power generating technology, providing energy at a cost around 13 mills/kWhe.

The principal problems with Solares are related to its scale and to the need to define credible buildup scenarios. At present, only the United States and the Soviet Union have total installed capacity in excess of 200GWe, so that each site would need to be a regional rather than a national undertaking, and there may be significant problems with terrestrial power distribution. Each site is about 30 km across; if it were possible to construct solar-electric conversion systems (using available solar radiation) at five such sites around the world, then buildup scenarios are conceivable in which the conversion system output is augmented by gradual installation of orbiting mirrors, reaching full baseload capability only when the network is complete.

It is not clear what ecological effects would result from the constant insolation and resulting heat islands at each site. Although sunlight is generally considered benign, the receiving sites would constitute a disruption of the natural environment which would be quite obvious to anybody living anywhere in the vicinity, so that problems of public acceptability might arise. The large number of Solares mirrors would be a serious nuisance to optical and perhaps radio astronomers. Since the high unit output (5 GW) of the SPS reference system is considered to be a disadvantage, the much larger output from each Solares site must be regarded as a serious problem. Therefore, the external impacts of Solares could be significantly worse than those of the SPS reference system.

Despite these comments, space augmentation of terrestrial solar power is a useful concept. Further system studies are warranted, particularly to find more nearly optimal systems (e.g., choice of mirror orbits), with more favorable scaling characteristics as an explicit objective of the design.

5.2.6 The Laser SPS[7]

A laser power transmission system (LPTS) may be regarded as an alternative to the microwave power transmission system (MPTS). Some studies[8] have merely grafted the LPTS to the SPS reference system, but this is a less than optimum approach. When properly designed to suit the characteristics of the LPTS, the laser SPS could be so different to the SPS reference system that it should be regarded as a different design concept.

From a systems point of view, the most important characteristic of the LPTS is that it permits a much smaller unit power output. As discussed in Appendix B, the aperture costs for transmission and reception (which determine the optimum output with the MPTS) are likely to be small compared to other costs for power output much above a megawatt, when the LPTS is used. The minimum specific cost ($/kW) for the laser SPS may be higher than that for the microwave SPS, but it occurs at a much lower output.

It is highly desirable to find techniques for designing the SPS with a smaller output. A smaller output SPS may be integrated more readily with power pools or individual utilities; it increases the number of nations which could consider the SPS as a viable energy technology; and it may allow significant reduction in the front-end investment before the first revenues are obtained from sale of power generated by the SPS. The laser SPS is an important approach towards this objective. A reasonable scenario may be constructed in which the LPTS is used for the first demonstration satellite, to minimize investment; several laser SPS's are deployed, providing power in areas of relatively low demand but high current energy cost (especially desert areas, where weather conditions are ideal for the LPTS); and the microwave SPS is introduced as demand builds, after confidence in the technology has been established. In many respects, the LPTS and the MPTS should be regarded as complementary rather than alternative technologies for the SPS.

Various LPTS options are discussed briefly in Section 5.4.2, together with the systems implications.

The laser SPS is potentially a promising area for system studies and device research. Of particular importance is work aimed at improving the conversion efficiency of solar radiation into laser energy aboard the satellite, and of laser light into electricity at the receiving station, for these factors are of primary importance in determining the overall cost. Careful attention must also be given to the possible environmental impacts of laser power transmission.

5.2.7 Station-Kept Arrays

The various subsystems of the SPS (solar collector, solar-to-electric conversion, electric-to-microwave conversion, etc.) need not necessarily be physically connected, but could fly in formation, using high-specific-impulse (I_{sp}) thrusters to maintain spacing and orientation in the presence of gravity- gradient forces and torques and other perturbations. Several variants of this concept have been investigated,[9] and the general conclusion is that this is a feasible technology.

The referenced study generally considered modifications of the SPS reference system, but it is worth noting that, other factors being unchanged, the thruster specific propellant requirements (i.e., the propellant consumed during the lifetime of the system, divided by the system mass) for station-keeping and attitude control, and the thruster specific power (thruster power divided by system power output) all scale linearly with the satellite's dimension. Station-keeping designs may thus be more attractive for lower-power SPS configurations.

Two specific concepts which are worthy of further consideration are: (i) a station-kept microwave reflector to redirect radiation from a fixed phased array aboard the satellite towards the rectenna (see Section 5.2.9); and (ii) a station-kept rotating mirror in the "sandwich" configuration (Section 5.2.4). In both cases, the objective is to eliminate rotating joints, and both systems may be adaptable to reduce power output. A superficial analysis suggests that these configurations are sufficiently promising to justify a relatively high priority for further study.

5.2.8 Iso-Insolation SPS

This concept,[10] envisages the SPS in iso-insolation orbit (Section 5.2.2), but the power produced is beamed directly to ground receiving sites, using microwaves. Because of the shorter range, much smaller power outputs (and hence rectenna areas) are possible than in the SPS reference system. A sufficient number of satellites can provide continuous power to a given rectenna, at least if its latitude is fairly high (Europe, most of the United States, etc.).

This system has scme problems in common with Solares. It becomes economic only when there are enough satellites in orbit to provide baseload power to a given rectenna, and enough rectennas to provide a reasonable duty cycle for the satellites. Although the lower unit power output is an advantage, it may be difficult to construct economically credible buildup scenarios.

The power beams are not stationary with respect to a given rectenna, but sweep through large zenith angles as the satellite pass by. This may create additional problems in connection with exposure of aircraft (especially small, uncontrolled aircraft, in which the occupants are not protected by a metal skin). On the other hand, the motion of the beams may be an advantage, permitting higher ionospheric flux densities because there is insufficient time for equilibrium heating of ionospheric electrons.

5.2.9 "Aperture-Augmented" SPS [11]

The spacetenna for the SPS reference system is a phased array. It is, of course, also possible to use a microwave reflector as the output optics for the power beam, with an intense microwave feed at the focus. An important advantage of this approach is that the feed may be fixed relative to the solar array, with only the reflector rotating to track the rectenna, thereby avoiding the use of sliprings. The size of the reflector is still determined by diffraction (see Appendix B) and will be of the order of one kilometer in diameter, so that active figure control is required; but the power required for this purpose is small compared to the SPS output, and could perhaps be generated by a photovoltaic array attached to the reflector.

Use of reflective microwave optics also relaxes the design constraint in the SPS reference system due to flux density limits at the output aperture. The feed to the reflector almost certainly requires active cooling, and this allows freedom in the choice of the output flux density. If a flux density higher than that in the SPS reference system is chosen, the optimum power output will increase, but the cost per kilowatt will decrease. Moreover, if it can be shown that the cost per square meter of output aperture is substantially less for the reflector, the penalty associated with operation at less than optimum output will be reduced; and it may be possible to use a high Fresnel number (providing a closer approximation to a "top hat" flux distribution at the rectenna). As in the case of the "sandwich" SPS design, these factors may allow a smaller unit output without excessive cost.

This concept has not yet received the serious systems analysis which it deserves. Further study is warranted, since it could lead to a flexible design which (i) is inherently somewhat cheaper (per kilowatt); (ii) permits a smaller (and hence) cheaper demonstration SPS); and (iii) allows matching the SPS output to demand, depending on the requirements of individual utilities.

5.2.10 SPS Concepts with Reduced Power Output

It is highly desirable to build variants of the SPS offering lower power output. A number of approaches to this end have been discussed above (the laser SPS, the solid state "sandwich," and the "aperture-augmented" system). Another concept[12] uses a phased-array microwave spacetenna which is rigidly attached to a curved photovoltaic array. Not all of the solar cells are illuminated in any given orbital position, so this system incurs a penalty in solar array costs, which can be reduced if a diurnal variation in output is acceptable (e.g., a low output during the nocturnal minimum in demand). It is expected that this type of SPS would have a higher cost per kilowatt, but it is worth investigating as a means for demonstrating satellite solar power at minimum initial investment.

5.2.11 High-Concentration Systems

The thermal conversion SPS must use high concentration ratios in order to produce the temperatures required for reasonable Carnot efficiency. Some photovoltaic systems (e.g., the GaAlAs option for the SPS reference system) use modest concentration, firstly because reflectors are cheaper per unit area than solar cells, and secondly because operation of GaAlAs cells at somewhat elevated temperatures (about 125°C) may permit self-annealing against radiation damage. Higher concentration ratios may be feasible with photovoltaic systems if more efficient cells can be developed (reducing the thermal dissipation), and/or if the spectral reflectivity of the concentrator is matched to the cell band-gap.

A study is needed to determine the cost optimum solar power conversion technique as a function of concentration ratio, taking account of configuration changes and more stringent array attitude control requirements as the ratio is increased. Most studies to date have been concerned with point designs, which do not necessarily provide a consistent basis for tradeoffs between different configurations.

5.2.12 Use of Extraterrestrial Resources

Several investigators[13,14,15] have strongly advocated the use of lunar or asteroidal materials for construction of the SPS. There is little doubt that useful resources for SPS fabrication (silicon, aluminum, titanium, steel, etc.) could be obtained from these extraterrestrial sources. Depending on the technique used, the total ΔV for launch from Earth to GEO may approach 12 km/sec, but the escape velocity from the Moon is only 2.3 km/sec., and there are a number of Earth-crossing asteroids (the Apollo and Amor group) which are accessible from high Earth orbit with a ΔV of order 3 km/sec. The energy required per kilogram to transport materials from the Moon or from suitable asteroids to GEO is only 5 percent to 10 percent of that needed from Earth. These low values of velocity and energy mean that radically different (and very probably much cheaper) technologies may be used for transportation; for some examples, see Section 5.6.3.

It should be noted that transportation is estimated[16] as representing about percent of the overall cost of the SPS reference system. If this figure is correct, cheaper transportation possibly can be used as one justification for the investment required to gain access to extraterrestrial resources (ETR). However, ETR, together with materials processing techniques which may be feasible in space (making use of abundant solar energy, free-fall conditions, etc.), may lead to SPS designs which are substantially cheaper—for example, heavier but cheaper silicon solar cells might be used. The case for the ETR scenario thus depends on demonstration that design economies may be effected. However, little work as yet has been devoted to optimal SPS designs using ETR.

It has been claimed[14] that the ETR scenario offers a low-cost route to the first operational SPS. The argument is based on the proposition that lunar (or asteroidal) industrialization may be capable of "bootstrapping"—i.e., that relatively little material and few personnel need be launched from Earth, ETR being used not only for SPS materials but also to build the tools needed to utilize these resources. The STS may be adequate for this purpose, avoiding development of the HLLV. If this scenario is correct, it does reduce the cash outlay, on Earth, but the claim that it is cheaper overall depends on the idea that extraterrestrial activities are somehow free—for example, once a self-supporting facility is established on the Moon, the work involved in mining and refining materials, building launch and fabrication facilities, and constructing SPS's is isolated from the terrestrial economy and therefore need not be taken into account as a program cost. This may be an untenable view of economics: if it were tenable, a somewhat similar advantage could be obtained by setting up, at minimal expense, a self-supporting colony in some resource-rich terrestrial area, which would then build the industrial infrastructure for the SPS at no further cost to the sponsors. There is, at least, an opportunity cost to this ETR scenario, for work to generate wealth on the Moon subtracts from wealth that could otherwise be generated on Earth. More fundamentally, money is only a means of accounting for human effort, wherever it may physically be located. Work on the Moon can be regarded as cheaper than on the Earth only if it can be demonstrated that productivity is higher there, which is not at all clear.

Most proponents of the SPS agree that the program could lead to space industrialization, including utilization of ETR. Indeed, one of the most attractive features of the SPS is that it provides economic justification for developing the technology needed to escape terrestrial resource limitations. The ETR approach may eventually be a desirable option, but only if ETR may be considered as part of the world economy. Is it more reasonable to expect ETR to become available as a result of an Earth-based SPS program, or should ETR development be undertaken as a precursor to the SPS?

There is an ideological dimension to this debate which should not be ignored. If it could be demonstrated convincingly that commitment to ETR would substantially reduce SPS program costs (and especially front-end costs), this would presumably increase the viability of the program. On the other hand, those who regard the SPS (in the form of the SPS reference system) as a fantasy are likely to see a prior commitment to ETR as a fantasy piled on a fantasy.

The most reasonable view appears to be that ETR research should continue, with no decision as yet concerning when or if ETR should be regarded as a line item in SPS development. An important aspect of such research is systems analysis aimed at finding the design concept for the SPS which is best adapted to making use of ETR.

5.2.13 The Multibeam SPS

It has been suggested[17] that a complex phase-control system would allow a single spacetenna to feed several rectennas. Under the usual assumptions (Appendix B) regarding SPS power output optimization, it is found that the area of each such rectenna should decrease as the square root of their number, while the areas of the spacetenna and the solar array should increase in the same proportion. This technique may allow reduction of the power from each rectenna (and hence of its area) by a factor of at least three. Alternatively, several multibeam satellites could feed one rectenna, maintaining the power output but reducing rectenna area without violating ionospheric flux density constraints. The multibeam approach may allow power satellites to be consolidated into a fewer number of larger units, reducing orbital slot availability problems in GEO.

With more detailed study of cost optimization, this approach could lead to rectennas about 4 km by 5 km (instead of 10 km by 13 km, as in the SPS reference system), with a power output below 1 GW. This would improve the acceptability of rectennas in crowded areas, ease utility integration problems, and increase the number of nations which could use the SPS.

5.2.14 The Spinnaker SPS[18]

Consider an element dA of a highly reflective surface, located a distance x away from the GEO plane, oriented at an angle of 45^o to the sun line, so that it reflects solar radiation along the orbit normal, towards the GEO plane. For simplicity, the Sun is assumed to lie in the orbital plane (as occurs at the equinoxes). The component of the force due to solar radiation pressure along the orbit normal is $I_s dA/(\sqrt{2}\,\Omega c^2)$, where I_s is the solar constant and c is the speed of light. The gravity-gradient force along the orbit normal is $\rho\Omega^2$ x dA, where ρ is the areal density of the surface and Ω is the orbital angular velocity. Radiation pressure exceeds the gravity gradient if

$$I_s/(\sqrt{2}\ c\Omega^2 x) \qquad [1]$$

For x = 10 km, the element may be supported by radiation pressure if the areal density is less than 65 gm/m^2. The possibility therefore exists of using radiation pressure to maintain a reflector, of the size required for the SPS, at least partly in tension. Such a reflector could provide some concentration, and be attached by halyards to a photovoltaic array lying in the orbital plane, which in turn could be rigidly attached to a spacetenna oriented towards the Earth. The reflector would be supported by radiation pressure in much the same way that an inflated spinnaker is supported by wind pressure. It would rotate once per orbit about the orbit normal through the center of mass of the system and would require a seasonal variation in attitude (controlled by halyards), in order to maintain the appropriate attitude with respect to the Sun.

However, a sufficiently flexible reflector is unstable under radiation pressure, and will collapse. Moreover, the reflector considered here would be in compression under the horizontal component of the gravity gradient. It may be possible to overcome these effects, maintaining a purely tensile structure, by spinning the reflector about an axis through the point of attachment of the halyards to the photovoltaic array. Alternatively, the system could be kept in tension, and some attitude and position control provided, by using high specific impulse thrusters; this variant would have some features in common with station-kept SPS concepts.

The spinnaker SPS has not yet received sufficient study to allow confidence about its feasibility. However, at least conceptually, it provides some of the advantages of the "sandwich" configuration and could prove less massive than other designs which have been proposed.

5.2.15 Energy-Storage Systems

If energy storage devices of sufficient capacity per unit mass were available, it would be possible to charge them from a solar array in orbit (perhaps in iso-insolation orbit) and return them physically to Earth, avoiding beam power transmission altogether. Even if launch and recovery costs could be reduced to $10/kg, economic practicality would require that the energy stored per unit mass be three orders of magnitude greater than in the best devices now known. This system requires an unforeseeable breakthrough (e.g., antimatter or some other form of nuclear storage) and is therefore included here only for completeness.

5.2.16 Solar-Orbit SPS

It has been suggested[19,20] that the best place to locate the SPS is in solar orbit at a fraction of an astronomical unit, where insolation is much higher than in the vicinity of the Earth. This scheme could reduce the cost per kilowatt of the satellite, but power transmission over interplanetary ranges poses a formidable problem. High-performance energy storage might solve the problem, but is not foreseeable. A laser at visible wavelengths can transmit power with reasonable efficiency over a distance of one A.U. if the (diffraction limited) output optics have a diameter of 100 meters and the receiver (a light bucket) has a diameter approaching 2 km. If the receiver were on the ground, power would be available only on the dayside of the Earth (or else a relay in high orbit would be needed). While it is conceptually possible to build optics of the required size, another major difficulty is the target tracking system: the pointing accuracy required of the laser is of the order of one millisecond of arc, and the round-trip light-time over one A.U. is nearly 17 minutes. During this time, the Earth moves 30,000 km. Another marginal possibility is a particle-beam for power transmission, but of course this does not solve the pointing problem.

Power transmission over interplanetary distances may have some useful applications (e.g., supplying energy to outer-planet probes, where high transmission efficiency is not necessarily a requirement), but it does not appear that energy for Earth from this source is likely within the time horizon for this study.

5.2.17 Integrated Advanced SPS

In a recent study[96], Rockwell International has integrated many of the results of the DOE/NASA SPS Concept Development and Evaluation Program into a new proposed design for the SPS Reference System. The new concept has the following principal characteristics:

- The solar array is sized to deliver 7.5 GW at the utility interface from each of two transmitting antennas and two associated rectennas (15 GW total per satellite).

- The maximum flux density in the microwave beam in the ionosphere is increased to 460 W/m^2(from 230 W/m^2) in the SPS Reference System.

- Power conversion is by multi-bandgap solar cells, operating with a concentration ratio of 5.3. The solar array is divided into a number of sub-arrays which are articulated to track the sun in declination while the axis of the satellite remains perpendicular to the orbital plane.

- The spacetennas use magnetrons for DC to RF conversion, and the diameter of each spacetenna is increased to 1.2 Km to permit higher flux density at the rectenna.

- The rectenna uses cylindrical microwave concentrators to reduce the number of required dipole rectifiers and improve their efficiency. Wind-loading of the rectenna is significantly reduced, as are the quantities of steel and concrete required for the structure.

The claimed advantages of this design (compared to the SPS Reference System) are:

i) The required solar cell area, per kW output, may be reduced to 70%.

ii) The satellite specific mass (kg/kW) may be reduced by 35% to 45%, with corresponding reductions in space transportation costs.

iii) Because of the higher power output from each satellite, the number of GEO sites required is reduced by two thirds, for a given total installed capacity.

iv) The land area requirements for rectennas are reduced by 30%, and rectenna costs by ~ 50%.

v) Overall, the capital cost/kW of the SPS system is reduced by about 40%. Because of the reduced utilization of components with large cost uncertainties (e.g., photovoltaic cells), the cost uncertainty of the overall system is also significantly reduced.

Most of the technologies required to effect these improvements are discussed in later sections of this report. The most significant changes are in the use of multi-bandgap photovoltaics at relatively high concentration and the higher flux density in the beam. This study illustrates the improvements which may be achieved without employing radically new technologies. The advanced SPS design appears quite competitive, in terms of the cost of delivered energy, with alternative technologies.

This study did not include effort aimed at reducing the "front-end" costs of the system, and this remains an important area for study.

5.3 Solar Power Conversion Alternatives

5.3.1 Thermal Conversion

This option was considered in general terms in Sec. 5.2.1.

5.3.1.1 Rankine Cycle

The Rankine thermodynamic cycle, which involves a phase change in the working fluid, is widely used in terrestrial thermal/electric power plants using water/steam. Both steam and potassium-vapor Rankine engines have been studied(21) for the SPS. Major concerns are the complexity of the system and the high absorber temperatures required to allow reasonable Carnot efficiency, especially if relatively high sink temperatures are used to minimize radiator mass.

5.3.1.2 Brayton Cycle

Brayton cycle turbomachinery for the SPS has been studied in some detail.(1) The working fluid employed is NaK. As discussed in Sec. 5.2.1. the overall efficiency may be somewhat higher than in the case of the SPS reference system, but the system is considerably more complicated. The turbine inlet temperature (using ceramic blades) is limited to somewhat less than 1900°K, and system optimization then leads to space radiators (of relatively conventional design, see Sec. 5.3.1.12) which make up about 50 percent of the mass of the satellite. If improved materials permit higher inlet temperatures and/or if improved radiators can be designed, the Brayton cycle SPS may however become quite competitive in terms of mass and cost.

5.3.1.3 Stirling Cycle

The Stirling cycle employs a reciprocating, externally-heated engine.[22] Each cylinder contains a drive piston with a free piston between it and the heat source. As the free piston oscillates in the space above the drive piston, heat is added to the working fluid (air, hydrogen or helium) at constant volume, and the hot gas is transferred via a bypass around the free piston to the face of the drive piston. The advantages of the Stirling cycle are that each cylinder contains a constant charge of working fluid, so that valving is not required, and the thermodynamic cycle is more nearly of the ideal Carnot type than in the Brayton cycle, where heat is added at constant pressure. As far as is known, there has been no study of the Stirling cycle for the SPS, but it seems virtually certain that its mechanical complexity and mass, the limited source temperatures which can be used, and the difficulty of removing waste heat would make it impractical for this application.

5.3.1.4 Magnetohydrodynamics

In magnetohydrodynamic (MHD) power-generation systems, a working fluid (usually an alkali metal such as cesium) is heated to high enough temperature to create substantial ionization. The ionized gas is then driven through a powerful magnetic field, where, being a conductor, it induces an electrical current between electrodes arranged perpendicular to the field. MHD systems are under development for terrestrial power plants. In order to preserve ionization in the MHD channel, the outlet temperature must be quite high so the system is intended to provide a topping cycle for more conventional thermodynamic cycles, increasing efficiency.

For the SPS, the principal advantage of MHD is that it allows operation at inlet temperatures of perhaps 3000°K. This means that it may be possible to obtain overall efficiency approaching 50 percent, without a bottoming cycle, allowing heat rejection at a temperature permitting an order of magnitude reduction in radiator area, compared to the conventional Brayton cycle. This could permit a reduction of the satellite mass by 40 percent.[23,24] The temperatures involved and the required working fluid are compatible with high-performance plasma solar absorbers (Sec. 5.3.1.8). Super conducting magnets are needed for efficiency and low mass; development of super conducting materials for operation at liquid hydrogen or liquid nitrogen temperatures, which may occur before the SPS could be operational, would simplify the required refrigeration system. A possible disadvantage is that concentration ratios of several thousand are needed to achieve the high absorber temperature, which implies accurate tracking of the Sun and tight reflector tolerances.

In some respects, the MHD system appears mechanically simpler than the Brayton cycle system and its performance may be significantly improved. The potential advantages are sufficient to warrant research to determine whether the problems involved can be overcome.

5.3.1.5 Thermionics

Apart from photovoltaics, thermionic systems (using nuclear heat sources) are probably the most common source of electric power for current satellite systems. Thermionic diodes have no moving parts, but require high operating temperature, and could offer long operating life, high reliability, and a modular design for the power-conversion system. Conversion efficiencies greater than 20 percent may be achievable[25] with a radiator temperature approaching 1000°K (i.e., radiators of low mass). Concentration ratios around 2000 are needed to achieve this performance, which means that the thermionic emitter area is small compared to the collector area (made from lightweight reflectors), but which requires fairly precise solar tracking.

Initial studies[26] suggested that a thermionic system was considerably heavier than the final version of the Brayton system.[1] However, part of the reason for this was the need to step up the output voltage of the thermionic diodes to drive klystrons in the spacetenna. Moreover, the system has not been optimized nearly as thoroughly as the Brayton system. Further study is warranted, perhaps including low-voltage microwave-conversion devices (e.g., solid state), as in the "sandwich" configuration (Sec. 5.2.4).

5.3.1.6 Weber Cycle

The Weber cycle[27] is an interesting direct thermal-to-electric energy conversion system, adaptable to solar energy. A liquid alkali metal (sodium) is heated at fairly high pressure and then passed through a porous plug (beta alumina), incurring a pressure drop which results in a phase change to vapor. Conducting electrodes on either side of the plug produce an electric current directly. The vapor is then cooled to liquid in a condenser and pumped back to the absorber.

This system has received relatively little attention, even for terrestrial applications. In the system studied by Weber,[28] with a hot side pressure of 0.6 atm. and temperature of 805°C, the electrode plug delivered 5 kW/m^2 at 0.5 volts, with an overall efficiency of 28 percent. It is not clear whether the high-temperature operation needed to permit cooling of the condenser with space radiators of reasonable size would be feasible. Materials problems may be severe, especially with design of the porous electrode for long life and to withstand the pressure drop across it.

5.3.1.7 Combined Cycles

MHD, thermionics, or other high-temperature thermal-conversion technologies could be used in the SPS as topping cycles to complement lower-temperature technologies such as the Brayton cycle. While there is insufficient data as yet for firm conclusions, most studies to date, of such combined cycles, suggest that little advantage is gained from an overall systems point of view. The situation differs significantly from that in terrestrial systems, where the sink temperature may be fixed by external factors (e.g., the ambient temperature of cooling water). Since space radiator area decreases as the fourth power of the radiator temperature, substantial mass penalties must be paid for efficiency increases from bottoming cycles in the SPS. In addition, combined cycles naturally imply greater system complexity. If a practical topping-cycle technology is available, it may be preferable to use it alone. Combined photovoltaic/thermal systems may also be worthy of consideration.

5.3.1.8 Plasma Absorbers

The Boeing thermal-conversion system uses a black-body cavity absorber.[1] The insolation from the concentrator heats the absorber wall, which transmits the thermal flux by conduction to the inner surface, which then heats the boundary layer of the working fluid flowing through the absorber. The thermal impedance of the wall, thermal flux problems and the temperature capability of the wall material, all limit the maximum temperature which can be attained. It is clearly desirable to find ways to add enthalpy directly to the working fluid from solar radiation. Neglecting window problems for the moment, there are several ways in which this could be achieved, including opaque gases, dust-laden working fluids, and plasma absorption. Plasmas are of particular interest, both because useful working fluids such as alkali vapors undergo considerable ionization at desirable temperatures (3000^{o}K and greater), and because plasmas are needed for MHD.

For good utilization of the energy in the solar spectrum, broad-band absorption is needed. Inverse Bremsstrahlung absorption (free-free electron transitions) provide one such plasma absorption mechanism, but quite high plasma densities and pressures are needed to give useful absorption lengths. Photoionization (bound-free electron transitions) appears to be a preferable mechanism. For the temperatures of interest, cesium offers the greatest bound-free absorption cross section across the visible spectrum because it has the lowest ionization potential of any element. In addition, cesium exhibits strong absorption in the red and near infrared, due to ground-state cesium dimers. It may be possible to achieve an average absorption length of a few centimeters across the solar spectrum in cesium at 4000^{o}K and a pressure of order 2 atmospheres. Studies[29] indicate that solar radiation, at a concentration ratio of a few thousand, can sustain a steady optical discharge in cesium vapor at a temperature of order 3000^oK and pressure $\sim$ 1 atm., in the right range for MHD conversion. This is an important area for further research.

The plasma absorber requires a window to admit solar radiation which must be protected from the hot plasma. If an inert carrier gas, such as helium, is mixed with the cesium, it may be used in a supersonic aerodynamic window of the type developed for laser cavities to maintain the required pressure in the presence of ambient vacuum. To simplify the aerodynamic design and eliminate leakage, a transparent window (e.g., sapphire) could be protected by an aerodynamic shield.[30] In either case, it would be necessary to scavenge the cesium from the helium gas somewhere in the thermodynamic cycle to provide clean helium flow for the window.

There is an alternative approach to the plasma absorber, at least conceptually,[31] in which a large volume (measured in kilometers) of low-density plasma is contained by a magnetic bottle, created by a pair of super-conducting coils. Possibly photoionization might be maintained by direct insolation. Electrons and ions leaking out the ends of the bottle transfer energy to a conversion process which has yet to be defined. While this system may, in principle, offer an absorber of low mass, the technical problems involved suggest that it would not be of interest for early SPS designs.

5.3.1.9 Thermoelectric Systems

Thermoelectric (Seebeck effect) devices were proposed for solar energy conversion as early as 1888,[32] and have been used in nuclear-electric (SNAP) generators in Space. A variety of experimental solar thermoelectric systems have been built,[33] many with space applications in mind, at power levels up to about 1 kW.

Thermoelectric conversion does not however appear promising for the SPS, at least with the present state-of-the-art, because of the cost and mass of these devices, problems with reliability and durability, and especially because of the low conversion efficiencies which have been achieved, typically ranging from 5 percent to 10 percent.

5.3.1.10 Dielectric Conversion

Thermal cycling of the dielectric in a capacitor changes the dielectric constant (through variation of the molecular polarization), and, hence the capacitance. Charging the capacitor in its high-capacitance state and discharging in its low-capacitance state allows conversion of thermal energy into alternating electric current. This system has been suggested for the SPS[34] with a predicted conversion efficiency of 37 percent for a particular complex device. While further research may be warranted to confirm the projected high efficiency, the mass and cost of the system presently do not appear to be competitive with other approaches.

5.3.1.11 Electrostatic Generators

Instead of driving a conventional electromagnetic generator, the turbine in a Brayton or other thermal-conversion system could be used to drive mechanically a Van de Graaf generator.[35] At high power levels, electrostatic generators may be much lighter than conventional systems; the potential reduction in the overall mass of the Brayton-cycle system could amount to 5 percent to 10 percent. Insufficient data is presently available to allow realistic assessment of this concept. One problem is the high voltage (tens of megavolts) which such generators typically produce, which may create arcing difficulties, hazards to maintenance workers, and would require transforming down to lower levels to power microwave-conversion devices.

5.3.1.12 Advanced Radiators

The mass of the required space radiators is important to nearly all thermal-conversion concepts for the SPS. One general approach to minimizing mass is to increase the source (absorber) temperature as far as possible, consistent with reradiation from the absorber and the materials limitations for a particular conversion technology, so that a relatively high sink (radiator) temperature may be used while preserving an acceptable Carnot efficiency.

The optimum source and sink temperatures depend on a number of factors, but decrease with the radiator specific mass (mass per unit radiating area), in such a way that the optimum efficiency increases. This means that a smaller collector area is required for a given power output. The mass savings from improvements in radiator technology can thus exceed the reduction in mass of the radiator itself. In addition, lower source temperatures generally imply simpler design for the conversion system.

A conventional radiator (e.g., for a Brayton-cycle system) consists of a thermally-conducting shell, with an exterior surface of high thermal emissivity, through which the working fluid flows. The configuration (shape, fins, etc.) and the location of the radiator are chosen to give the maximum radiating area per unit mass and to protect it from direct solar radiation. The required surface area to radiate away a given power varies as the inverse fourth power of the absolute temperature and becomes very large for sink temperatures comparable to those used in terrestrial power systems, for example, it is more than 2 m^2/kW at 300°K.

An alternative approach has been proposed,[36] called the dust radiator, in which small particles are heated to the sink temperature and then ejected to free space on a trajectory which takes them to a catcher, perhaps several kilometers away. The basic idea behind this concept is that the total surface area of a given mass of particles varies as the inverse square of their diameter, and can provide a large radiating area if they are small enough, and if the cloud is sufficiently diffuse so that the total solid angle of free space seen by each particle is large.

In order to give a precise trajectory which simplifies catcher design, and to allow electromagnetic acceleration of the particles, small metal spheres might be used[37] instead of dust.

Although the total mass of particles required may be very much less than the mass of a conventional radiator designed to operate at the same sink temperature and power level, there are a number of problems with this concept.

The sink temperature in the power conversion system is actually the hot side temperature in the heat exchanger which heats the particles, and relatively good thermal transfer is needed to minimize the mass of this component. An accelerator and a catcher are required, together with a means to return particles from the catcher to the heat exchanger. Finally, the equilibrium temperature in sunlight of a particle of high thermal conductivity and equal emissivity and absorptivity is about $280^{o}K$, which means that the particles cannot cool below this level unless the trajectory is in shadow. If the trajectory is sunlit, the sink temperature must be considerably above this value in order to permit efficient energy storage in the particles—but conventional radiators rapidly become competitive with this system as the sink temperature increases.

The practicality of particle radiators has not yet been demonstrated, but the potential performance (if the problems can be solved) is sufficient to warrant inclusion in further research on thermal-conversion systems.

5.3.2 Photoconversion

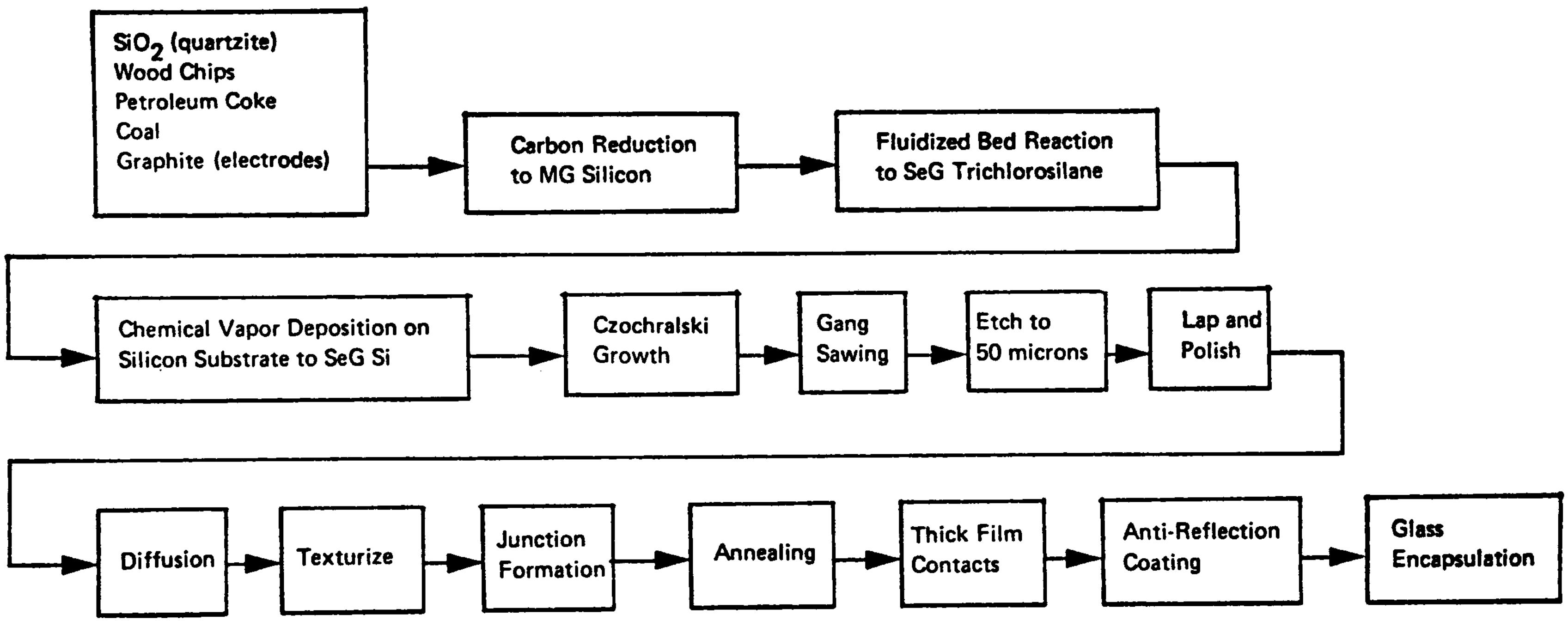
5.3.2.1 Advanced Photovoltaics

The SPS reference system uses single-crystal silicon solar cells and gallium arsenide as alternatives. Given the present state-of-the-art for photovoltaic devices, these are appropriate choices.[38] Single-crystal silicon cells are presently best understood in terms of their characteristics, potential improvements, and production problems. However, a substantial reduction in their mass and especially in their cost is needed if they are to be considered seriously for the SPS.

The reasons for the high cost of single-crystal silicon cells are quite clear.[39] Figure 5.1 shows the steps required to produce cells for the SPS, 50 microns thick, using the Czochralski process to grow single-crystal ingots from semiconductor-grade silicon (SeG Si), followed by sawing to produce wafers. The process shown is similar to that now widely used, except that, after sawing, etching with hot NaOH is used to reduce wafer thickness. In this process, only

Figure 5.1

PRODUCTION STEPS IN THE CZOCHRALSKI PROCESS FOR 50-MICRON SINGLE-CRYSTAL SILICON PHOTOVOLTAIC CELLS



about 3 percent of the silicon in the initial charge of SiO_2 ends up in the cells, and the energy required to fabricate a cell is such that the SPS must operate for about nine months to pay it back. There are several ways in which the yield could be improved (e.g., recycling silicon now wasted as kerf losses in sawing). It is particularly important to reduce the energy requirements for reducing SiO_2 to metallurgical-grade (MG) silicon and for sawing wafers.

Ribbon processes for silicon solar cells could reduce energy requirements considerably and increase solar cell production rates because kerf losses are eliminated and rectangular cells could be fabricated.

Gallium arsenide cells have so far been produced only at laboratory scale, but the chemical vapor deposition (CVD) process employed promises lower costs and relatively simple scale-up to the required production quantities. They also offer somewhat higher efficiency and (if solar concentration is used to increase the operating temperature to $\sim$ 125°C) self-annealing against radiation damage.

There are at least 20 other candidate photovoltaic materials and many of them are under active investigation[40] in the National Photovoltaic Program (NPV). It is important to note, however, that the NPV is concerned primarily with terrestrial applications, and cells produced under its auspices may not be suitable for the SPS because cell mass is not a serious consideration. It is highly desirable to coordinate photovoltaic studies for the SPS with the NPV, as cells produced for the SPS may well be adaptable to terrestrial use, perhaps with a thicker cover glass to increase ruggedness. The SPS could also provide the mass market needed to reduce cell production costs to the level where they are cost effective in terrestrial systems.

If efficiencies can be improved, thin-film silicon and amorphous silicon cells may be of particular interest to the SPS, offering low mass and potentially low cost, but most importantly, greatly increased production rates.[39] Some photovoltaic cell production processes may be well adapted to operations in LEO[41] (for example, a ribbon growth process may allow much wider and longer thin silicon ribbon to be grown in free fall than on Earth), reducing costs and eliminating the need to launch fragile cells in the HLLV. These possibilities may prove a significant factor in the final choice of cell type.

Solar concentration provides collector area in the form of lightweight, relatively cheap thin-film plastic mirrors. As concentration ratio is increased, individual cells which are more complex, costly and massive, may be used. However, the efficiency of most cells decreases rapidly with temperature, so the thermal effects of high concentration must be controlled. Active cooling, used in some high-concentration photovoltaic systems for terrestrial use, is probably impractical for the SPS application. The thermal load may be reduced by the use of spectrally-selective concentrators, with reflectivity matched to the cell band-gap energy. Increasing efficiency also helps, leaving less waste energy to be dissipated as heat. Multispectral photovoltaics (i.e., several different types of cell, matched to different regions of the solar spectrum) may offer useful increases in conversion efficiency; monolithic multilayer cells may be feasible, with each cell transmitting the spectral region which it does not efficiently convert, or beam-splitters may be used to direct different spectral regions to different cells.[42]

Photovoltaics is a very fertile field for innovation and a most important area of research for the SPS.

5.3.2.2 Photoemissive Systems

Light detectors based on collection of photoelectrons from an illuminated cathode have been in wide use for many years, but have not generally been regarded as serious competitors to photovoltaic cells for power production. In part, this is because the simple photocell is a vacuum tube, and solid-state photoconversion devices have advantages not unlike those of the transistor in electronics, in terms of mass, cost, reliability, and complexity. More importantly, a typical photoemissive device shows an overall conversion efficiency for solar radiation which is well below one percent.

There are indications, however, that recent work on photocathodes of high quantum efficiency[43] and innovative design may lead to rugged devices of low specific mass and much higher efficiency. Particularly interesting is the suggestion[44] for a cell consisting of fine serrations on the surface of an insulator—when the cell is illuminated, photoelectrons from a cathode plated to one face of each valley are collected by an anode on the opposing face. The valleys are electrically in series, and it may be possible to produce large-area cells with outputs in the kilovolt range. The predicted efficiency, as yet unconfirmed, is 35 percent, much better than any existing photovoltaic cell. If a thin insulating substrate of low density can be used, and/or if the cell can be used at moderate concentration ratios, it could prove competitive with photovoltaic conversion for the SPS. The fact that efficiency is highest when the illumination is normal to a valley face, rather than to the overall cell surface, may lend itself to equimomental SPS designs (which minimize gravity gradient torques), or to some systems using reflectors.

The photoklystron (Sec. 5.3.3.1) is another example of a photoemissive device of potential value to the SPS.

5.3.2.3 Photochemical Systems

Photochemical utilization of solar energy is of growing interest. Photochemical conversion requires that a reactant be converted by solar radiation to a product of higher free energy, which can be converted back to the original reactant with the release of energy in a useful form. There are a very wide variety of reactions of potential interest for solar heating and cooling, power generation, or the production of chemical fuels. An important possibility with many of these reactions is that the back reaction (i.e., energy release) can be delayed relative to solar absorption and initiated on demand—in other words, many photochemical conversion devices may provide intrinsic energy storage.

For power production, a photogalvanic cell can be used in which photochemically-induced electron-transfer reactions (redox reactions) occur in a fluid;[45] passive electrodes extract electric power from the chemical products, as in a battery. Other approaches are possible, such as the liquid-junction photovoltaic cell and photoelectrolysis (for example, producing hydrogen and oxygen from water for use in a fuel cell). Ultimate conversion efficiencies of 20 to 40 percent may be feasible.[46]

It seems probable that these types of system, involving liquid media, will be heavier, more complex, and perhaps less reliable than other photoconversion technologies for the SPS. The energy storage feature is of little direct utility to the SPS (although it could overcome one of the most challenging obstacles to widespread terrestrial use of solar energy). If photochemical systems proved competitive, and if some storage could be provided at little extra cost, it might maintain SPS output during some types of maintenance, and, perhaps, even during equinoctial eclipses.

Although it is too early to draw conclusions about application of this technology to the SPS, it is important to maintain cognizance of developments in this field which is presently of lower priority for SPS research.

5.3.3 Direct Conversion

As used here, direct conversion refers to systems which convert solar energy directly to radiation suitable for a power beam, without an explicit use of electric power as an intermediate form of energy.

5.3.3.1 The Photoklystron

The photoklystron[47] is a reflex klystron in which the thermionic cathode is replaced by a photocathode. An experimental model has been built (although not at S-band). Further development is needed before its potential utility to the SPS can be evaluated.

Because the photoconverter and the microwave source are part of the same tube, the photoklystron would have a strong impact on the configuration of the SPS. The most likely approach is to use reflectors to illuminate a photocathode array which is perpendicular to the local vertical, with the other side of the array forming the spacetenna, as in the "sandwich" configuration (Sec. 5.2.4). However, it could also be adaptable to systems such as the gravity-gradient stabilized SPS (Sec. 5.2.3) in which on-board power distribution uses microwaves in waveguides.

In principle, it is preferable to use solar energy directly to provide the electron beam in a microwave conversion tube than to generate electricity as an intermediate step. In this connection, it may be worth investigating direct solar heating of a thermionic cathode, as an alternative to photoemission. In practice, however, most of the savings in complexity (in terms of power distribution, etc.) arise from the sandwich configuration rather than from the photoklystron (or "thermoklystron") itself. It is not clear that this technology is preferable to devices of the LITOMIC type (Sec. 5.2.3), in which a photovoltaic cell is integrated with a solid-state microwave device. The sandwich configuration lends itself to a large spacetenna, in which the flux density is low and the thermal dissipation is consequently within the range tolerable by solid-state systems. If the photoklystron is to operate at efficient power levels, it may be necessary to use either high concentration (resulting in a relatively small sandwich array) or microwave wave guides to distribute the tube outputs over the spacetenna phased array. The feasibility of solid-state conversion has. however, not yet been demonstrated (Sec. 5.4.1.8) and more information is needed to allow evaluation of the relative merits of the two approaches. Continued research on the photoklystron is warranted at the system, as well as at the device level.

5.3.3.2 Superconducting Microwave Pumps

It should be possible to design a low-loss (superconducting) microwave cavity which supports a standing wave at relatively low frequency, and then to compress it to S-band frequency and higher power with a super-conducting piston, mechanically driven. It seems clear that the complexity, mass, low-power density and cost of such a system would be such that it need not be given serious consideration at this time.

5.3.3.3 Sun-Pumped Lasers

The possibility of using solar energy more or less directly to provide pump power in a lasing cavity is considered in Sec. 5.4.2.8.

5.4 Power Transmission Alternatives

5.4.1 Microwave Systems

5.4.1.1 The Multibeam MPTS

This concept was discussed in Sec. 5.2.13. Using a single spacetenna to beam energy to several rectennas allows a reduction in the size and power output of each rectenna (by a factor equal to the square root of the number of beams), without otherwise changing the power optimization conditions discussed in Appendix B.

Some complications arise if the retrodirective array principle (Sec. 4.2) is to be used to establish and control multiple beams. The phase-front leaving the spacetenna is naturally much more complex than in the case of a single beam. In order to avoid interference patterns across the spacetenna, the pilot transmitters at each rectenna should not all have precisely the same frequency. It might be possible to use discrete frequencies for each power beam also (with separate phase conjugation systems for each one), but it is certainly possible to use separate frequencies for the pilot and power beams[48] and it may be feasible to design phase-conjugation circuits which accept multiple pilot-beam inputs and generate the required power beam phase front at a single frequency. The best approach needs further study.

5.4.1.2 Aperture Augmentation

Use of a microwave reflector to provide increased spacetenna aperture at possibly lower cost was discussed in Sec. 5.2.9.

5.4.1.3 High-Gain Spacetennas

Apart from the aperture-augmented system, all the variants on the MPTS discussed so far use a phased array, in which the individual radiating elements are effectively dipoles (slot antennas). It would also be possible to use an array of end-fire S-band antennas, of which there are many types, to increase the gain from each element and reduce the number required. It is not clear that this would necessarily be cheaper, but there may be advantages in reducing microwave wave guide installation where the system design requires widely separated microwave conversion devices, as may be the case with the photoklystron (Sec. 5.3.3.1).

More complex spacetenna designs could also allow a circularly-polarized power beam (with an appropriately-designed rectenna), which would be effective in reducing small fluctuations in rectenna output due to Faraday rotation of the plane of polarization in the ionosphere, but this is too small an effect to be of significant concern at present.

5.4.1.4 Phase Reference Systems

As discussed in Sec. 4.2.4, a retrodirective array with central phasing can tolerate flexing of the spacetenna structure. It is impractical to make a structure of the size of the spacetenna rigid on the scale of a wavelength at S-band (c. 12 cm), but the instantaneous shape of the structure could be monitored (e.g., with automatic laser surveying equipment). The independent information thus obtained would permit phase-conjugation devices to be distributed across the rectenna, avoiding the dispersionless, constant-length transmission lines needed to carry phase information to central phasing systems. The savings, if any, from this approach would be relatively minor, and the trade offs have not been studied.

An independent means for measuring reflector figure is almost certainly required in aperture-augmented systems and in the LPTS.

5.4.1.5 The Amplitron

The microwave generators in the SPS reference system spacetenna are klystrons, which are high-gain microwave amplifiers, driven by solid-state oscillators whose phases are controlled by the ARA phase-conjugation circuits. The klystron uses a well-defined electron beam (e-beam) which passes a resonant cavity driven by the input signal. The velocity of individual electrons is modulated according to the phase of the input signal, and the resulting velocity differences lead to bunching of the beam downstream (space charge wave). An output cavity is located where bunching is maximum. These tubes are well developed, reliable, and capable of high output power (70 kW/tube in the SPS reference system). The klystron employs relatively high voltages (tens of kV) to accelerate the beam, leading to low mass for the power-distribution system, and the efficiency can be quite high (86 percent).

An alternative which has been advocated by Brown[49] is the amplitron, a crossed-field device in which electrons from a cylindrical cathode are accelerated towards a surrounding anode but deflected into cycloidal paths by a magnetic field paralled to the cathode axis. A slow-wave RF structure inside the anode is fed by the input signal; at a critical value of anode voltage, the angular velocity of the electrons coincides with that of the RF wave, and the resulting resonance forms a space-charge distribution consisting of rotating spokes, which couple to the RF circuit to provide amplification. Some of the emitted electrons are returned to the cathode due to repulsion by the space-charge distribution, and this provides sufficient energy so that a separate heater is not required. The efficiency of the amplitron can be slightly higher than that of the klystron, and its mass is significantly less ($\sim$ 0.4 kg/kW vs. $\sim$ 0.7 kg/kW). There is less experience with high-power amplitrons than with klystrons, so the tube output assumed in studies of the amplitron for the SPS is generally an order of magnitude less than that in the SPS reference system. The increased number of tubes, together with a somewhat lower voltage supply for each tube, makes the power distribution system and assembly of the spacetenna considerably more complex. It should be noted, however, that amplitrons with CW outputs up to 400 kW have been built.[50] The amplitron is also somewhat noisier than the klystron and requires more extensive output filtering; because of the high beam power, the SPS requires a clean signal to avoid RFI with terrestrial systems.

The amplitron should be regarded as a strong contender for the SPS. If high-power, low-noise tubes can be developed, it could allow a 5 percent reduction in the overall mass of the satellite.

5.4.1.6 The Magnetron

The magnetron[51] is a crossed-field device like the amplitron but lacks the RF slow-wave structure. Instead, the anode consists of a set of radial vance which create a cylindrical array of coupled resonant cavities in which the mode corresponding to a phase shift of radians per segment is excited by the rotating electrons, the interaction itself creating resonant, oppositely rotating standing waves in the space-charge distribution.

The magnetron is a cheap, simple, reliable device which has been produced in great quantities. Present U. S. sales (mostly for microwave ovens) amount to about 2 GW per year (compared to perhaps 50 MW per year for klystrons). The tube tends to be noisy, and most of those produced have power outputs below 1 kW. However, recent work by Brown[52] has shown that the noise can be greatly reduced by switching off the cathode heater once the tube is warm and has also given promising results regarding phase control and very simple feedback control of the power output. It may be possible to build magnetrons with power outputs in excess of 100 kW.[51]

5.4.1.7 The Gyrocon

The gyrocon is an e-beam microwave amplifier whose primary development (in the U.S.S.R.) has been to meet the requirements of accelerators.[53] It differs from the klystron in that the input resonator is fed by two signals displaced 90°

apart in space and time, resulting in a conical motion of the beam. When the beam is refocused at an output resonator of toroidal geometry, an azimuthal bunching is produced which is considerably cleaner than the temporal bunching in the klystron, which leads to a very high efficiency and power capability. The RF gain in present devices is less than 25 db, considerably less than in the klystron, but new designs [54] promise improvement to about 35 db.

Gyrocons have not yet been operated above 1 GHz, but it should be possible to achieve operation at the 2.45 GHz frequency of the MPTS. Both efficiency and gain improve with the power level, and individual tubes with outputs above 2 MW appear feasible, which would allow a dramatic simplification in the spacetenna. The devices are presently rather heavy (c. 1 kg/kw), but there has been little work as yet on designs for use in Space.

With careful design, gyrocons may possibly achieve overall DC-to-RF efficiencies in excess of 90 percent. Cooling may, however, be a problem (requiring integral heat pipes) for individual tubes of very high power. It should be noted that small improvements in the high efficiency of all the microwave tubes discussed so far have important systems implications. A one percent increase in efficiency means a 10 percent decrease in the waste heat to be radiated to Space, which implies a higher flux density at the spacetenna and a reduction in the cost of power (see Appendix A).

The gyrocon is a most interesting device which deserves serious investigation for the SPS application. It is too soon to make a definitive choice between the klystron, the amplitron, the magnetron and the gyrocon as a microwave power tube.

5.4.1.8 Solid-State Microwave Devices

A wide variety of solid-state devices (Gunn diodes, transit-time oscillators, high-frequency transistors, etc.) have been used to generate low-level microwave power. The principal disadvantages are a low output per device (of order 100 watts) and strictly limited temperature capability. A very large number of devices may be needed in a solid-state spacetenna, but on the other hand, they may be better adapted to automated fabrication and assembly than are microwave tubes. The need for relatively low-temperature operation limits the heat dissipation capability of the spacetenna and thus will reduce the achievable flux density unless very high conversion efficiency can be achieved. This may not, however, be a problem for SPS configurations (such as the sandwich, Sec. 5.2.4) which permit large spacetenna arrays at acceptable cost.

The great advantage of solid-state devices is their reliability and useful life. It is probable that microwave tubes would need replacement several times during the 30-year design life of the SPS reference system, but solid-state generators may exhibit mean times to failure of 50 years or more.

5.4.1.9 Masers

Direct solar pumping of masers appears impractical because of the great difference in energy between solar and microwave photons.[55] If solar energy must be converted to electric power, masers offer little advantage for the SPS application over other microwave generators and have much lower efficiency.

5.4.2 Laser Systems[56]

As discussed in Sec. 5.3.6., the LPTS is an important option for the SPS, allowing much lower unit power output than the MPTS. The laser SPS should be regarded as complementary to the microwave system, rather than as an alternative to it, because it provides a means for demonstrating space solar power at lower cost and for broadening the market, even if the cost of power from a mature system proves lower with the MPTS.

Laser technology is improving very rapidly. Over the last decade, for example, the doubling time for demonstrated power output from a single lasing cavity has averaged less than two years. It appears to be entirely possible to build individual lasers with CW outputs in excess of 100 kW; and any desired output can be obtained by parallel operation of multiple cavities. The conversion efficiency is also increasing, and levels above 50 percent (electric power to laser light) seem feasible.

At present, the CO_2 subsonic electric-discharge laser (EDL) is the type which has seen the greatest development for practical applications (both CW and pulsed). CO_2 EDL's with CW outputs up to 20 kW are now used routinely for industrial purposes such as metal-working. However, there are many other types in laboratory development, and the variety available is expanding rapidly. It is reasonable to assume a laser of demonstrated feasibility for near-term systems studies of the LPTS, but it should be borne in mind that improved devices are very probable in the time frame of interest for the SPS.

A most important parameter for the SPS is the overall efficiency of the system, from insolation at the satellite to electric power at the terrestrial receiver, since it is this which determines the solar collector size for a given power output. The efficiency chain includes conversion of sunlight to an intermediate form of energy (e.g., electricity), conversion to laser light, transmission to the ground, and conversion to power at the receiving site. Improvement in any of these factors can have a significant effect on the economics of the laser SPS. For example, direct sun-pumping of the laser, even if relatively inefficient, may be a desirable technology because it avoids the inefficiencies of conversion of sunlight to electric power.

Given the rate of innovation in laser technology, it would be premature to attempt a choice between laser systems.

5.4.2.1 LPTS Applications

A first choice to be made in designing the LPTS is the ground flux density. If the flux density is high enough, high power lasers can punch through clouds, providing essentially all-weather operation; but a beam of this type may pose hazards to aircraft and airborne biota and could conceivably be used as a weapon. At a mean flux density of 10^4 W/cm,^{2} for example, a 1 GW beam would require a receiver of diameter only 3.5 m; if the wavelength is 10.6 microns (as in a CO_2 laser), the transmitter output aperture in GEO would then be c. 270 m. At the other extreme, it would be possible to use a receiver of diameter 100m, requiring output optics in GEO of diameter only 9.5 m. (at 10.6 microns): the mean flux density in the atmosphere of a 1 GW beam would then be only 13 W/cm,^{2} equivalent to the flux from a black body at 1200°K. If higher fluxes are needed for conversion to electricity, they can be achieved using simple light-bucket concentrators at the receiver. The disadvantage of low-flux systems is that the beam will be interrupted by clouds, so that a network of redundant receivers is required, connected by terrestrial transmission lines, sufficient to give a high probability that receivers will be available at all times. The optimum flux density and the overall cost of the system thus depend on the climatic conditions.

It is desirable that the receivers be located at altitudes of several kilometers, in order to avoid clear-air absorption, although reasonable efficiency to sea level may be achievable by choice of the lasing wavelength. The most efficient atmospheric windows are in the visible and near infrared, although it may be possible to avoid line absorption by using a rare-isotope lasant to detune the beam with respect to the absorption spectra of atmospheric constituents.

These considerations suggest that the laser SPS will be most cost effective when feeding receivers in high altitude, desert regions. Because the cost of power may be higher from the laser SPS than from microwave systems, target regions should be chosen where the cost of alternative sources of electricity is high.

5.4.2.2 Space Laser Relays

The possibility of building the SPS in iso-insolation orbit, with a laser relay in GEO to provide continuous power to designated terrestrial receivers, was considered in Sec. 5.3.2.

5.4.2.3 The CO_2 Electric Discharge Laser

As noted above, the primary advantage of the CO_2 EDL is its present state of development. The operating wavelength (10.6 microns) is not optimum, either for atmospheric transmission or in terms of minimizing the size and cost of output optics. Absorption of the beam by atmospheric CO_2 can be minimized (at significant cost) by using Carbon 13 in the lasant, but radiation at this wavelength is also absorbed by water vapor, requiring a relatively high-altitude receiver. The overall conversion efficiency may be of order 25 percent—if photovoltaic cells are used to generate electric power, the efficiency of conversion from sunlight to laser light is thus likely to be no more than 4 percent.

5.4.2.4 The Supersonic CO Electric Discharge Laser

The CO EDL is a more promising candidate laser than the CO_2 EDL, because the operating wavelength is 5 microns, giving somewhat better atmospheric transmission, and because conversion efficiencies up to 50 percent can be achieved for CW devices and up to 70 percent for pulsed machines.[56] A major problem with this type of laser is that the cavity is in effect a supersonic wind tunnel; a machine with an output of 1 GW may require a gas throughput of about 7 tons/sec. However, the CO EDL is fairly well understood, so that it is a suitable choice as a baseline design for current trade-off studies.

5.4.2.5 Excimer Lasers

Lasers based on excimer lasants (i.e., molecules, such as xenon fluoride, which are stable only in the excited state) offer operating wavelengths in the visible and potentially high power and efficiency. As far as is known (i.e., from the unclassified literature), these lasers have not yet been operated as CW machines, and much is yet to be learned about designing efficient, lightweight systems.

5.4.2.6 Chemical Lasers

Chemical lasers produce population inversion by a chemical reaction (e.g., hydrogen/deuterium with fluorine) and do not need a separate source of power. They are thus of considerable interest for military applications where lightweight systems are needed but short operating times are involved. If an efficient photochemical means could be found to dissociate the reactants (using sunlight as the energy source), it might be possible to build a closed-cycle chemical laser system avoiding electric power as an intermediate form of energy in the SPS. Research is needed to find a molecular species adapted to photochemical energy storage (Sec. 5.4.2.3) which can also serve as an efficient chemical lasant.

5.4.2.7 The Free-Electron Laser[57]

The free-electron laser (FEL), which may be regarded as an approximate optical-frequency analogue of the klystron, is a very interesting candidate for the LPTS. In this device, an e-beam is established along the axis of an evacuated optical cavity, and the beam is modulated by passing through a "wiggler" magnet, which has periodic reversals of field direction. When the beam energy and cavity optical resonance are appropriately matched, optical amplification occurs, with the light beam extracting energy from the e-beam. Only a small fraction of the e-beam energy is extracted on each pass, but conversion efficiency in excess of 50 percent may be feasible if the e-beam is maintained in a storage ring, or if its residual energy is extracted efficiently during deceleration beyond the lasing cavity. The FEL has the capability of becoming a high-power device and is readily tunable. The fact that lasing takes place in vacuum makes it particularly suitable to space applications, avoiding window problems.

The accelerator needed to create and sustain the high-energy e-beam is likely to be by far the most massive component of the FEL, especially if a storage ring is used. Even if superconducting magnets are used in the accelerator, it is not yet clear that the FEL can compete, in terms of mass, with other candidate laser systems.

5.4.2.8 Sun-Pumped Lasers[58]

It is not easy to pump a lasing medium directly with sunlight. The absorption bandwidth for population inversion in the lasing medium may be wide compared to the emitted laser line, but it is likely to be very narrow compared to the solar spectrum, leading to serious inefficiency and thermal dissipation problems. The thermal problem may be overcome, to a large extent, by use of a spectrally selective concentrator, but the collector area will still be large for a given output, being determined by the efficiency.

A possible approach to this problem has been suggested by Christiansen,[59] in which a thermally isolated intermediate black body is heated by concentrated sunlight to temperatures of 2000°K to 3000°K, and the infrared radiation from this is used to pump a suitable laser. Since the peak in the black-body spectrum at 3000°K is shifted to the infrared (compared to the solar spectrum), the spectral intensity in the far infrared (5 microns) is only a factor of 2.5 below that in sunlight, and the intermediate body can surround the lasing cavity, providing high pumping rates. Inside the cavity, an absorption hole develops in the black-body spectrum at the pump frequency, but this is continually filled so that the efficiency of utilization of sunlight becomes primarily a function of the ratio of the rate of absorption in the lasing medium to the thermal losses, and can in principle be many orders higher than in the case of direct solar pumping.

The utility of this indirect solar pumping technique to the laser SPS, is being investigated in experimental studies[60] .

5.4.3 Particle Beams

High-energy particle beams are under study in this country and in the U.S.S.R. as potential beamed-energy weapons. Although such beams could, in principle, be used as an energy transmission system, very little information is available (in the unclassified literature) on which to base an estimate of possible performance. Their principle advantage over lasers is a higher power density on target, which is irrelevant for power transmission. As far as is known, virtually no work has as yet been undertaken on devices for conversion of particle-beam energy to useful power at a receiver—direct energy deposition at a target is sufficient for weapons applications. Since this technology is in an early stage of development under military auspices, it is presently deemed sufficient to maintain cognizance of this work without research specifically dedicated to the possible SPS application. If particle beams were to be used in the SPS, means must be found to avoid use of the system as a weapon.

5.4.4 Energy Storage

The possibility of physically transferring energy storage devices from the SPS to Earth was briefly considered in Secs. 5.1.3 and 5.2.15. It was concluded that this will not be a realistic technology in the foreseeable future.

5.4.5 The Orbital Tower

As noted in Sec. 4.2.3., if the orbital tower could be built it would provide a means for shipping power to Earth along a superconducting transmission line. While the orbital tower may be technically feasible, the scale of the enterprise is much too ambitious for serious consideration at present.

5.5 Technologies for Power Reception and Conversion

5.5.1 Microwave Power Beam Reception

5.5.1.1 High-Gain Rectenna

The receiving elements in the baseline rectenna are dipole rectifiers which involve immediate rectification of microwave power received by a simple tuned dipole. Some 10^{10} dipole rectifiers are required in the rectenna. This very large number can be reduced by using elements of higher antenna gain. The simplest possibility is to use yagi antennas, but there are other options (e.g., the hogline rectenna).[61] As the gain is increased, the complexity and cost of each element naturally increases, and this must be traded against the reduction in the number required. This is an important area for study as it could result in a significant reduction in rectenna costs. There is also a limit to the gain which can usefully be employed, because of the cost of accurate orientation of high-gain elements, and because satellite station-keeping requirements can become stringent if the rectenna antenna pattern is too narrow. It may be desirable to retain sufficient flexibility in the system to allow a given rectenna to be fed by different satellites at different longitudes, which suggests that the antenna pattern of the rectenna should be broad in the East-West direction.

5.5.1.2 Site-Specific Rectennas

The overall cost of a single SPS system (satellite plus rectenna) is of order $10 billion, which means that considerable variation in the design to meet special requirements should be economically feasible. As a case in point, it has been shown[62] that the cost-optimum power output of the system decreases if rectenna costs increase faster than rectenna area, a situation which may exist if topographic factors or land-use contraints limit the area available. It is also clear that the design and construction techniques for a rectenna can vary considerably for different sites—for example, automated construction on site, starting at the dipole rectifier level, may be appropriate for a flat desert site, but prefabricated billboards may be preferable at a mountainous location. Very little work has been carried out as yet to determine the range of rectenna designs which may be needed or the effects on system design.

5.5.1.3 Parabolic Antenna

One possible site-specific rectenna which is worth separate mention is use of a parabolic dish (as in the Arecibo radio-astronomy facility in Puerto Rico). It may be possible to find potential rectenna sites in hilly terrain in which the required rectenna area could be created from a close-packed array of hexagonal dishes. The optimum diameter of each dish depends on the terrain, but is probably of the order of hundreds of meters, in order to avoid excessive construction costs. Since it is not necessary to achieve high microwave image quality, the figure of each dish may have errors of up to a few centimeters, and low f-number reflectors can be used to minimize the height of the receivers at the focii. A rectenna of this type might have up to several thousand such dishes and receivers. Although the antenna gain would be fairly high, it could be pointed at the satellite and perhaps track it in the presence of orbital drift by controlling the horizontal position of the receivers.

5.5.1.4 Offshore Rectennas[63]

Many of the land-use problems associated with rectenna siting could be avoided by locating the facility offshore. This option may be of particular interest because most populous areas are relatively close to coasts (Atlantic Ocean, Gulf of Mexico, Pacific Ocean, or the Great Lakes). In several areas of the world (e.g., Japan and perhaps Europe), offshore rectennas may be essential to utilization of the SPS because of the unavailability of onshore sites.

If appropriately designed, an offshore rectenna island could support a variety of ancillary uses in addition to its principal function. Some examples are:[64]

- Artificial reef for enhancement of natural fisheries;
- A fish weir/trap for improved harvesting;
- Mariculture of various types;
- Fish processing plant;
- Docking facility/fuel depot for fishing fleets;
- Deep water port (for oil tankers and other large vessels);
- Oil refinery;
- Port and storage facilities for liquefied natural gas;
- Aluminum refinery, using imported bauxite and power from the rectenna;
- Industrial plants which should be close to but isolated from population centers (because of environmental impacts, etc.); and
- Wave energy conversion facility.

These secondary uses may be important, not only because the revenues from them could offset the increased construction and operational costs at an offshore site, but because they could improve the acceptability of the structure to other interests which might be impacted by it, such as the fisheries industry.

An offshore rectenna, designed to withstand the marine environment, will not be very similar in structure to an onshore one. Some of the secondary uses listed above would impose design requirements (e.g., microwave shielding of workers below the rectenna and sufficient clearance above the water to allow access by work boats). Two design concepts have emerged from a preliminary study by Freeman et al. The first is a "clothesline" rectenna (see below), suspended from bottom-mounted pylons,[63] and the second uses horizontal rectenna billboards, suspended from spar buoys.[64] In the latter design, the vertical frequency response of the buoys is chosen so that the rectenna surface conforms to swells passing beneath it, but surface waves are attenuated by wave dampers around the periphery, perhaps with the extraction of useful energy.

5.5.1.5 Other Rectenna Concepts

The SPS reference system rectenna is a relatively massive structure with a cost of perhaps $2 billion.[65] Significant savings may be effected by innovative design. Concepts which have been proposed include:

- The Clothesline Rectenna.[63] This system uses rectenna elements (dipole rectifiers or, more probably, low-gain yagi rectifiers) which are encapsulated and suspended from cables. The objective is to reduce the cost of the structure, protect the rectenna elements from the environment (especially at offshore sites), and to minize the wind resistance.

- Filament Yagis.[66] In this concept, each East-West row of the rectenna is made from an array of nonconducting filaments (e.g., nylon monofilament), with the plane of the array inclined to the vertical so that it includes the satellite. At intervals along this fence, yagi antennas are constructed by metal plating the filaments, with the bottom filament supporting a dipole feeding a rectifier.

- The Greenhouse Rectenna.[67] Because a rectenna can be at least 80 percent transparent to sunlight, the structure could be integrated with a greenhouse to allow intensive large-scale agriculture, offsetting costs. This concept could be particularly useful in desert areas, where agriculture is otherwise impossible, and at relatively high-latitude sites, where the growing season could be extended. A study is needed to determine the impact on rectenna design (e.g., elevation of the structure to allow sufficient greenhouse space beneath), the cost/acre of greenhouse using the rectenna for support, and the net revenues to be expected from intensive agriculture at different sites.

5.5.2 Laser Power Beam Reception

As noted previously, the efficiency with which laser light can be converted to other forms of energy, such as electricity, is an important factor in the economics of the laser SPS. The low entropy of the laser beam should allow efficient conversion, but this technology is in a very immature state. However, a number of options have been proposed.

5.5.2.1 Photovoltaic Cells

The band-gap energy in known photovoltaic materials is at least one eV. Photons of wavelength greater than about one micron thus do not have sufficient energy for photovoltaic conversion. For lasers in the visible or near infrared, however, with the wavelength matched to the band-gap energy, conversion efficiencies approaching 50 percent may be feasible.[68] Schottky barrier cells, in which the normal p-n junction is replaced by a metal semiconductor interface, are particularly promising.

Photovoltaic conversion appears best adapted to the low-flux LPTS (Sec. 5.4.2.1), although a concentrated beam could be diffused at the receiver if necessary. The higher efficiency with laser light reduces the thermal load at the cell somewhat, compared to solar photovoltaic conversion (by up to 30 percent for similar flux densities), but the thermal dissipation per unit area from a 1 GW laser beam, spread uniformly over a circle of diameter 100 meters, is still equivalent to that in a solar cell operating at a concentration ratio of 50. It is probable that (water) cooling of the cells would be required for photovoltaic conversion of the SPS laser beam, but this is not expected to be a serious problem as the receiver is a terrestrial installation.

5.5.2.2 Laser Boilers

The laser boiler is a conventional heat engine in which the laser energy is absorbed by a cavity absorber and transferred by thermal conduction to a working fluid. Stirling engines have been driven by laser boilers in experimental studies,[69] but Brayton-cycle turbine systems are preferable for high power levels. The efficiency is limited by absorber material properties, but values up to 65 percent have been predicted.

5.5.2.3 Resonance Absorption Engines

This type of device bears the same relationship to the laser boiler as the plasma solar absorber (Sec. 5.3.1.8) does to the solar cavity absorber—the laser power is admitted through a window and absorbed directly in the (seeded) working fluid. However, it is much easier to provide short absorption lengths in a fluid for laser light than it is for sunlight because of the narrow bandwidth. If the laser frequency is matched to a vibrational transition of the gas, resonance absorption followed by rapid thermalization can provide a much higher temperature than in the laser boiler because the walls of the absorber are thermally isolated, to some extent, by cool gas around the absorbing region, and this can, in principle, enhance the thermodynamic efficiency. If the flux density is high enough, resonance saturation combined with superelastic collision quenching can provide a very efficient means for coupling laser energy into a gaseous medium.[70] The remainder of the thermal conversion system may be of a relatively conventional type (MHD, Brayton-cycle turbines, etc.). Overall efficiencies up to 75 percent may be achievable.[68]

5.5.2.4 Photon Engines[71]

A photon engine is a device in which laser energy is stored in a working fluid in some form (vibrational excitation, molecular photodissociation, etc.) other than translational energy. This energy can then be extracted at constant (translational) temperature, and the theoretical conversion efficiency can approach 100 percent. This is an intriguing idea, but practical design concepts for such an engine remain to be developed.

5.5.2.5 Thermoelectronic Conversion (TELEC)

Laser-powered thermionic devices are clearly feasible, in which laser energy boils off electrons from a cathode for collection by an anode. In conventional thermionic devices, low pressure alkali vapor (e.g., cesium) in the diode gap neutralizes space charge and lowers the work function of the emitter, permitting high current densities. In the thermoelectronic laser energy converter (TELEC), the conversion efficiency is substantially improved by direct laser heating of the plasma between the electrodes.[72] Inverse bremsstrahlung can be used as an absorption mechanism, although calculations show that (for 10.6 micron (CO_2) laser radiation), the flux density in the (cesium) plasma must be of order 10^4 W/cm,^{2} and the absorption length may be in excess of 10 meters. Since a high-temperature plasma is required for this absorption mechanism, it must be started by some means such as an electric arc. It is possible[70] that saturated resonance absorption combined with superelastic electron heating will allow somewhat lower flux densities and much shorter absorption lengths. Conversion efficiency in TELEC devices may approach 50 percent.

5.5.2.6 Optical Diodes

An optical diode is a thin metal-barrier-metal junction in which application of a coherent beam establishes an optical frequency electric field which promotes electron tunneling through the barrier.[73] If there is a work function difference between the metals, the tunneling is asymmetric, resulting in direct rectification of the light beam to electricity. Devices of this type can rectify light at frequencies from the ultraviolet to the far infrared. The demonstrated efficiency is only about 5 percent, but there are indications that this might be improved to about 50 percent. A principal probjem is that of fabricating arrays of such diodes on a scale sufficient to intercept the laser beam from the SPS.

The development of lithography techniques at submicron scales may allow tuned structures at optical frequencies (at least, in the far infrared). It is thus conceptually possible to build an infrared analog of the dipole rectifier in the microwave rectenna, providing improved coupling to the laser beam and perhaps much higher efficiency than in less complex optical diode arrays.

5.5.2.7 Photochemical Conversion

The photochemical devices discussed in Sec. 5.3.2.3 may, in principle, also be used to convert laser radiation into other forms of useful energy, such as artificial fuels or electricity. The nature of laser radiation again allows a broader variety of options than in solar photochemical systems. A particularly interesting candidate is photocatalytic dissociation of water to hydrogen and oxygen.[74] It may be possible to reach efficiencies around 40 percent in the conversion of laser energy to stored chemical energy. The fuels produced may, in some cases, be used directly (e.g., in transportation); but, if they are used to generate electricity, the costs and inefficiency of this extra step may make the overall process economically undesirable compared to some of the alternatives discussed above. Laser photogalvanic cells (redox reactions) are also possible as a means of conversion to electrical power, but the attainable efficiency again seems relatively unpromising.

5.6 Space Transportation

Space transportation is estimated[16] as representing $\sim$ 33 percent of the overall cost of the SPS reference system. There is a widespread impression, based on experience in the space program, to date, that getting into orbit is an impressive and enormously expensive technological feat.

In the Apollo era, launch to orbit cost ~ \$4000/kg of payload (1980 dollars); in the STS, the cost will be of order \$850/kg. The reasons for these high costs are well understood, including throwaway vehicles (Apollo) or vehicles of limited reusability (STS); limited-launch vehicle production runs; infrequent launches, implying inefficient use of launch facilities; and complex, special-purpose command and control operations. It is probable that launch costs can be reduced to levels acceptable for the SPS (below \$50/kg) without major new technology. Convincing demonstration of economical transportation from Earth to LEO, and from LEO to GEO, would greatly enhance the credibility of the SPS.

There are several technologies which promise significant reductions in space transportation costs for the SPS. The variety of options which are available should increase confidence that acceptable costs can be achieved. There may be a multiplier effect in which lower transportation costs shift the optimal SPS design towards heavier and cheaper systems—for example, lower-launch costs would reduce the penalty associated with large space radiators, allowing improved efficiency in thermal conversion SPS designs.

5.6.1 Earth Launch

5.6.1.1 Shuttle-Derived Systems

In its present configuration, the STS will be useful for preliminary space experiments in the SPS development program, but its operational costs are probably too high for building a full-scale SPS demonstrator, and certainly too high for SPS production. However, development and capital costs would be minimized by building a launch vehicle for the SPS which was derived as far as possible from established STS technology.

In a recent study,[75] Boeing has examined the possibility of modifying the STS by substituting a fly-back, liquid-propellant booster and adding a cargo-carrying shroud to an enlarged orbiter external tank (ET). The orbiter would carry additional cargo or, when required, a module providing accommodations and life support for 30 to 40 personnel. Some of the ET's would have improved insulation to permit orbital lifetimes with fuel of several weeks, and these would be assembled and refueled in LEO to create a large, chemically-propelled OTV for transportation to GEO, the orbiter again being used for personnel.

It was found that this system optimizes with a rather large booster, with a gross lift-off weight GLOW of 5000 to 6000 metric tons, and a payload to LEO of 300 tons (compared to a GLOW of 11,000 tons and payload of 400 tons for the SPS reference system HLLV). The development costs for the new booster and modified ET's was estimated as $\sim$ 65 percent of that for a smaller version of the HLLV (see below), and the recurring costs were predicted to be twice as high.

5.6.1.2 Deploy-Only Launcher

A more radical proposed modification of the STS[76] is based on recognition that up-cargo capability only is required for most flights in support of the SPS, so that it is unnecessary to carry orbiter structure (e.g., wings) which is required for reentry. The most expensive components for the orbiter, and the ones for which reusability is most desirable, are the main propulsion engines and guidance system. These could be packaged with a heat shield for ballistic reentry. If the STS solid boosters were replaced by reusable liquid-propellant boosters, using current technology, the payload to orbit (carried in a shroud) would be increased by a factor of 3, to 90 metric tons. If four such boosters were used, the payload would rise to perhaps 160 metric tons.

The deploy-only launcher may reduce costs to LEO below \$150/kg, a level which is still excessive for construction of operational SPS systems. However, it is possible that development of this system would be justified as an interim vehicle, with more advanced launchers to be introduced when the market for the SPS has been established. It may be desirable to accept higher launch costs for the first few satellites in order to reduce the front-end investment, improve cash flow for the project, and reduce the cost risk.

5.6.1.3 Air-Breathing Boosters

An obvious way to reduce the GLOW of a launch vehicle is to use an air-breathing booster, a concept which was studied several times in the 'Sixties. A typical example[76] proposed a hydrogen-fueled supersonic-combustion ramjet (scramjet), with stage separation at Mach 10 and at an altitude well above 100,000 feet. An advantage of this approach is that air-breathing cruise allows insertion to LEO at an inclination less than the latitude of the launch site, with much less penalty than an orbital plane change in Space. Rockwell International has studied this type of concept more recently for the SPS.[77]

At the time of these studies, hypersonic air transportation seemed a probable development, amortizing much of the investment in new technology needed for the scramjet booster. Rapid increases in jet fuel costs, opposition to the American SST, and the disappointing cost performance of the Concorde SST have led to reduced interest in hypersonic aircraft, but it should be noted that continued escalation in petroleum prices may make the hydrogen-fueled aircraft competitive within a decade. High-altitude cruise at speeds in excess of Mach 10[78] would allow trip times of about two hours to anywhere in the world, minimal sonic boom impact, and minimum costs per seat mile (because of high aircraft productivity). It is possible that the high development costs, which are one of the principal impediments to the air-breathing booster, will have been overcome before the end of the century. It is, however, also possible that advances in booster technology will make two-stage vehicles for launch to orbit unnecessary.

5.6.1.4 Single Stage to Orbit (SSTO) Vehicles[76]

There have been many proposals[79,80] for building launch vehicles capable of reaching LEO with a single stage. One approach is a hydrogen-fueled vehicle, with oxidizer requirements reduced by use of scramjets for initial climb and acceleration. The ratio of payload to GLOW may be less than in the case of a separate air-breathing booster, but avoidance of staging could reduce total cost. Separate rocket engines would complete orbit insertion. Once again, development of hypersonic hydrogen-fueled aircraft would increase the cost effectiveness of this system.

An interesting alternative is based on development of the dual-fuel engine,[76] a rocket engine using LO_2 as oxidizer but which is capable of successively burning a hydrocarbon fuel and LH_2 in the same thrust chamber. Hydrogen/oxygen engines provide a relatively high specific impulse (up to 440 seconds), but the very low density of LH_2 (0.09 gm/cc) results in excessive fuel tank mass when used in a first stage. The dual-fuel engine permits the average specific impulse during boost to be traded against tankage mass, and an optimized system may be capable of SSTO performance. There has been one study of this type of booster for the SPS, where it was concluded that staged ballistic systems have a cost advantage; but increases in the packing density of SPS payloads since that time may have invalidated this result.

5.6.1.5 HLLV Optimization

The Boeing study[75] considered the possibility of reducing development costs by using a smaller HLLV (4000 metric tons GLOW, 120 metric tons payload, vs. 11,000 MT GLOW and 400 MT payload in the SPS reference system HLLV). The smaller vehicle has a significant effect on the design of the SPS reference system (for example, smaller solar array blankets are required) and the GEO construction base, and requires more frequent flights. It results in a slightly higher recurring cost (about 3 percent increase in the cost of each SPS), but gives a reduction in RDT&E and other capital costs amounting to $5 billion. The advantages seem to outweigh the disadvantages, and a smaller HLLV could be considered for the SPS reference system.

5.6.1.6 Small-Launch Vehicle

The HLLV is based on the economies of scale which result from increasing the size of individual vehicles (e.g., decreased stage mass fractions). However, there are other economies of scale (in utilization of launch facilities, tooling for launch vehicle construction, etc.) which result from increasing the frequency of launch operations, and hence using smaller vehicles. A study by Akin[81] suggests that, if only one SPS is to be built, the optimum launch vehicle payload is comparable to that of the STS. If larger numbers of SPS systems are contemplated, the optimum payload increases, but the curves become very flat and little is to be gained by exceeding a payload of about 40 metric tons. This leads to a new approach to the logistics of major Space enterprises, in which space launches become routine operations comparable to those at a major airport, with launches every few minutes.

Confirmation of Akin's results requires a detailed study of the effects of payload size (including volumetric limitations) on design of and space construction operations for the SPS. Adoption of a small-launch vehicle would have a significant effect on the future course of SPS development, so such a study should be given a high priority.

5.6.1.7 Laser Propulsion[82,83,84]

The feasibility of rocket engines powered by a laser beam has been demonstrated[85] at laboratory scale. A launch vehicle driving up a laser beam has the advantage that the energy source for boost remains on the ground, but a more significant implication is that the choice of working fluid in the engine is not constrained by the requirements of combustion, and the enthalpy per unit mass deposited in the working fluid by the laser may be much higher than that in combustion—this means that, within broad limits, the specific impulse may be chosen to suit the mission. Analysis shows that the power-optimum propellant is a fairly dense liquid such as liquid argon, and that the optimum mass ratio is about 3, for most missions. The power required naturally decreases as the range is increased. It may be cheaper to launch directly to a transfer ellipse to GEO rather than to LEO, because in the latter case the vehicle disappears over the horizon before reaching the maximum useful range (which is limited to ~ 1000 km by atmospheric beamspread effects). For launch to GEO, a specific impulse of about 1000 seconds is optimum. Taking into account engine inefficiencies, etc., a laser of output 1 GW could launch a payload of mass one metric ton every three minutes. If a chemical kick stage is used for orbit circulatization at apogee of the transfer ellipse, a 1 GW laser could deliver 100,000 tons per year to GEO, sufficient to meet the SPS buildup rate of 10 GW/year. Launch costs to GEO below $20/kg may be achievable at full utilization.

If the launch site is adjacent to a rectenna, laser propulsion offers a bootstrapping approach to the SPS, in which power from the first satellite is used to launch further satellites.

Laser propulsion is an intriguing possibility for the SPS. Some of the consequences (including military implications) have been examined briefly,[86] but a major area which needs analysis before this launch system could be seriously considered is the feasibility of launching SPS components in sufficiently small packages (~ 1 metric ton) and the effects of such small payloads on SPS design and construction.

5.6.1.8 Linear Accelerators

It is conceptually possible to launch payloads from Earth using a linear accelerator.[87] Magnetically levitated payloads would be accelerated inside an evacuated tube, perhaps subterranean, which led up the side of a mountain (to about 20,000 feet). A rapid-acting door at the end of the tube would open as the payload approached, admitting the atmosphere, and another would close behind the payload, to limit evacuation requirements before the next shot. The payload would emerge from the tube at a velocity somewhat above orbital velocity and at an angle of about 15° above the horizontal. Surprisingly, the deceleration when the payload hits the atmosphere is not a serious problem, as it (and the energy lost traversing the atmosphere) can be made as small as desired by giving the payload a high ballistic coefficient (i.e., a high mass per unit frontal area). The difficulty is instead that of coping with high aerodynamic heating rates at the stagnation point, a problem which is also faced (and solved) in some military systems.

The peak power per unit payload in such an accelerator is proportional to the final acceleration, and the length of the system is inversely proportional to the acceleration. For payloads of one ton, the optimum acceleration may be of order 50 g, leading to an accelerator length of 70 km, and a peak power of 5 GW. A new payload could be launched every three minutes.

Linear accelerators for Earth launch have only received a sketchy analysis but appear to be worthy of more detailed study.

5.6.1.9 Bolo Satellites

A bolo satellite for Earth launch consists of a pair of masses connected by a cable whose length is approximately twice the orbital altitude of the center of mass of the system. The bolo rotates in the orbital plane at an angular velocity such that the tip speed is close to the orbital velocity of the CM. At its lowest point, the tip of the bolo dips into atmosphere at relatively low velocity. A payload picked up at this time can be transferred to orbit by hauling it up the cable, or it can be launched to an escape trajectory by releasing it from the tip at its highest point.

While bolo satellites of this type are conceptually feasible, the cable strength-to-mass requirements are beyond foreseeable improvements, so that the system must be regarded as impractical at present. Less demanding applications of bolo satellites are discussed in Sec. 5.6.2 and 5.6.3.

5.6.1.10 The Orbital Tower

The orbital tower, a satellite in GEO with a cable reaching to the ground, has been discussed several times elsewhere in this report. The scale of the undertaking involved in building such a tower with available materials makes it presently impractical.

5.6.1.11 Electromagnetic Propulsion without Ionization

An intriguing concept has recently been proposed by Cox[88] for propulsion in the atmosphere to high altitudes. The vehicle emits a circularly polarized microwave beam which spins air molecules by interaction with their dipole moments. A strong, synchronously rotating magnetic field, transverse to the beam axis, then accelerates the molecules to produce thrust. Preliminary calculations of the thrust to power ratio appear promising, but it is too early to form a judgment concerning the feasibility or utility of this propulsion scheme for launch to orbit.

5.6.2 Orbital Transfer

OTV's propelled by chemical rockets, ion engines and plasmadynamic engines have been considered for transportation between LEO and GEO. All of these may be within the scope of the SPS reference system. This section considers less conventional alternatives.

5.6.2.1 Solar Sails

It appears to be possible to construct solar sails of very high performance if the reflecting film is made in orbit.[89] An orbital tug using such a sail, driven by solar radiation pressure, could have an acceleration and trip time to GEO comparable to that of an ion-engine OTV, but would be a relatively simple and reliable device and would require no propellant. Although solar sails seem better adapted to interplanetary missions than to Earth-orbital transfer, further study of this concept is indicated.

5.6.2.2 Laser Propulsion

Laser propulsion can be used for orbital transfer as well as for launch from Earth, and the performance requirements are much simpler because the velocity change required for insertion to a transfer ellipse from LEO to GEO and for circularization at GEO totals less than 4 km/sec. If the laser is in space, much greater ranges during boost may be feasible than in the Earth launch case, reducing power requirements. Lasers may be used to power electric propulsion systems, but the cost-optimum mass ratio (while lower than in the Earth launch case because of the cost of bringing up propellants to LEO) is in a range where thermodynamic propulsion (i.e., laser heating of a working fluid) is preferable.

The laser for this type of OTV may be in LEO, in GEO, or perhaps on the ground (although the latter option leads to limited transfer orbit insertion windows). Laser-powered OTV's for the SPS have been briefly considered,[86] but the advantages and disadvantages need to be assessed in comparison with other options.

5.6.2.3 Bolos and Skyhooks

Bolo satellites for Earth launch were mentioned in Sec. 5.7.11. A skyhook is a bolo which is permanently oriented along the local vertical.

A relatively small bolo in LEO, with a tip speed slightly above 2 km/sec, is capable of injecting a payload to a transfer orbit to GEO.[90] If the cables are exponentially tapered and constructed from Kevlar, their total mass need only be about 20 times that of the payload. If the tip acceleration is chosen to be one g, the required cable length is 400 km and the orbital altitude of the CM should be about 900 km. The payload is released from the bolo tip at its highest point, and the energy and angular momentum of the bolo is then replenished using thrusters of high specific impulse. This system combines the advantages of rapid transit to GEO with those of ion-engine propulsion.

There are additional advantages to the LEO bolo for orbital transfer. For launch from Earth to rendezvous with the tip at its lowest point, the velocity required is 6.2 km/sec (compared to 8 km/sec for launch to the lowest possible orbit). For a launch vehicle of given GLOW, using an upper stage powered by LO_2/LH_2, this reduction in velocity implies an increase in the payload by about 50 percent. A single-stage launch vehicle for suborbital rendezvous with the bolo is also much more practical than for launch into orbit.

A skyhook in LEO, with a cable extending about 1100 km above the CM, is also capable of transfer orbit injection, but the savings in Earth launch to rendezvous with a skyhook are much smaller.

At apogee in the transfer ellipse, payloads could rendezvous with a bolo in GEO, or with a skyhook (which needs to have a length of about 11,000 km below GEO, in order to match the apogee velocity).

A system of this type can exhibit a high throughput to GEO. A bolo in LEO weighing less than 5000 tons, and a skyhook in GEO weighing less than 1000 tons (in both cases including orbit make-up thrusters, solar power supplies, etc., which represent most of the mass), could deliver 100,000 tons per year to GEO in 25-ton increments. Payloads in transit require no thrust capability, other than for course correction and rendezvous, and the system can also be used to return from GEO to LEO.

Although bolos and skyhooks are a radical approach to orbital transfer, the technology involved is fairly simple. A more detailed study is needed of the technical feasibility of these systems, and of the effects on SPS design requirements.

5.6.2.4 Mass-Driver Propulsion

The mass-driver is a solar powered linear electric motor[91] which produces thrust by accelerating any available waste mass (e.g., chopped-up STS external tanks) to high velocity. In order to minimize mass utilization in an orbital transfer from LEO to GEO, an effective exhaust velocity of 10 km/sec is suggested.[92] While this concept is technically feasible, and the idea of using any waste mass as propellant is attractive, the size of the device is a disadvantage. The suggested acceleration is 1000 g, but this still leads to an accelerator length of 5 km, and the mass must be minimized to provide high performance. The mass-driver may have other space applications (see below), and continued research into its use for propulsion is clearly warranted, but it seems unlikely to have a significant impact on SPS development in the near term.

5.6.2.5 Linear Accelerators

Another approach to using devices of the mass-driver type for orbital transfer is to build a linear accelerator in LEO, accelerating payloads rather than propellant. The advantages are that the velocity required for transfer orbit injection is only about 2.5 km/sec, and the accelerator can be relatively massive as it remains in LEO. If the payloads can withstand an acceleration of 100 g, the length of the accelerator would be about 3 km. The orbital energy and angular momentum of the accelerator would be made up between launches, using thrusters of high-specific impulse--like the LEO bolo. Such a system combines the advantages of rapid transit to GEO with those of ion propulsion. However, the bolo may be a lighter and simpler system.

A bolo or skyhook in GEO could be used to circularize the transfer orbit in this case also.

5.6.3 Lunar Launch and Landing

If lunar materials were to be used in SPS construction (see Sec. 5.2.12) an economical means would be required for launching payloads from the Moon and (to a lesser extent) for landing personnel and equipment on the Moon. It is, of course, possible to use chemical rockets for this purpose--the velocity needed to reach low lunar orbit is 1.7 km/sec, which can be achieved by a rocket burning LH_2 and LO_2 with a mass ratio of 1.5. Some 89 percent of the propellant load is oxygen, which is available from lunar sources (e.g., as a by-product of metal refining). The mass of hydrogen required at lunar lift-off is 6 percent of the payload; if this must be obtained from the Earth, then, taking into account the propellants needed to land this fuel on the Moon, it is found that 85 kg of propellants must be delivered to lunar orbit for every metric ton to be launched. Assuming that the propellants are delivered from LEO by a tug using engines of high-specific impulse, the conclusion is that lunar mining, supported by chemical rockets, could reduce the mass which must be launched from Earth by an order of magnitude. It is not clear that this is sufficient to offset the costs of lunar operations.

Since it is so much easier to escape from the Moon than from the Earth, some of the transportation options discussed in Sec. 5.7.1 may be much more practical for this purpose.

5.6.3.1 The Mass-Driver

The use of a linear accelerator (mass-driver) for launching payloads from the Moon has been studied in considerable detail.[92] The proposed mass-driver would launch payloads of about one kg, several times a second, on precisely defined trajectories leading to a "catcher" in space (perhaps at one of the unstable lunar Lagrangian points). In principle, the most challenging technical problem is that of controlling the exit velocity from the mass-driver (especially transverse components) with the extreme precision needed to reach a catcher of reasonable size; however, by appropriately locating the mass-driver on the Moon, it is possible to use "achromatic" trajectories which minimize miss distance at the catcher in the presence of launch velocity errors.

O'Neill[93] has constructed scenarios which suggest that both the non-recurring and recurring costs of SPS production may be minimized by starting with the installation of lunar mining facilities, using mass-driver propulsion (Sec. 5.6.2.4) for transferring equipment to lunar orbit from LEO and a mass-driver to launch payloads from the Moon, but his cost figures must be regarded as uncertain and controversial. Miller and Akin[94] suggest that a mature operation of this type could produce SPS systems at an installed cost below $1000/kW (1978 dollars).

5.6.3.2 Laser Propulsion

The escape velocity from the Moon is 2.3 km/sec, and there is no atmosphere to interfere with propagation of a laser beam. Laser propulsion (Sec. 5.6.1.9) could be used for launch from the Moon, the primary objective being to allow the use of lunar materials (e.g., liquid oxygen) as a propellant, rather than to give high-specific impulse. The usable range during boost is limited by gravity losses to about 700 km, but the laser power required is found to be two orders of magnitude lower than for Earth escape, or about 10 MW/metric ton.[95]

The advantages of lunar laser propulsion over the lunar mass driver include the following:

- The installation on the Moon is much lighter and more compact.

- It is possible to use the laser beam for landing as well as launch, reducing costs and giving the possibility of a boot-strapping operation in which a small laser is installed on the Moon and used to land components to increase its capacity.

- The laser beam may be used to define the launch trajectory very precisely.

- Individual payloads may be large enough to permit some on-board guidance, and perhaps enough to allow carrying personnel (the peak acceleration is about 0.5 g).

- The laser may be located at a mining site, avoiding lunar surface transportation.

The principal disadvantage of laser propulsion is that it is less energy efficient than the mass-driver (by a factor of about 4). If a solar power plant is used for the system, this is unimportant unless the launcher is used continuously.

Lunar laser propulsion appears to be preferable to the mass-driver, especially in the early stages of lunar industrialization. This technology would have to be interpreted with scenarios for lunar development to determine the cost impact.

5.6.3.3 Lunar Bolo Satellites

Bolo satellites are probably a feasible means for launch from and landing on the Moon. If the CM is at an orbital altitude of 260 km, the cables reach to the surface at their lowest points, and the tip speed is equal to the orbital velocity (1.6 km/sec), the tip acceleration will be one g. As seen from the surface, the trajectory of the tip is a catenary, descending almost vertically for payload pick up. The touchdown points along the orbital path can be controlled and terrain variations accommodated by reeling the cables, without propellant expenditure. The orbit and angular momentum of the bolo would be maintained by thrusters of high-specific impulse. To provide frequent launch opportunities, the orbit and, hence, the pick-up points should be equatorial.

APPENDIX A

APPENDIX A
SPS REFERENCE SYSTEM

The SPS Reference System has evolved from system definition studies conducted primarily by Boeing Aerospace Company and Rockwell International and is based on numerous trade-off studies and engineering analysis from 1976 to 1978.[1] The SPS Reference System is an interim working concept which provides the technical and operational information needed to conduct environmental, socio-economic and comparative assessment studies which will provide information to influence future system designs. The SPS Reference System will evolve and mature as further details will be developed.

System Overview

The SPS Reference System is sized for a 5 GW dc power output into a conventional power grid. The satellite has one end-mounted antenna which transmits to a rectenna on the ground. This concept is illustrated in Fig.A-1.

The configuration of the satellite consists of a planar solar array structure built from a graphite composite material. Two conversion options are presented. One uses the single-crystal gallium-aluminum-arsenide (GaAlAs) solar cells with a concentration ratio of 2 as illustrated in Fig. A-1. The other energy conversion option is the use of single-crystal silicon (Si) solar cells with no concentration.

The size of the solar array is dictated primarily by the efficiency chain of the various elements in the system. Fig. A-2 shows the end-to-end efficiency chain for the GaAlAs and silicon solar cell options. With the satellite designed to provide 5 GW of DC power to the utility busbar and an overall efficiency of approximately 7%, it is necessary to size the solar arrays to intercept approximately 70 GW of solar energy as indicated in Fig. A-2. The quoted efficiency is the minimum efficiency, including the worst-case

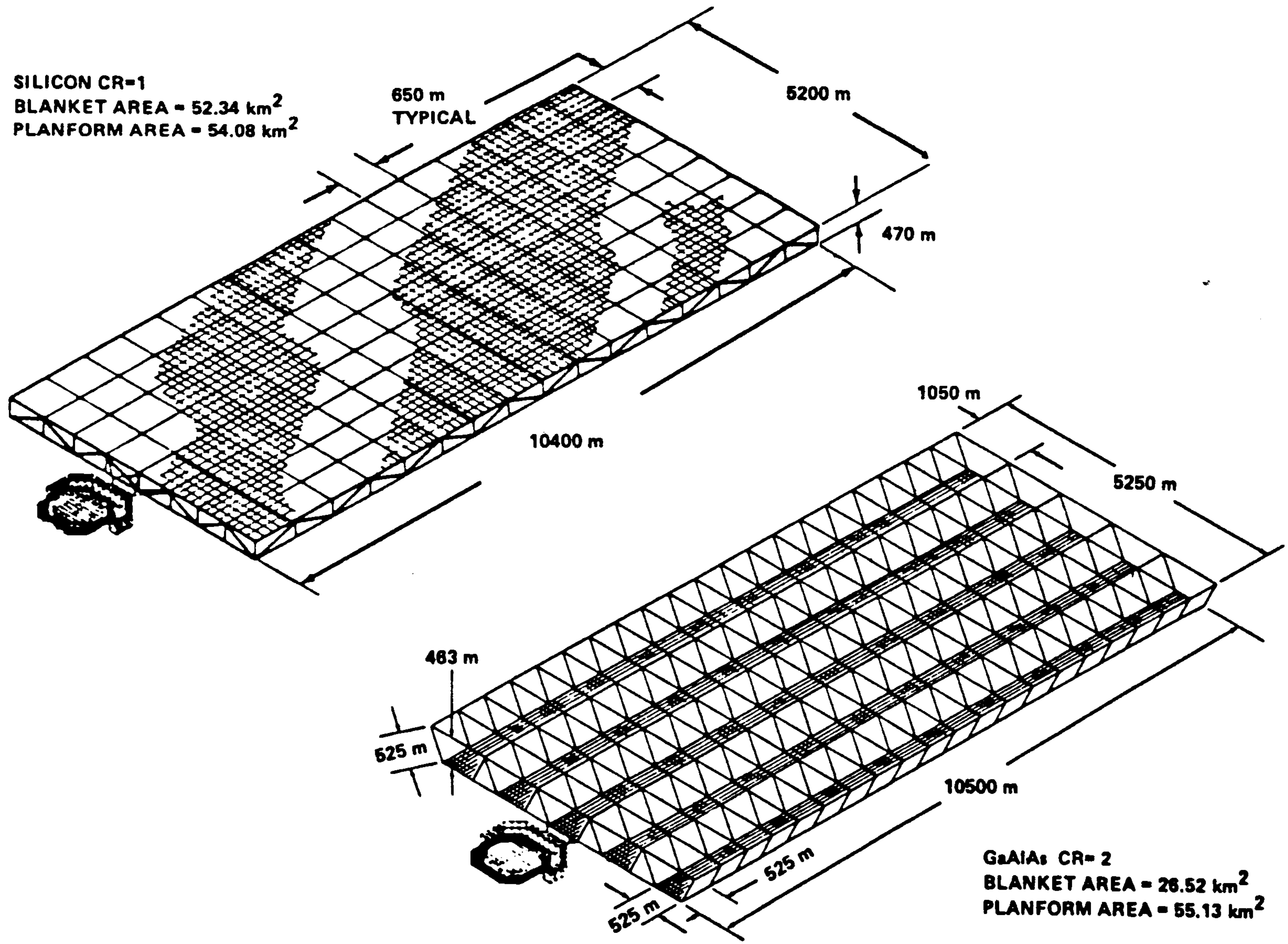


FIGURE A-1. SPS REFERENCE SYSTEM - SATELLITE CONFIGURATION

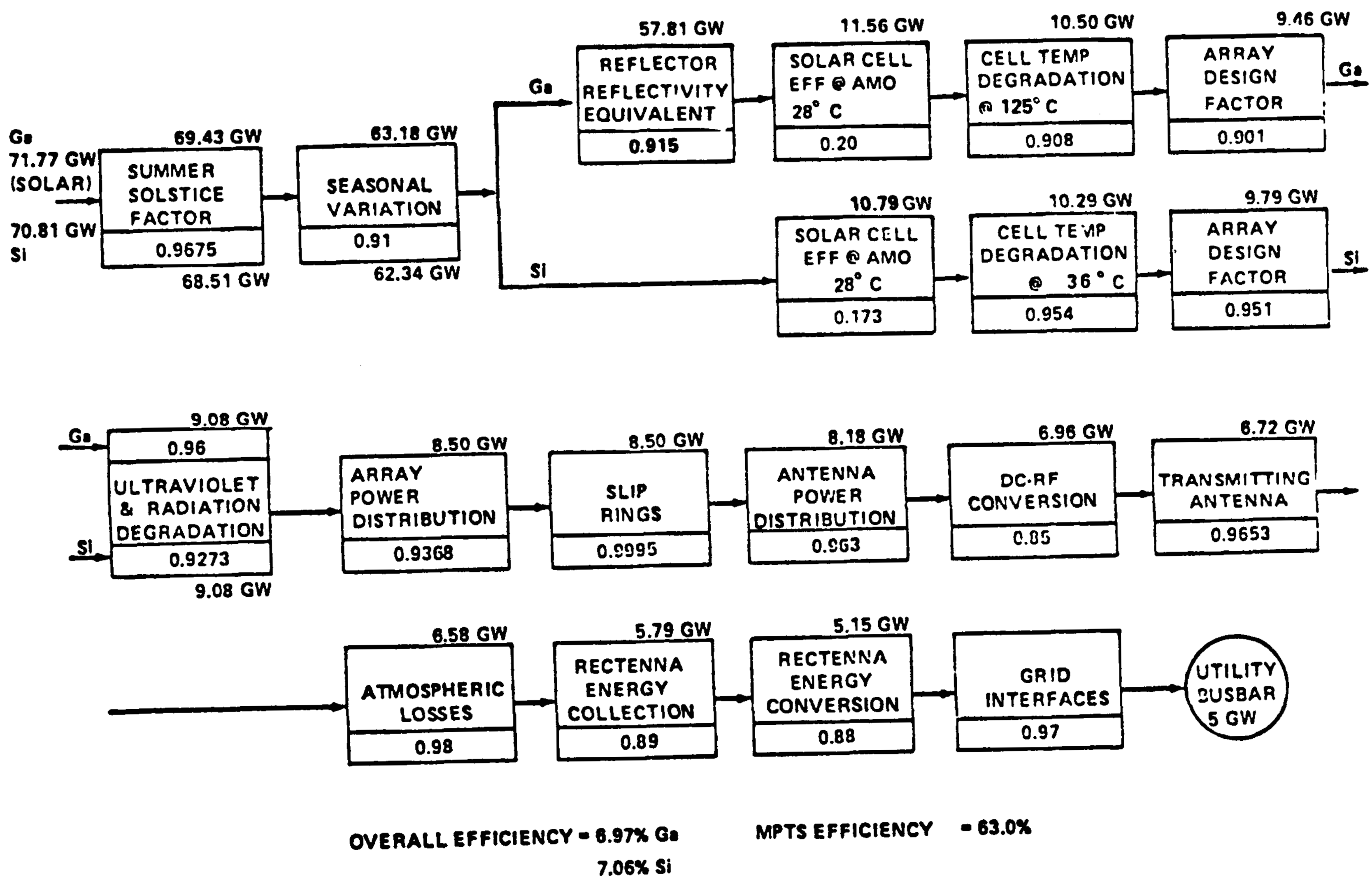


FIGURE A-2. SPS EFFICIENCY CHAIN (GaAlAs CR2 and Si CR1) summer solstice factor (0.9675), the seasonal variation (.91), and the end-of-life (30 year) solar cell efficiency assuming annealing. For the GaAlAs case, the end-of-life (30 year) concentrator reflectivity is 0.83. Since only half of the intercepted solar energy is reflected by the concentrators, the equivalent overall efficiency is 0.915.

The GaAlAs option is a five-trough configuration with a solar blanket area of 26.52 km^2, a reflector area of 53.04 km^2 and an overall planform area of 55.13 km^2. The silicon option has the solar blanket with no concentration resulting in a blanket area of 52.34 km^2 and a planform area of 54.08 km^2.

The satellite in either option is oriented so that the antenna main rotational axis remains perpendicular to the orbital plane.

The end-mounted microwave antenna is a one kilometer diameter phased-array transmitter. The phase control system utilizes an active, retrodirective array with a pilot beam reference for phase conjugation. Klystrons are used as the baseline power amplifier with slotted waveguides as the radiating element. The ground rectenna has subarray panels with an active element area of 78.5 km^2. The basic SPS Reference System Characteristics are shown in Fig. A-3.

The satellite is constructed in geosynchronous orbit with construction time projected to be six months. The initial estimates of construction crew size are 555 for the silicon option (480 in GEO and 75 in LEO) and 715 for the GaAlAs option (680 in GEO and 35 in LEO).

The transportation system is made up of four major items. These include: (1) the Heavy Lift Launch Vehicle (HLLV), the Cargo Orbit Transfer Vehicle (COTV), the Personnel Launch Vehicle (PLV), and the Personnel Orbit Transfer Vehicle (POTV). The HLLV is a two-stage, vertical launch, winged, horizontal land-landing, reusable vehicle with 424 metric ton payload to low earth orbit. The earth launch site was chosen as Kennedy Space Center pending further study. The COTV is an independent, reusable electric engine-powered vehicle which transports cargo from the HLLV delivery site in low earth orbit (LEO) to the geosynchronous earth orbit (GEO). For the GaAlAs

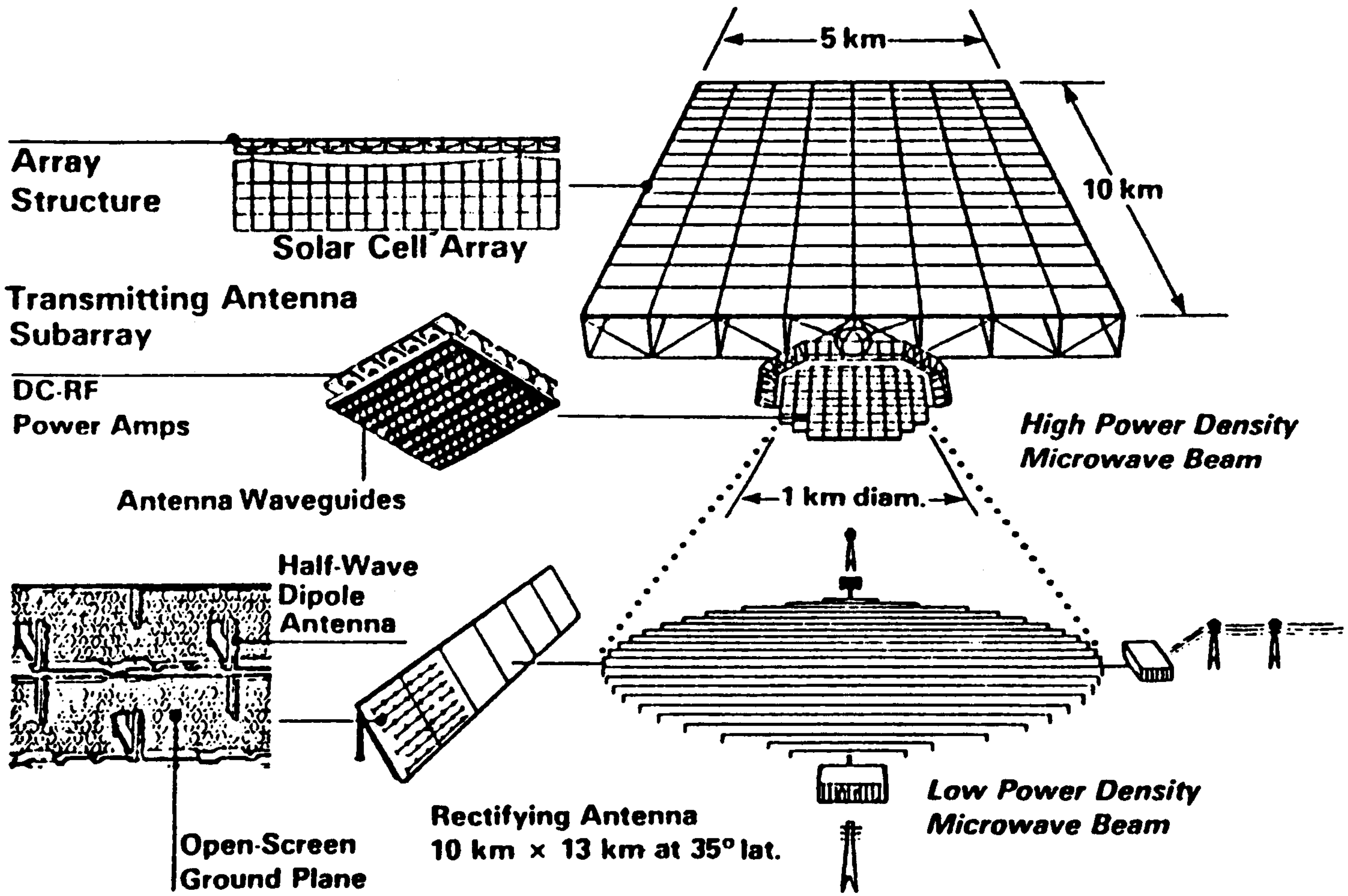


FIGURE A-3. BASIC SPS REFERENCE SYSTEMS CHARACTERISTICS

SPS option, the COTV is powered by GaAlAs solar cells, whereas a silicon solar cell power supply is used for the silicon SPS option.

Personnel for the orbital construction and support functions are transported to LEO via the PLV which is a modified space Shuttle Orbiter with a passenger module. The POTV, a two-stage reusable, chemical fuel vehicle is used to transfer personnel from LEO to GEO and return to LEO.

Table A-1 summarizes design parameters for the Reference System.

TABLE A-1. REFERENCE SYSTEM DESIGN PARAMETERS

SPS generation capability (utility interface)	5 GW	
Overall dimensions (Km)	5.3 x 10.4	
Power conversion-photovoltaic	GaAlAs (CR=2)	Silicon (CR=1)
Satellite Mass (Kg)	34×10^6	51×10^6
Structure material	Graphite composite	
Construction location	GEO	
Transportation		
• Earth-to-LEO -Cargo (payload)	Vertical take-off, winged 2-stage (424,000Kg)	
-Personnel (Number)	Modified shuttle (75)	
• LEO-to-GEO -Cargo	Dedicated elect. OTV	
-Personnel (Number)	2-stage LOX/LN_2 (75)	
Microwave power transmission		
• No. of antennas	1	
• DC-RF converter	Klystron	
• Frequency (GHZ)	2.45	
• Rectenna dimensions (Km)	10 x 13	
• Rectenna power density (mw/cm^2)		
Center	23	
Edge	1	

APPENDIX B

APPENDIX B

SPS OUTPUT POWER SCALING

The power delivered to the utility grid by the SPS may be expressed in the forms

$$P = \eta_1 I_r^\circ \beta_r A_r = \eta_1 \eta_2 I_t^\circ \beta_t A_t \qquad [1]$$

The normalized average illumination of the transmitting antenna (assuming cylindrical symmetry) is given by

$$\beta_t = 2\pi \int_{A_t} f(\rho)\, \rho d\rho \qquad [2]$$

where $f(\rho)$ is the power taper (i.e., the flux density at radius ρ, divided by the peak flux density I_t°). Once the power taper and the transmitter phase function (i.e., the focussing condition) is given, the rectenna average illumination function β_r is determined.

For present purposes, it is convenient to use a Fresnel parameter defined by

$$\tau = \pi\rho_1\rho_2/\lambda x \qquad [3]$$

which allows the product of transmitting and receiving antenna areas to be written as

$$A_r A_t = (\tau\lambda x)^2 = A_0^2\, \tau^2 \qquad [4]$$

with $A_0 = \lambda x$. It has been shown[1] that the condition for maximum power transfer between two antennas in the Fresnel zone (appropriate to the SPS) is that the transmitting antenna should be focussed on the receiver (i.e., the phase fronts emerging from the transmitter should be spherical, with radius equal to the separation x), and the power taper should have a form which depends on τ, but which can be approximated by a truncated gaussian function. There is very little absorption of the beam in the atmosphere at S-band, so the beam transfer efficiency η_2 is limited mostly by spillover around the edges of the rectenna: with the optimum power taper,

$$\eta_2 > .95 \text{ if } \tau > 2.3.$$

In most SPS studies to date, the maximum power transfer condition has been assumed, with $\tau \simeq 2.3$. The validity of this assumption is discussed below.

Combining (1) and (4) gives a relationship between the average flux densities

$$I_r I_t = \frac{1}{\eta_2}\left[\frac{P}{\eta_1 A_0 \tau}\right]^2 \qquad [5]$$

where $I_t = I_t^\circ \beta_t$, etc.

For a preliminary analysis, it is sufficient to use a simple linear deterministic cost model for those parts of the overall system whose cost depends on the transmitter and receiver areas and the output power:

$$C = \gamma_r A_r + \gamma_t A_t + \gamma_p P/\eta_1 \eta_2 \qquad [6]$$

The inclusion of the efficiencies in the last term is due to the assumption that the power-dependent cost (e.g., for the photovoltaic array) depends on the transmitter output power rather than the busbar power. It should be noted that the total cost may not be linear in the system parameters, that γ_r and γ_t may depend on I_r and I_t, respectively, and that there are many costs (e.g., construction and transportation) which can only be represented in part by this model. Neglecting these limitations, however, (1) and (4) enable (6) to be written

$$C = \left[\frac{\gamma_r}{I_r} + \frac{\gamma_p}{\eta_2}\right]\frac{P}{\eta_1} + \gamma_t \eta_1 I_r A_o^2 \tau^2/P \qquad [7]$$

For a given low power output P, there is an optimum receiver flux density

$$I_r = \left(\frac{\gamma_r}{\gamma_t}\right)^{1/2} \frac{P}{\eta_1 A_o \tau} \qquad [8]$$

and a corresponding optimum transmitter flux density

$$I_t = \frac{1}{\eta_2}\left(\frac{\gamma_t}{\gamma_r}\right)^{1/2} \frac{P}{\eta_1 A_o \tau} \qquad [9]$$

When these expressions are used in (A.1), it is found that

$$A_r = \left(\frac{\gamma_t}{\gamma_r}\right)^{1/2} A_o \tau \qquad [10]$$

and

$$A_t = \left(\frac{\gamma_r}{\gamma_t}\right)^{1/2} A_o \tau \qquad [11]$$

so that, as one would expect, the optimal transmitter and receiver areas are independent of the power. The optimization condition is simply that the transmitter and receiver be sized, subject to the restriction (4), so that they cost the same. The optimum cost is then

$$C = 2(\gamma_r \gamma_t)^{1/2} A_o \tau + \gamma_p P/\eta_1 \eta_2 \qquad [12]$$

Note that the optimum flux densities (8) and (9) increase with the power. This analysis is thus applicable only if the power is so low that the flux densities do not exceed limits due to atmospheric, engineering, environmental or arms-control considerations. For the microwave SPS, as the power is increased (with a given value of τ and the corresponding optimum value of η_3), it is found that the first limitation to be encountered is that due to the ionospheric flux density. Thereafter, if the optimum power transfer condition is maintained, the cost curve follows (7), with I_r fixed.

The limitation due to the transmitter flux density may be found by substituting from (1) and (4) in (6), to give

$$C = \left[\frac{\gamma_t}{I_t} + \gamma_p \right] \frac{P}{\eta_1 \eta_2} + \gamma_r \eta_1 \eta_2 I_t A_0^2 \tau^2 / P \qquad [13]$$

with I_t fixed.

Figure 1 shows three curves of specific cost (dollars/watt), obtained by dividing (7), (12) and (13) by P. In the low-power regime, the region accessible without violating the received-flux constraint lies between the optimum and fixed-I_r curves; after the curves touch, the optimum flux is above the limit, so only the region above the fixed-I_r curve is accessible. However, the fixed-I_t curve bounds the accessible region from above (at least, out to the power where this curve touches the optimum curve). The accessible region is thus that shown cross-hatched. Beyond the point where the two flux-limit curves cross is a region which can be reached only by increasing the product A_rA_t above the diffraction limit (i.e., by increasing τ above the value required for optimum power transfer).

In constructing these curves, the following representative values were used:

γ_t = 1900 \$/m²	γ_r = \$42 \$/m²	γ_p = 600 \$/kw
I_t = 7.7 kw/m²	I_r = .077 kw/m²	(Note that these are average values)
η_1 = 0.89	η_2 = 0.93	

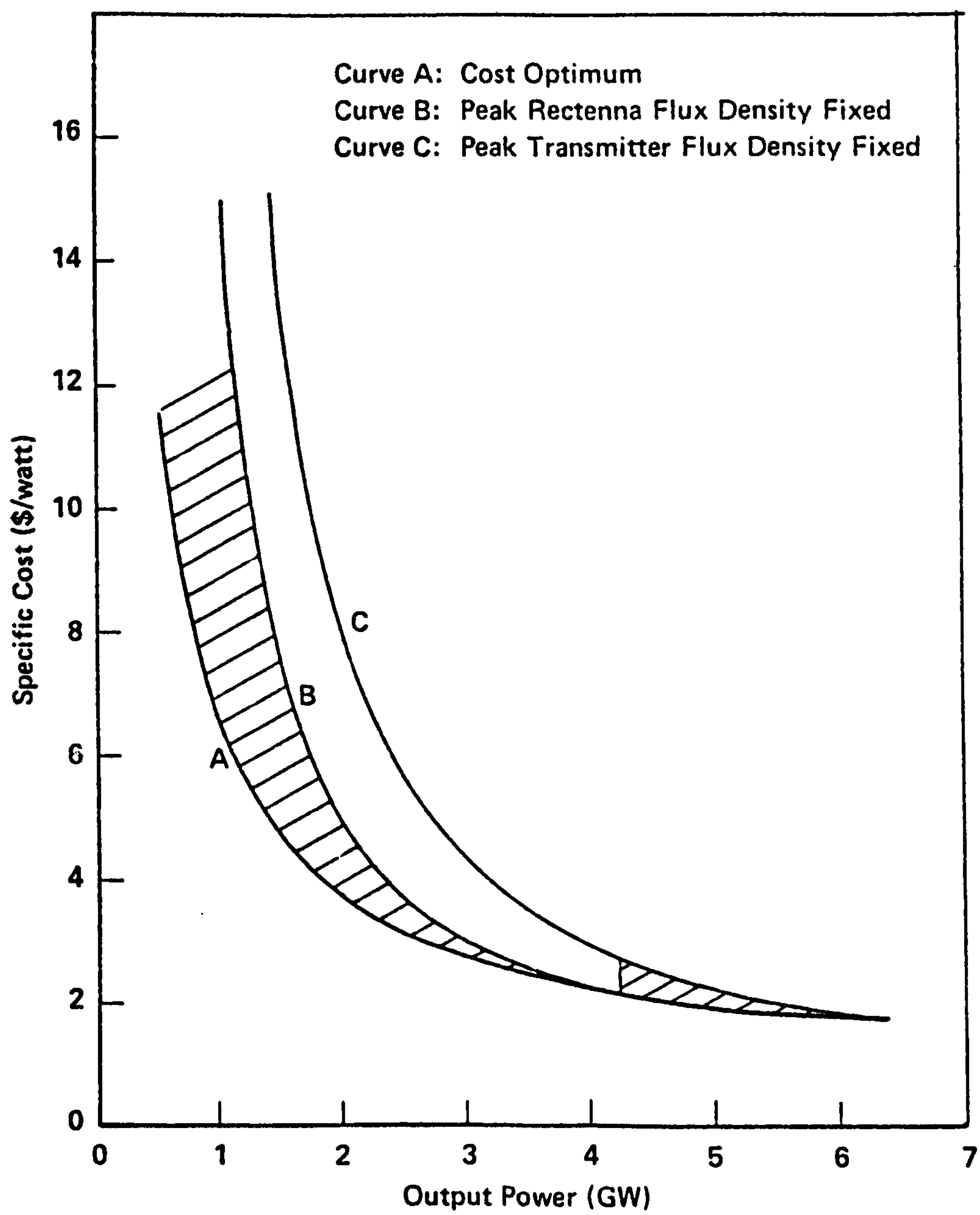
Other values would of course change the curves, but the general behavior remains the same.

According to the figure, use of the optimum values of A_r and A_t, as given by (10) and (11), would minimize the cost penalty involved in building a system with an output below about 4 GW, but the cost still increases rapidly as the power is reduced below about 2.5 GW.

There are, however, serious deficiencies in this analysis, arising from the assumption of a fixed value for τ and a corresponding unconstrained optimum power taper. This condition is at least possible at low power, but, once a flux constraint is encountered, it is clear that the optimum power taper should be derived by a variational analysis *subject to that constraint*. As τ is increased, the unconstrained optimum shrinks the ground diffraction pattern, leading (for a given power) to increasing values of the central flux. This behavior cannot be corrected by imposing the flux constraint ex post facto: in fact, it is intuitively clear that, for large τ, the optimum ground flux distribution, with the constraint imposed, approaches a top hat shape.

Figure 5.5

SPS Power Output Scaling



In any case, the objective of the optimization is not to maximize the power transfer for a given τ, but to minimize the cost. In the low power regime, where flux constraints are not encountered, the cost optimum condition may be found by differentiation of (12) with respect to τ; using (8), the result may be expressed in the form

$$\tau \eta_2'/\eta_2^2 = 2\gamma_r/\gamma_p I_r \qquad [14]$$

where $\eta_2' = d\eta/d\tau$ 2. Even if I_r, is given its maximum value for this regime (i.e., the flux limit), the solution to this equation[2] (with the cost parameters given above) is $\tau \cong 1.5$, with a corresponding beam collection efficiency $\eta_2 \cong 0.85$. In other words, it is worth wasting some power as spillover to reduce the transmitter and receiver areas.

The situation is considerably more complicated in the flux-limited regime. Writing $I_r = I_r^o \beta_r$ in (7), the variational problem is to find the transmitter power and phase tapers which minimize this expression, subject to a fixed value for I_r^o. The optimum value of τ will of course emerge in the course of this calculation, and the results will depend on P. A similar calculation with I_t^o fixed will give the specific power cost under this limitation.

This variational problem has not yet been addressed, so it is not yet possible to assess the error involved in assuming the unconstrained optimum power taper and choosing τ for very high efficiency. It is at least possible that the optimum power output will have a lower value, and, even more importantly, it seems probable that the penalties involved in operation at lower power will be reduced. In view of the importance of lower unit powers, it is highly desirable that this calculation be undertaken. using a more accurate cost model than that employed here.

Once the constrained variational problem has been set up, it should not be difficult to extend it by imposing a limit on the flux density in first side-lobe of the beam, which would allow assessment of the cost of meeting limits on long-term public exposure.

There are at least two other approaches to reducing the effective power output of the SPS. The first of these, due to Maynard,[3] is the use of a larger transmitting antenna to feed a number n of smaller rectennas. Within the limits of the above fixed-τ analysis, it has been shown[4] that each of the n rectennas should have an area which is reduced by the factor $\sqrt{n}$ (so that, for fixed I_r, the power from each rectenna is reduced by the same amount) and the area of the transmitter should be increased by the same factor. Since the total power from the photovoltaic array increases correspondingly, the transmitter flux density remains essentially the same (although the phase taper is complicated, to allow transmission to several locations simultaneously). One of the possible advantages of this system is that it increases the size of individual satellites, thereby reducing possible congestion in GEO.

The other approach which requires investigation is the use of laser power transmission. The above analysis is applicable to this case, except that the transmission efficiency may be significantly affected by atmospheric absorption. The optimum cost is thus given by an expression like (12). It is clear that the first term can be neglected (i.e., the cost of the transmitting and receiving apertures is negligible compared to the power-dependent cost) if

$$P \gg 2\eta_1\eta_2 \left(\frac{(\gamma_r\gamma_t)}{\gamma_p}\right)^{1/2} A_o\tau \qquad [15]$$

From (8), this will be the case if

$$I_r \gg 2\eta_2 \gamma_r / \gamma_p \qquad [16]$$

It is a fairly safe assumption that, for laser systems and associated power supplies, $\gamma_p >$ \$1/watt. The value for γ_r depends on the type of energy conversion which is used in the receiver: a reasonable value is $\gamma_r \leq 250/m^2$. The transmission cost may thus be neglected if

$$I_r \gg 500 \text{ watts/m}^2 = 50 \text{ mW/cm}^2 \qquad [17]$$

By laser standards, this is an extraordinarily low flux density — it corresponds to the surface flux from a black body at only 300 °K.

Assuming that γ_t is an order of magnitude greater than γ_r (because the transmitter must be diffraction limited and is located in GEO), the optimum transmitter and receiver areas are given by (10) and (11) as

$$A_t = 260 \text{ m}^2 \qquad A_r = 2600 \text{ m}^2 \qquad [18]$$

for λ = 10 microns (which precludes use of photovoltaics in the receiver). The corresponding transmitter and receiver diameters are

$$D_t = 18 \text{ m} \qquad D_r = 58 \text{ m} \qquad [19]$$

which are certainly modest. In order that the aperture costs may be relatively small, the power output is given by (1) and (17) as

$$P = \eta_1 I_r A_r \gg 650 \text{ kw} \qquad [20]$$

Despite the uncertainties in this elementary analysis, it seems virtually certain that the laser SPS need not be scaled by reference to the laser power transmission system (LPTS), and that it will be possible to build the system with very low unit powers. Even though the laser SPS may not be competitive with the microwave SPS at high powers, its favorable scaling characteristics may make it the system of choice where low power is desired and interruptions due to clouds are infrequent and tolerable.

The laser SPS may also provide a means for building a small-scale SPS demonstrator in GEO, without excessive commitment of resources.

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