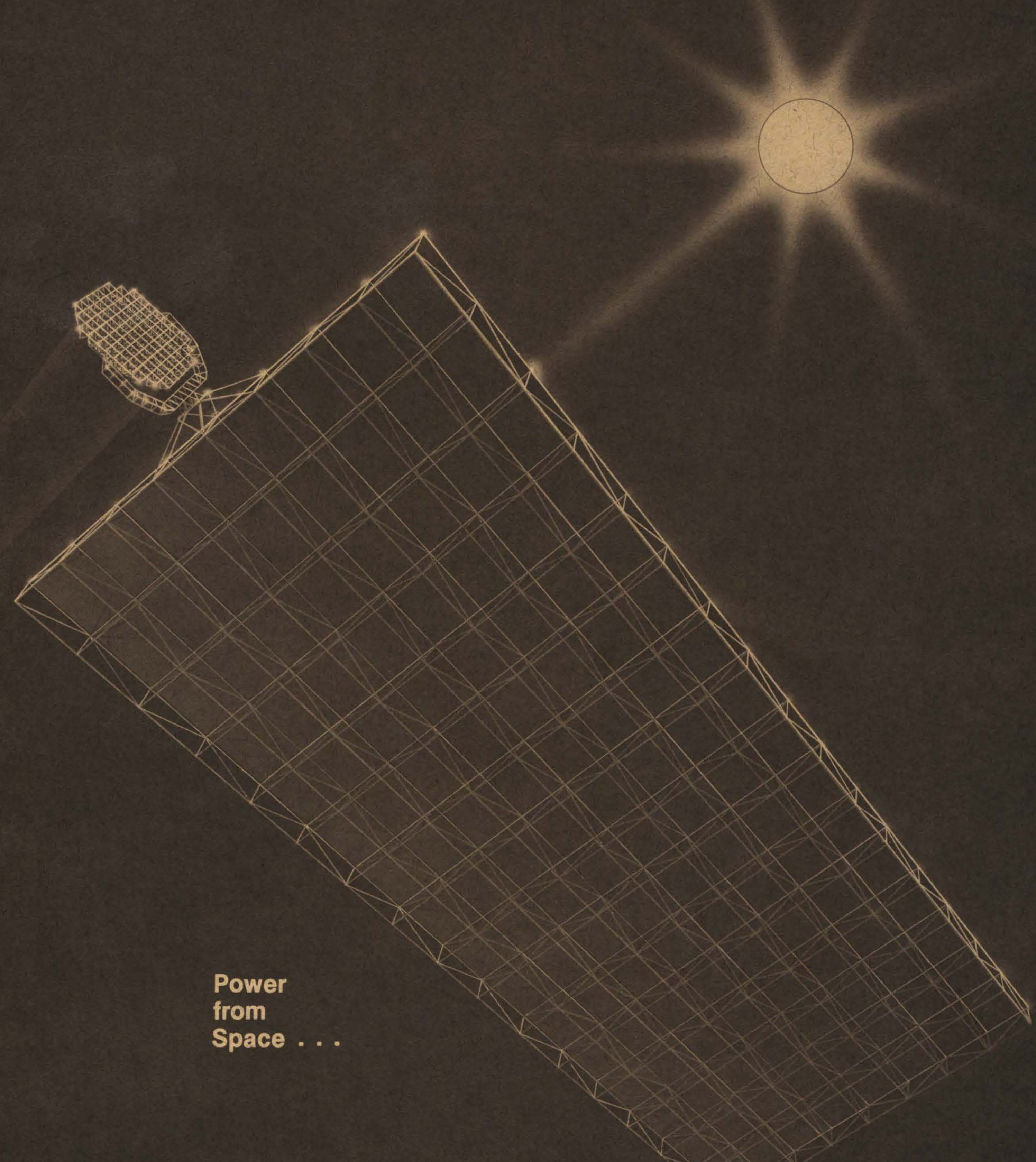
NASA

Solar Power Satellite



Power from Space . . .

a new opportunity

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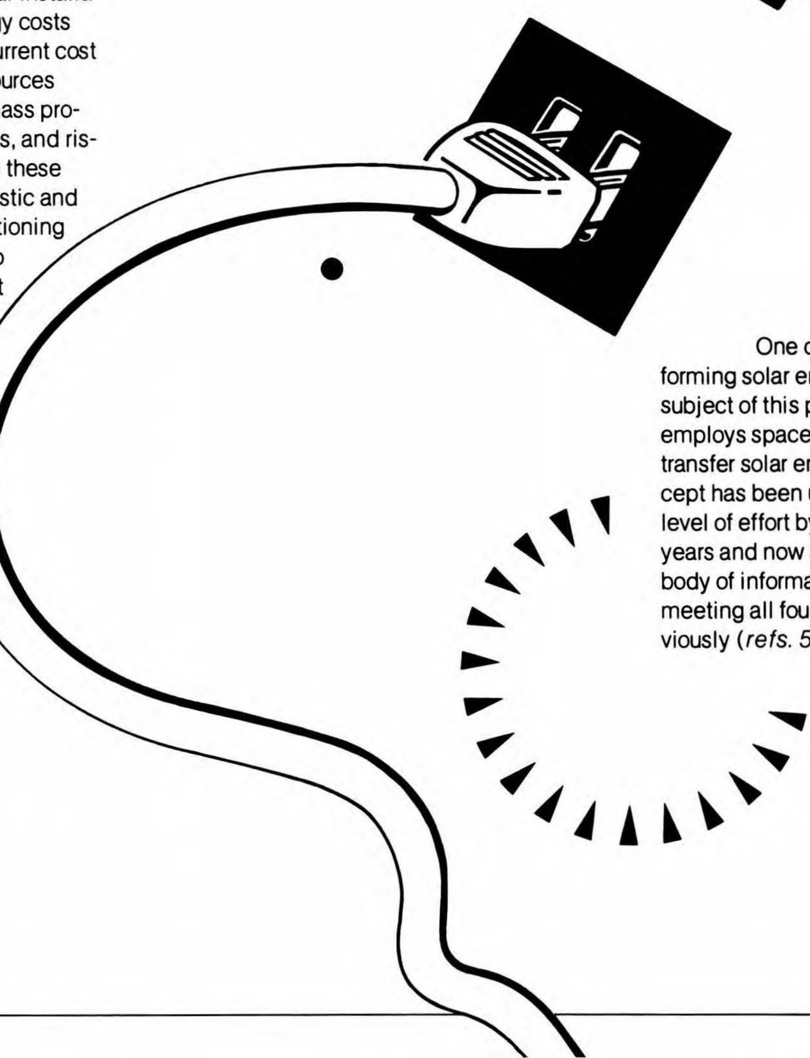
Introduction

Conservation, rapid development of known and new fossil fuel deposits, and refinement of nuclear fission reactors will play dominant roles in meeting the needs for primary energy for the remainder of this century (*ref. 1*). Inevitably, however, mankind must turn to new sources, preferably nondepletable sources, for much of his energy. Material resources, such as natural gas, will eventually prove to be of more value for the products they yield than for use as fuel. The search for nondepletable energy sources of sufficient potential contribution is therefore of vital importance to avoiding long-range energy shortages. For example, nuclear fusion research is progressing in the scientific laboratories of the world. The difficult plasma-containment problems may eventually be resolved sufficiently to permit large-scale replication on Earth of the fusion process which drives the Sun.

Direct engineering application of the solar energy potential is beginning, with major emphasis upon low-temperature heating of water and air, and lesser emphasis upon the more difficult and larger challenge of supplying a part of the industrial energy supply. The amortization of capital costs for many of the existing demonstration solar installations has resulted in true energy costs significantly higher than the current cost of energy from conventional sources (*refs. 2 and 3*). Tax credits, mass production, distribution economies, and rising fuel prices should increase these uses of solar systems for domestic and light-commercial space conditioning and thus permit this source to make a modest but important contribution to the total energy supply in the near future (*ref. 4*). The conversion of solar energy into baseload electricity at centralized generating plants will also be necessary if solar energy is to support the energy density of our industrial structure.

If the solar energy systems are to capture a significant portion of the investment in new electrical power generation capacity, the power generation concept should fulfill several criteria:

- Provide nonintermittent, baseload power
- Provide power at costs which are competitive with alternative sources
- Be nonregional in its geographical availability and cost
- Be environmentally acceptable



One of the options for transforming solar energy into electricity is the subject of this paper. This concept employs space satellites to collect and transfer solar energy to Earth. The concept has been under evaluation at a low level of effort by NASA for the past 4 years and now appears, from this limited body of information, to hold promise of meeting all four of the criteria cited previously (*refs. 5 and 6*).

System Concept

The solar power satellite (SPS) concept is illustrated in figure *1*. A large solar collector is located in space, some 35 800 km (22 000 s. mi.) above the Earth in geosynchronous, equatorial orbit. The period of this orbit is 24 hours; therefore, the satellite remains apparently fixed relative to a location on Earth.

Solar energy is received by a satellite at this altitude essentially full time, without attenuation by the atmosphere and cloud cover. During predictable days near the equinox, the satellite is shadowed from the Sun by the Earth for an interval of as long as 75 minutes, centered on midnight.

Six to fifteen times more sunlight falls annually on a collector in space than on a similar sized collector on Earth. Operation of the capital equipment thus is maximized. Of equal importance, the space collector provides baseload electrical power nearly continuously without expenditure for and losses of massive energy storage systems. Energy conversion losses of the SPS are encountered primarily in space. The waste heat of conversion is radiated to space directly rather than altering the thermal balance of the Earth as do fuel-burning plants.

Because microwave transmission of the power to the ground is unaffected by cloud cover, a high degree of geographical flexibility is provided for the location of receiving stations within the temperate and tropical zones of Earth.

The near-continuous access to sunlight provided by the high-orbit location and the freedom from atmospheric and cloud-cover influences are the basic advantages of the solar power satellite. These advantages must be evaluated considering the costs of deploying the solar collector in space and of providing the microwave power-transmission link to Earth.

Numerous studies of the concept have been made by industry and government agencies during the past four years. The results of one of the more recent studies, conducted under contract to the NASA Lyndon B. Johnson Space Center by the Boeing Company (*ref. 7*), are summarized here.

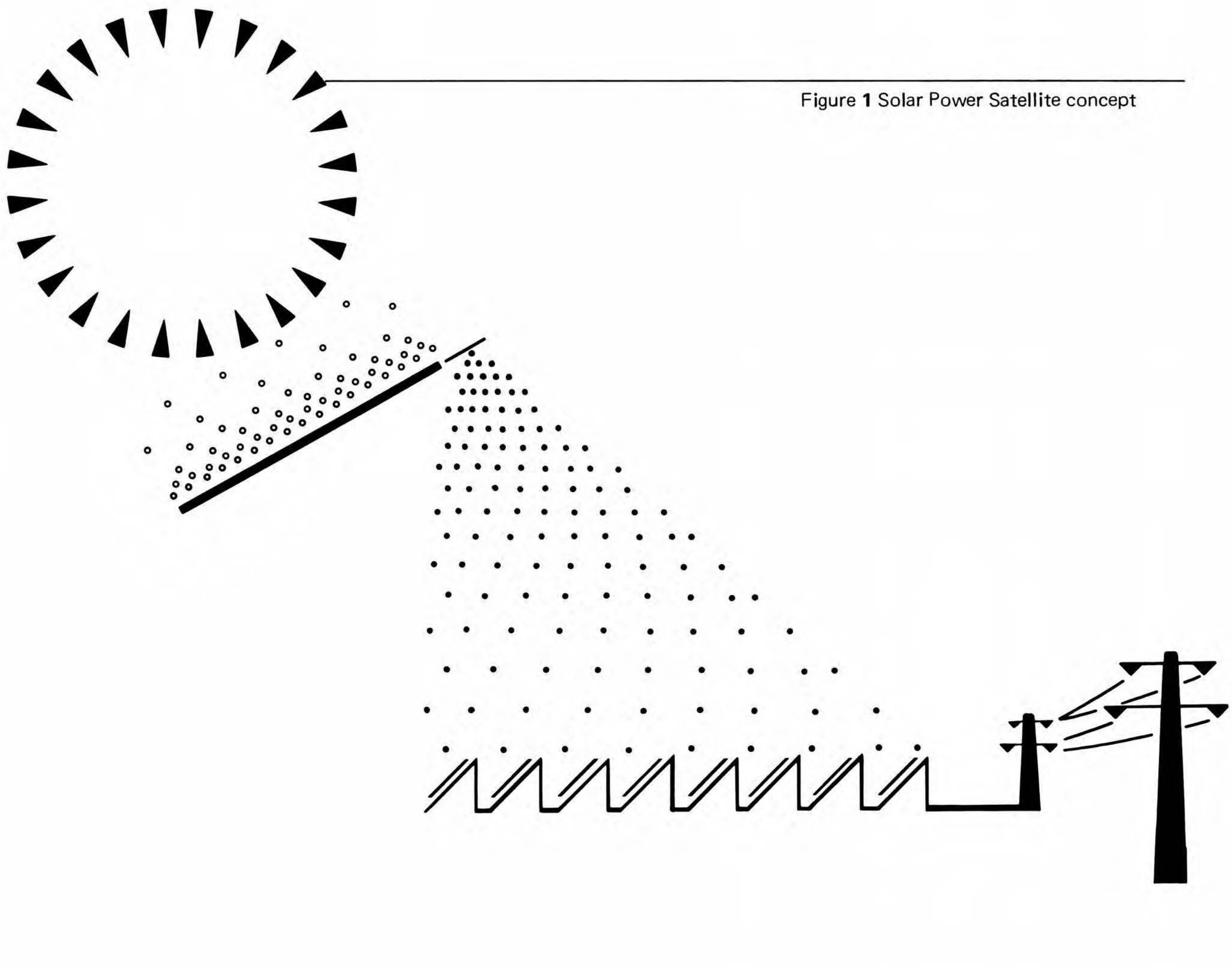


Figure **1** Solar Power Satellite concept

System Description

Figure **2** illustrates a typical system configuration for the solar power satellite. This space system provides a total of 10 000 MW of electrical power to the ground receiving stations for introduction into the electrical power grid. Five thousand megawatts of either conventional alternating-current (ac) power or high voltage direct-current (dc) power is distributed to the grid from each of two ground stations which share the power output of a single satellite. The two transmitting antennas may be directed to ground stations separated by half a continent. This twin-transmitting-antenna arrangement of the satellite is not imperative, but it is convenient to "balance" the spacecraft and thus reduce the orbit-keeping propellant requirements and may be advantageous to the power grid operation. The configuration may be thought of as two independent, 5000-MW-output satellites coupled together in geosynchronous orbit.

The large size (5 by 25 km) of the satellite is related to its large power output capacity. Additional studies are now underway to determine the cost-effective size and general arrangement. As a part of these studies, the projected requirement for large electrical power "parks" of this size class in the year 2000 and beyond will be explored. The mass of the completed 10 000-MW solar power satellite is now estimated to be slightly less than 100 000 metric tons, including a 20% growth allowance. The size and mass of this satellite will require multiple-launch-vehicle flights and development of the new art of construction in space.

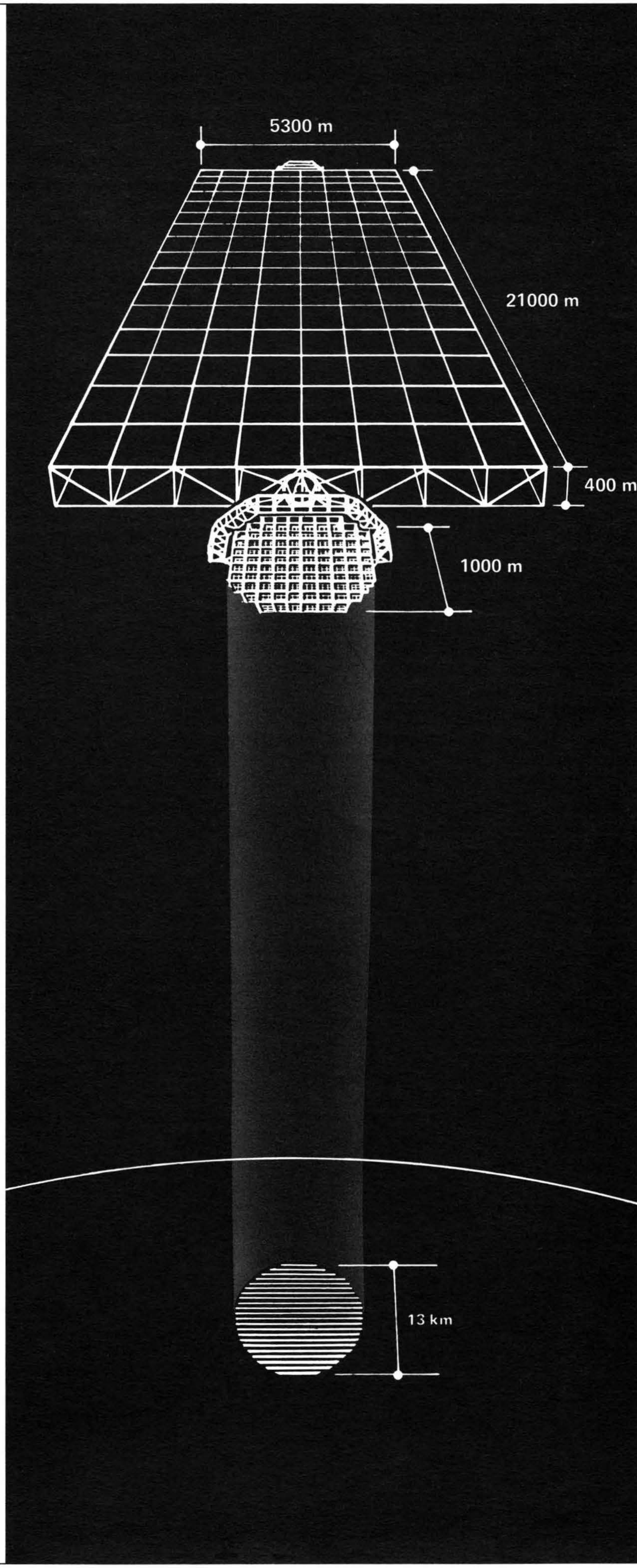


Figure **2**
Typical system configuration

The solar collector illustrated by figure **2** contains single-crystal silicon solar cells operating at a basic cell efficiency of 15.75% at 25° C. The effective solar-blanket output is 13.35% of the 1353 W/m² available from the Sun, or 180.6 W/m², operated at 36.7° C (98° F).

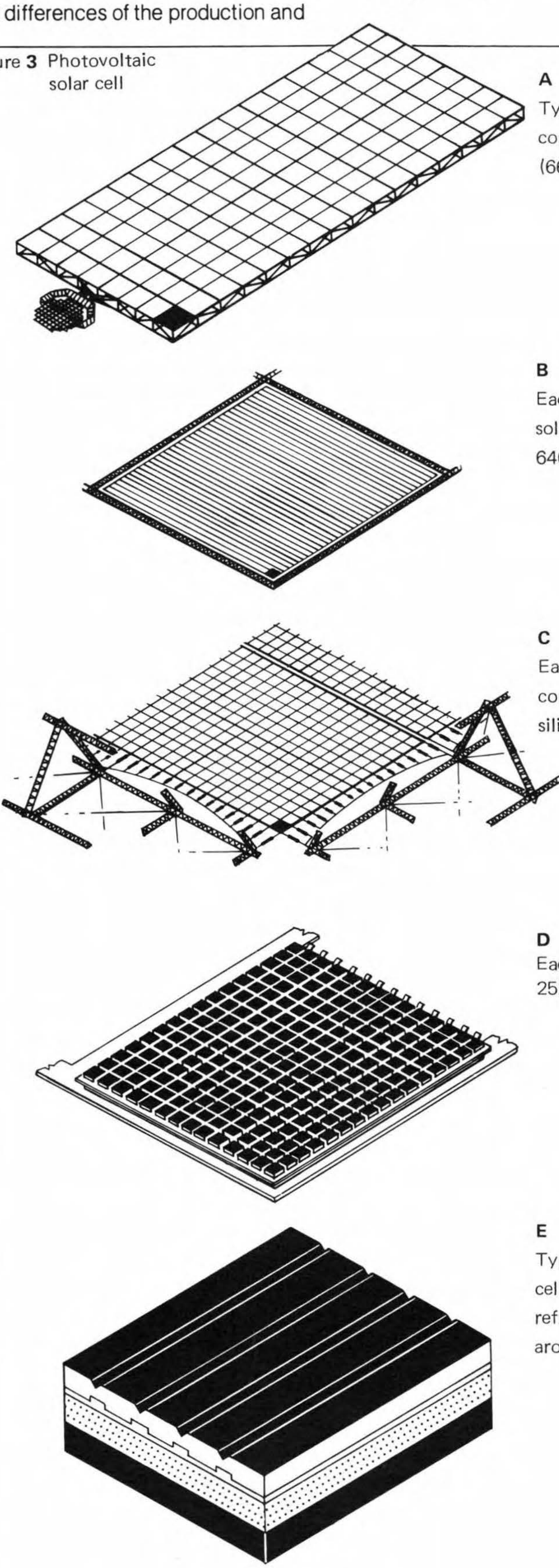
The balance of the energy of the incident sunlight is reflected, transmitted through, or dissipated by radiation from the solar blanket to space. The conversion losses of the power collection and conversion system of the SPS do not interact with the biosphere, an advantageous distinction from any fuel-fired energy converter.

Other energy conversion systems have also been considered for the solar power satellite, including thermal cycles using reflector arrays to concentrate the sunlight on a boiler surface integral to the spacecraft, coupled to turbine-driven generators and space radiators. In the photovoltaic device category, the gallium arsenide cell offers higher efficiency, less degradation of output at high temperature and less susceptibility to damage by the natural radiation in space than does the more common single-crystal silicon cell. The disadvantages of gallium arsenide cells are uncertain availability of gallium in the quantities needed for a large SPS program and a present lower state of development than silicon cells. Other promising photovoltaic cell candidates include thin-film cadmium sulfide and polycrystalline silicon cells. One intriguing possibility is a solar cell "sandwich," which exploits the selective spectral absorption of gallium and silicon cells to produce a composite cell that may achieve a conversion efficiency between 30% and 40% (*ref. 8*).

These more advanced photovoltaic approaches may prove to be preferable to silicon cells for the SPS and may result in significant reductions in the projected weight and cost of the satellite.

Current JSC studies assume that single-crystal silicon cells, with borosilicate glass covers and substrates, will be employed for the SPS. This cell is illustrated in figure **3**. About 2×10^{10} cells, each 6.5 cm by 7.5 cm by 0.175 mm (2.6 in. by 2.9 in. by 7 mils) are required for each 10 000 MW satellite. The photovoltaic cell challenge is therefore largely one of developing highly automated production techniques for lightweight, low-cost cells. The current Department of Energy (DOE) photovoltaic development and demonstration projects are expected to generate significant advances, within the next 6 or 7 years, in the cost-effective high-rate production of silicon cells for terrestrial application. The similarities and differences of the production and processing of solar cells for space and terrestrial application have not yet been determined.

Figure **3** Photovoltaic solar cell



A
Typical 5-GW satellite is composed of 128 bays (660 m²)

B
Each bay consists of 32 solar blankets (20 m by 640 m)

C
Each solar blanket is composed of 448 silicon panels

D
Each panel is made of 252 silicon solar cells

E
Typical silicon solar cell has grooves to refract sunlight around conductors

Since the energy collected and converted to electricity aboard the satellite is for use by the terrestrial power grid, a high-efficiency power-transfer technique is required. In choosing the 2.45-GHz microwave power-transmission link, considerations were link efficiency, equipment mass, thermal dissipation, cost, and environmental effects. The present microwave system has dc-to-radio frequency (rf) power converters feeding a 1-km-diameter phased-array transmitting antenna. The antenna is designed to provide a tapered illumination across the array surface. The antenna is composed of about 7000 subarrays, each about 10 m on a side, having slotted waveguides as the radiating surface with dc-rf power tubes mounted on the back side of the antenna.

Each transmitting-antenna subarray has its own rf receiver and phasing electronics to process a pilot-beam phasing signal emanating from the Earth-based (and controlled) receiver station. The subarrays are phased together in response to the pilot-beam signal to provide a single coherent beam focused at the center of the ground antenna/rectifying system (rectenna). This power beam contains about 88% of its energy within a 5-km radius of boresight, at Earth distance.

These transmitter characteristics are compatible with the selected ground receiver, or rectenna, parameters. The rectenna (*fig. 4*) has an active panel area of about 75 km^2 (30 s. mi.^{2}) consisting of a series of serrated sections perpendicular to the incident beam. Each section is composed of a structural support system, a wire mesh screen opaque to microwave energy but with 80% optical transparency, and half-wave dipole antennas feeding Schottky barrier diodes. Filters between the dipoles and diodes suppress the generation of harmonics and assure clean dc power output from the rectenna.

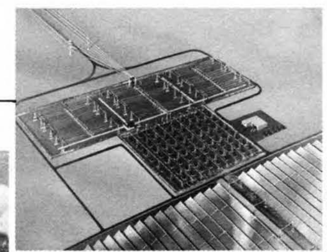
These parameters of the microwave beam were established by:

1. Thermal limitations of 22 kW/m^2 output of the transmitter array
2. Peak power in the ionosphere of 23 mW/cm^2 to preclude nonlinear heating of the ionosphere which could interfere with communications
3. rf power levels incident on the rectenna which are sufficient for efficient reception.

The dc-to-dc efficiency of this microwave power link has been the subject of highly detailed analysis, and the efficiency of this link is now expected to exceed 60%. Tests conducted in 1975-76 by the NASA Jet Propulsion Laboratory (JPL) at the Goldstone, California, deep-space tracking radar site have demonstrated the reception efficiency of the prototype rectenna elements to be 82% (*fig.* **5**). Laboratory tests at Raytheon in 1975 demonstrated 54% dc-to-dc efficiency of a complete microwave power link at bench scale with relatively undeveloped components (*ref. 9*). Boeing and Varian have recently completed a design study of high-power klystron tubes for the transmitter, defining a tube producing 50 to 70 kW of 2.45-GHz power with a predicted efficiency of 83.6%. The 70-kW rf power tubes are predicted to weigh about 50 kg (110 lb) each. About 100 000 such tubes are required for each of the two transmitting antennas of a 10 000-MW SPS. An alternative dc-to-rf converter is the amplitron. Both devices may be displaced before final SPS design selection by high-power solid-state dc-to-rf converters with lower cost, lighter weight, and essentially maintenance-free characteristics.

The peak power densities at the ground are limited by the design to 23 mW/cm^2 at the rectenna boresight. At the edge of the rectenna, the power density decreases to 1 mW/cm^2. This level is an order of magnitude below the U.S. continuous exposure standard of 10 mW/cm^2. For comparison, the intensity of the natural solar flux at ground level is about 100 mW/cm^2 and microwave oven door seals are permitted external leakage as great as 5 mW/cm^2.

If a total failure occurs within the SPS phase control system, the total beam will be defocused and the power level reduced to 3 μW/cm^2. The rf power-transmission system therefore is inherently fail-safe and under control of the people on the ground who transmit the pilot beam.



Detail view of busbar

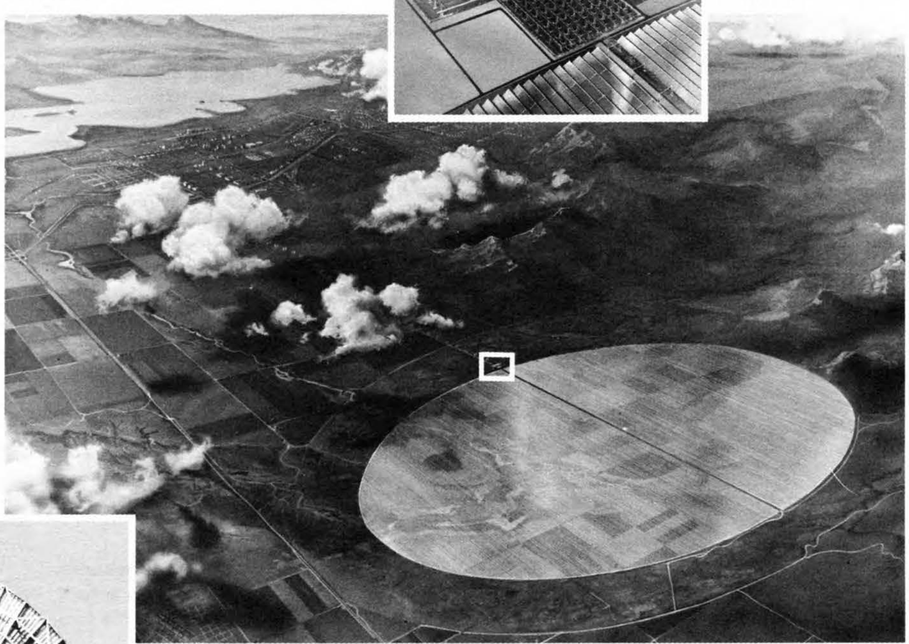


Figure **4** Rectenna

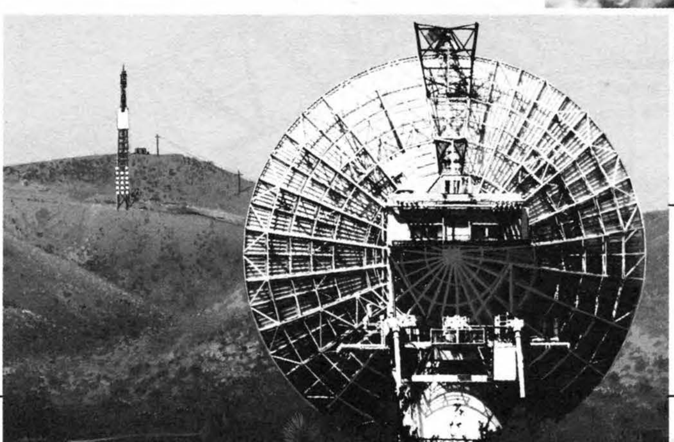


Figure **5** NASA Jet Propulsion Lab Goldstone, California

Construction in space of the large structures required by the SPS is a problem which is obviously formidable in scale but has been found to be amenable to analysis in the studies conducted to date. Concepts have been developed for automated construction techniques which are now believed to be capable of completing a satellite within 1 year. Space construction requires protection of the work force from the hard vacuum, intense sunlight and natural radiation fields. Space is however, an environment that, in many ways, is ideal for the construction process. First, because of the absence of significant gravitational forces, the structural loads are minute when contrasted with terrestrial or aircraft structures. Structural members may therefore be much lighter than terrestrial structures of the same span and stiffness. Second, the absence of gravitational forces in Earth orbit greatly facilitates the movement of material and equipment. Movement of material absorbs a large portion of the total work by personnel and machines involved in terrestrial construction. Third, the absence of an atmosphere, with its attendant wind loads, inclement weather, and unpredictable change, permits work to be planned and executed readily and without interruption. No protection would be necessary from wind loading, corrosion, or water infiltration.

Since repetitive operations are more readily automated, regular, uniform-cross-section structural members are planned for use in construction of the SPS. The basic structural element of the SPS is shown in figure **6**. A process similar to the familiar roll-forming of light sheet metal members has been adapted to the space environment and can produce these structural members at a rapid pace. These basic structural members may be produced from coils of aluminum strip stock or from a graphite/thermoplastic "pre-preg" roll (*ref. 10*). The latter material has the advantages of high modulus and low coefficient of thermal expansion. The basic structural element of the satellite, a triangular cross-section shape about 30 cm (12 in.) on a side and 0.96 mm (38 mils) thick, may be assembled into primary structure triangular trusses about 7.5 m (25 ft) on a side, as shown on figure **7**. These members are then assembled into a trussed box structure with 670 - by 670-m bays 470 m deep (2200 by 2200 by 1500 ft) for the structural support of the solar-blanket membrane.

Similar structural elements are assembled into a tighter structural configuration (104-m (340 ft) bays) for the microwave transmitter structure to achieve the necessary stability and surface flatness for operation of the phased-array rf system.

Two orbital locations for the primary construction activities in space are under consideration. The first is a low Earth orbit at about 500 km (about 300 s. mi.) altitude. This orbit provides the advantages of close proximity to Earth and sharing, with Earth, the protection from space radiation provided by the trapped radiation (Van Allen) belt. Gravitational attraction varies with altitude, so that very large structures built in low Earth orbit must overcome "gravity gradient" torques during construction and transit. To lessen these torques, low-altitude construction of the SPS in 8 to 16 modules was recommended, with final joining of the modules (berthing) at the high-altitude, geostationary operational orbit.

Delivery of the construction materials in packaged form directly to the geostationary orbit offers the construction process the advantages of continuous sunlight, decreasing the thermal effects upon the structure under construction and reducing the need for artificial illumination of the workplace. Additionally, the construction process can be designed to produce the SPS in its final operational form, eliminating the berthing operation.

The number of persons involved in the construction process is a function of the degree of automation employed. The size of the staff also depends on judgments as to the amount of maintenance the construction equipment will require. Present estimates are that about 500 persons, including support personnel, will be needed in orbit to support SPS construction at the rate of 10 000 MW of new capacity per year. Contrary to possible first impressions, cost analyses have indicated that the SPS system cost is relatively insensitive to crew size in space.

Figure **6** Typical Structural Beam Element

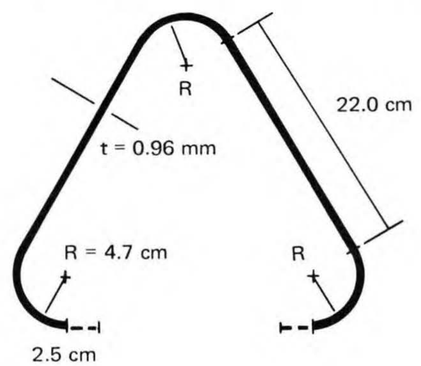
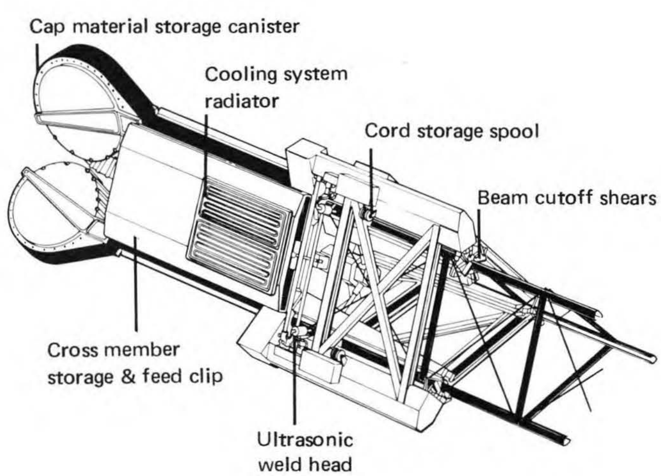
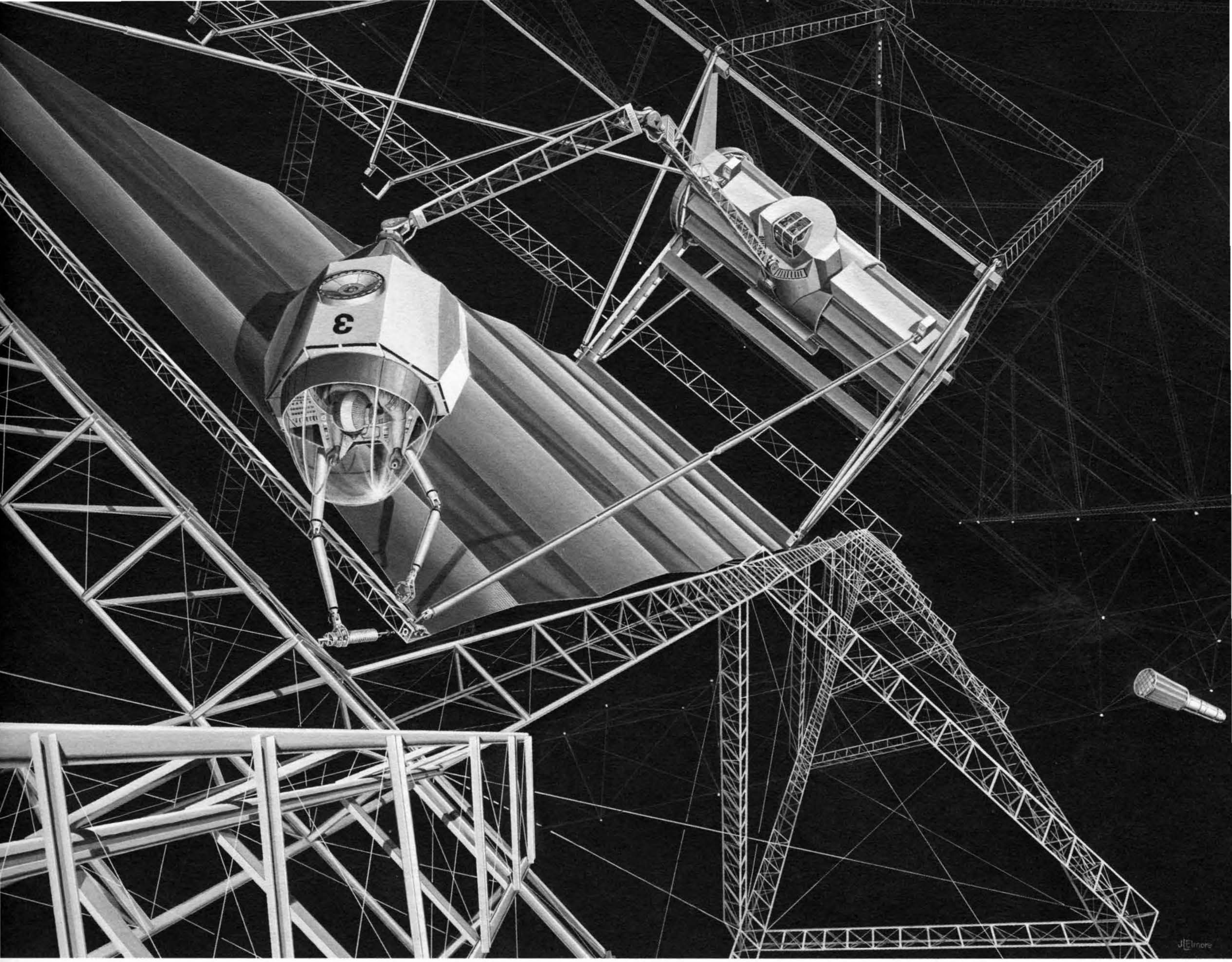


Figure **7** Beam construction

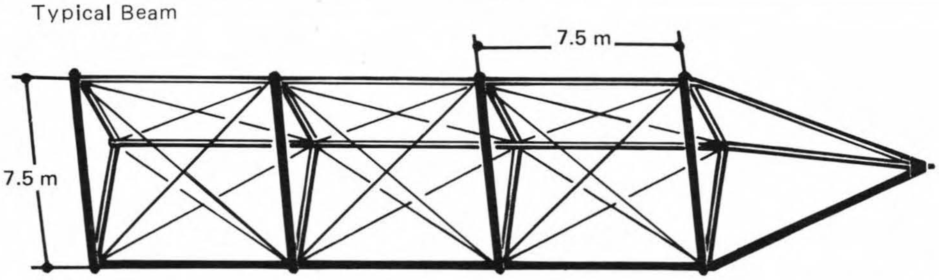
▼ Automated beam builder

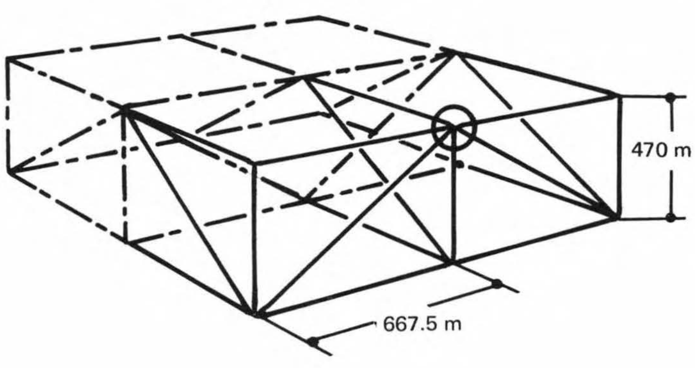


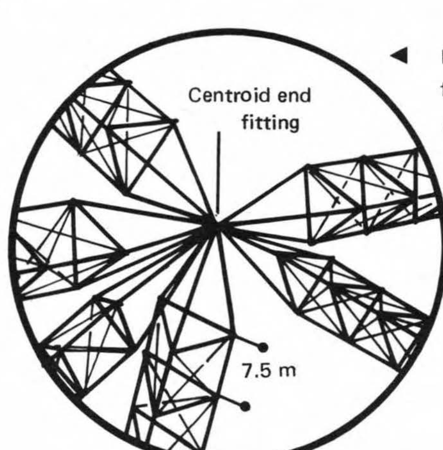


▲ Rendering depicts installation of tension devices on solar blankets

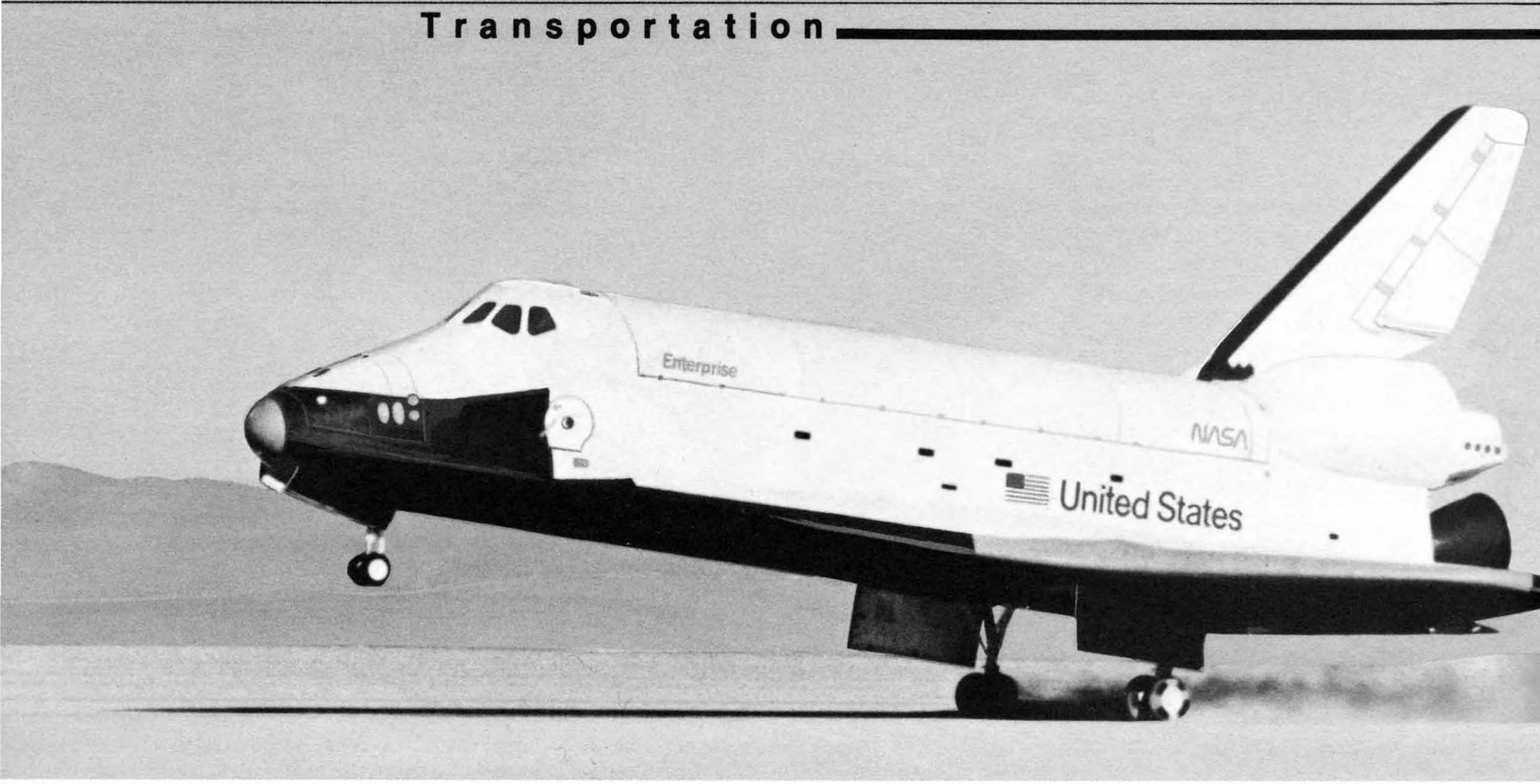
Typical Beam







◀ Beam elements join to form large satellite structure



The United States began transporting man-made objects into space with "Explorer I" on February 1, 1958 (*ref. 11*). This satellite had a mass of about 14 kg (about 31 lb). Just 4 years later, on February 20, 1962, John Glenn became the first American to reach orbit, in a Mercury spacecraft which weighed more than 1300 kg (2900 lb).

Just one year later, on January 20, 1963, in the Apollo Moon landing program, the Saturn I vehicle placed more than 17 metric tons (37 700 lb) in orbit. On December 21, 1968, Frank Borman, Jim Lovell, and Bill Anders were launched by a Saturn V vehicle in a spacecraft which circumnavigated the Moon. The payload of this launch vehicle to low Earth orbit was more than 100 metric tons. The first lunar landing mission was launched by a Saturn V on July 16, 1969, followed by six additional Apollo missions using this launch vehicle. The last of these was launched on December 6, 1972.

The Skylab orbital workshop launch, on May 14, 1973, was the last mission to use the Saturn V. The three manned missions to this space station increased the U.S. cumulative man-hours in space to 21 851, with space-flight participation by 41 persons.

Thus, in the span of 15 years, the U.S. launch capability increased from 14 kg to about 110 metric tons—a factor of 8000 to 1. All of these vehicles employed the technology of their day and were expended in a single flight. Recognition of the inherent limitation to space activity caused by one-time use of the launch vehicles led to studies, in the 1960's, of the Space Shuttle—a reusable craft which carries a crew of as many as seven persons to low Earth orbit along with a payload of 29.5 metric tons (65 000 lb), carried in a payload bay large enough to enclose a transcontinental bus (*fig. **8***). The only expended element of the Shuttle is the relatively inexpensive propellant tank, resulting in predicted total cost per flight of $15 to $20 million (*fig. **9***).

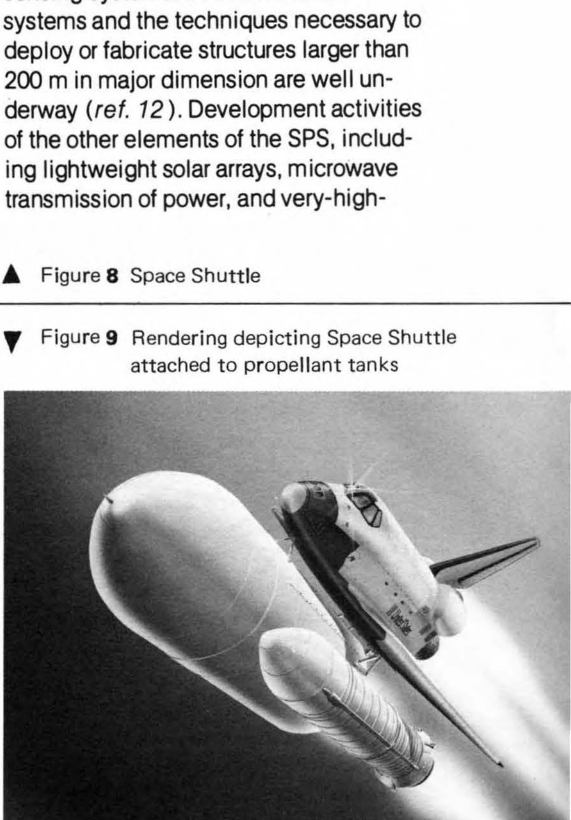
The Space Shuttle is currently NASA's largest development project and the vehicle has already been successfully tested as an aircraft for the vital recovery operation (*fig. **8***). First manned orbital flight is now scheduled to occur late next year (1979), with full operations scheduled to begin in 1980 from the NASA John F.Kennedy Space Center, Florida. The capability of the Space Shuttle fleet is planned to reach 60 flights per year by the mid 1980's, with launch operations from the Western Test Range at Point Conception, California, augmenting the east coast activity by 1984. It will be the basic launch capability of the United States for the 1980's, replacing a number of types of expendable launch vehicles now in use.

"Bookings" for the early Shuttle operational missions is now underway with a mixture of NASA, Department of Defense, commercial and foreign customers for the services provided. A "sell-out" of flights well into 1982 is already accomplished and rapid expansion of traffic up to the full capability of the system is expected.

The Space Shuttle can have a vital part in the early development and demonstration of the solar power satellite concept. Development of space construction techniques, vital to the SPS concept, has several other, earlier applications for communications and Earth-sensing systems. Studies of these systems and the techniques necessary to deploy or fabricate structures larger than 200 m in major dimension are well underway (*ref. 12*). Development activities of the other elements of the SPS, including lightweight solar arrays, microwave transmission of power, and very-high-

▲ Figure **8** Space Shuttle

▼ Figure **9** Rendering depicting Space Shuttle attached to propellant tanks



performance propulsion systems such as the ion engine, are either underway or in the planning stage.

Moderate-scale SPS demonstration programs for the late 1980's have been discussed, and the launch system requirements to fulfill these larger needs have been evaluated (*ref. 13*). Straightforward extension of Shuttle capabilities and preservation of Shuttle reusability concepts can restore the greater than 100-metric-ton capability of the Saturn V launch vehicle by the late 1980's, without the high costs associated with the Saturn V (*ref. 14*).

Figure **10** Rendering of Space Freighter

For deployment of a commercial network of solar power satellites, a new, tailored launch system would be necessary to achieve the economies of scale and preservation for reuse of all vehicle elements, including propellant tanks. Concepts considered in the SPS evaluation process have resulted in the selection of a two-stage launch vehicle, based on near-term technology. This vehicle design has been optimized for economy of a single mission—delivery of about 425 metric tons (950 000 lb) to low Earth orbit. This vehicle is illustrated by figure ***10***. It has a height of 154 m (500 ft) and has wings on both stages for intact recovery of the vehicle. The maximum wing span is about 80 m (262 ft). Landing weight of the second stage, or orbiter, is about 390 metric tons (864 000 lb) or about twice the landing weight of the Boeing 747 airplane. Fuel for the second stage is liquid hydrogen. To reduce propellant costs, the first-stage fuel is methane rather than hydrogen. Both stages use liquid oxygen in large quantities.

Based on frequency of use and full reusability, launch costs for this vehicle are predicted to be slightly less than those for the Shuttle, at about $13.5 million per flight (*ref. 15*). The costs of fuel used in this prediction are those of hydrogen and methane obtained from the gasification of coal. This cost per flight yields a payload delivery cost to low Earth orbit of about $32 000 per metric ton ($15/lb). It is this cost for space transportation that has been used in the JSC and Boeing evaluations of the commercial SPS network. Each 10 000-MW SPS is expected to require about 400 flights of the launch vehicle.

Each SPS launch-vehicle flight will make delivery of 425-metric-ton payloads consisting of SPS components, building materials, construction equipment, and expendable supplies. The destination of this vehicle is a low Earth orbit, tentatively selected to be at an altitude of about 480 km (300 s. mi.) and at an inclination to the equatorial plane of 31°. This orbit provides two launch opportunities per day, 3 hours apart, from a launch site at Kennedy Space Center, Florida.

If solar power satellite modules are fabricated at the low-orbit altitude, completed SPS modules will be "self-powered" to the 35 800-km (22 000 s. mi.) equatorial orbit over a period of about 6 months. The electrical output of less than 20% of the SPS module solar array will provide sufficient electrical power to panels of "ion drive" electric propulsion rocket engines. The remaining 80% of the array on the SPS module would remain protected from the Van Allen belt radiation. These ion engines use argon as propellant with very high exhaust velocity (about 70 km/sec) and therefore good propellant economy. Rocket engines of a similar concept were flown on an experimental basis more than 10 years ago (*ref. 16*), and development of first-generation ion propulsion flight engines is nearing completion at the Hughes Research Laboratories. Their first space-mission application may be for NASA's Space Science Office for rendezvous in deep space with one of the comets; for this application, ion-engine exhaust velocity will be about 30 km/sec, using mercury vapor as the propellant.

The proposed SPS orbit transfer thus represents extension and growth of existing technology and involves no new principles.

Conventional chemical rockets, using hydrogen-oxygen propellants, may also be employed to transfer launch-vehicle cargo to geostationary orbit, permitting construction at that location. Because of the relatively poor performance of chemical rockets compared to the electric propulsion ion-drive system, much larger quantities of propellants must be delivered to low orbit, approximately doubling the number of launch-vehicle flights necessary to place SPS in operation.

An option for the low orbit to high orbit transfer which is just now beginning to be understood is to employ electric propulsion systems with an "independent" ion-drive transfer stage. The solar array to produce the necessary electrical power would, for this option, remain a part of the vehicle and be returned to low orbit for reuse. This option would combine the opportunity to perform construction at the final geostationary orbit with the propellant economy of electric propulsion. Repeated flight of a solar array through the inner Van Allen belt constitutes a severe technology development problem. The silicon solar cell suffers significant reduction of electrical output from each passage through the trapped radiation belt. Exploratory work now underway on localized thermal annealing of silicon solar cells, by laser or electron beams, may demonstrate that this radiation damage can be reversed between missions (*ref. 17*). Solar cells with higher tolerance to radiation dose than the silicon cell may prove to be available and attractive for the "independent electric orbit transfer vehicle." Additional studies of both construction and orbit transfer will be needed before any decision can be made as to construction location and mode of transfer to geostationary orbit.

Each year, the Electric Power Research Institute (EPRI), a utility-funded research group, publishes a Research and Development Program Plan which includes their current projections of electricity consumption, capacity expansion, and economic factors. The most recent plan was issued July 15, 1978 (*ref. 18*).

In the 1978 plan, EPRI projected an average annual growth rate of electricity consumption to be in the range of 4.0% to 6.6%, with a base planning figure of 7.0 trillion kWh in the year 2000 (*fig.* ***11***). To produce this energy, total capacity requirements are estimated to be 1595 GW, with 559 GW from coal-fired plants, 450 GW from light-water nuclear reactors, and 330 GW from peaking plants using almost 15 000 m³/day (4 x 10⁶ bbl/day) of liquid and gaseous hydrocarbon fuels. As a point of reference, 1977 capacity was 550 GW, producing 2.15 trillion kWh. Renewable energy resources (hydroelectric, geothermal, and solar) are expected by EPRI to contribute about 8% of the total required capacity in the year 2000, with the balance of the capacity provided from fossil or uranium fuels.

Without reprocessing of nuclear fuels, failure in providing the needed capacity may occur by the mid 1990's. Even with nuclear reprocessing and the liquid-metal-fast breeder reactor (LMFBR), shortfalls are predicted to begin about the turn of the century. The electrical energy shortage may reach a level of about 70% of our total 1977 consumption by the year 2020 (*fig. 22*, p. II-43 of *ref. 18*). Figure ***12*** illustrates the EPRI assessment of primary energy source for power generation and the onset of shortfalls.

The rising costs of fossil and nuclear fuels and major increases in plant costs have reversed a long-term trend of decreasing real costs of electricity. The EPRI forecasts that the busbar costs of electricity produced by plants entering service in 1986 will be 4 to 5 cents per kWh, roughly twice comparable costs in 1977. About half of these revenues are expected to be expended by the utility companies to amortize the capital investment, with the other half used for the purchase of fuels and for plant operation.

The Tennessee Valley Authority (TVA) staff prepared background information for a May 1977 board meeting which summarized their cost experience and forecasts for the fuel costs of power generation from coal and light-water

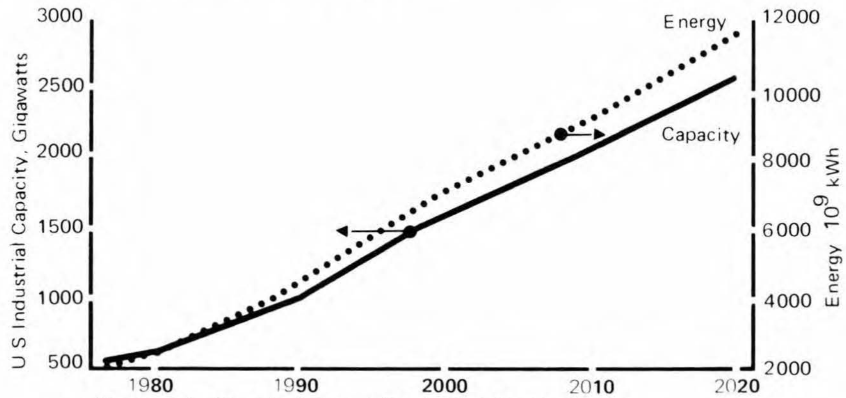
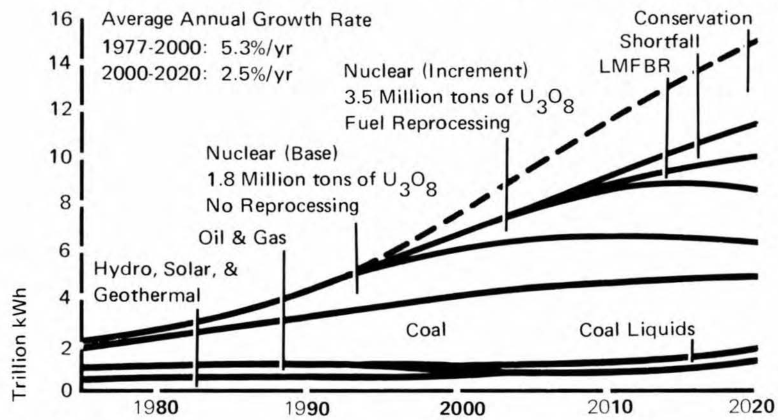


Figure **11** Electrical Energy Production Forecast

Figure **12** Electricity Generation Mix Projections 1975 – 2020



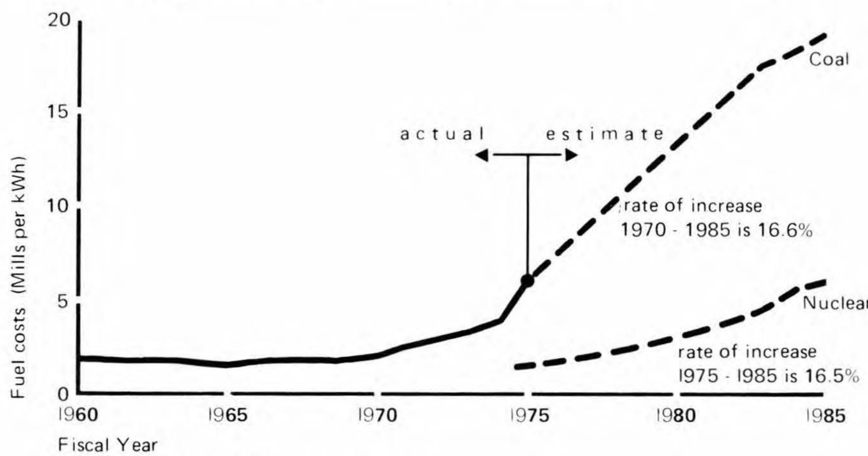
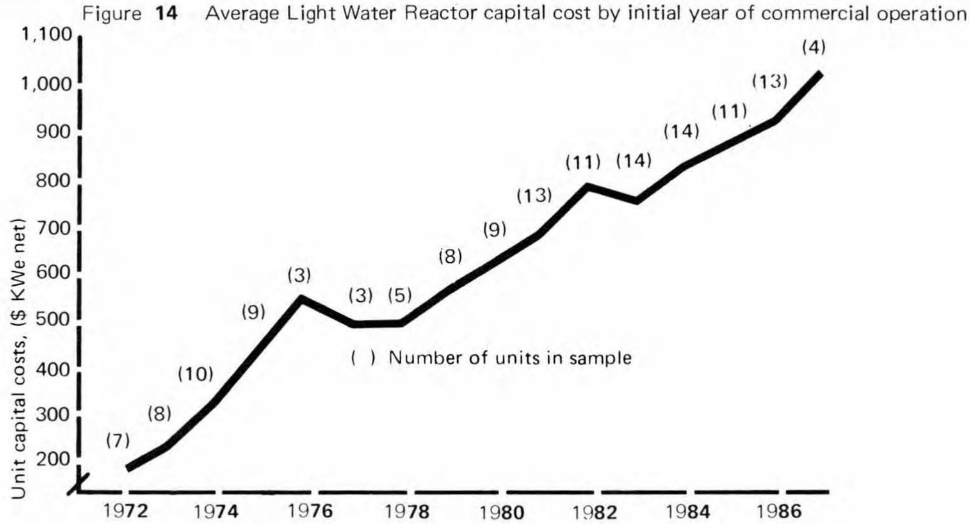


Figure **13** TVA Fuel Costs

Figure **14** Average Light Water Reactor capital cost by initial year of commercial operation



reactors. Figure **13** indicates that TVA has experienced or is forecasting an annual rate of increase of fuel costs of 16.5%. The TVA staff also summarized the capital investment history of light- water reactor plants and the forecasted capital costs of plants under construction. Figure **14**

The investment in new capacity in 1986 is expected by EPRI to exceed $45 billion, increasing to $78 billion annually by 2000. These capital investments are predicated upon an average cost of new facilities of $1020/kW, expressed in 1976 dollars.

Advanced Systems Cost Projections

Cost projection for any advanced energy system is a much less than perfect art. Broad divergence of opinion exists for each of the several options, as illustrated by the following discussion.

Steiner and Clark of Oak Ridge National Laboratory and Department of Energy, respectively, offer some comparative data on the anticipated costs of representative "Tokamak" fusion power reactors and LMFBR's (*ref. 19*). They predict that a 20-year development program costing $10 to $15 billions can result in commercial fusion power reactors at an average plant cost of $1000 to $1500 per kW, in 1976 dollars, not including interest during construction or cost escalation. Fiscal year 1979 (FY79) fusion research is budgeted at above $400 million. On the same basis, they estimate direct costs of LMFBR plant capacity to be $600 to $1000 per kW and solar terrestrial electric plant cost in the range of $1500 to $3000 per kW.

Parkins of Atomics International expresses the opinion (*ref. 20*) that the fusion plant, if successfully developed, will incur additional costs to safely contain the tritium fuel and to provide continuing protection, during the useful life of the plant, for the pressure vessel which must operate in the presence of an intense nuclear radiation field. He derives a total cost for the fusion powerplant of $4450/kW, resulting in electricity costs to amortize investment of 10.8 cents/kWh. On a comparable basis, he estimates the LMFBR total construction cost to be $1820/kW.

The EPRI summarizes the status of fusion power research as follows: "The possibility of generating electricity still remains to be proven. . .will not likely contribute to the generation mix before 2010." EPRI does not offer a fusion plant cost estimate.

Advanced coal-fired system development is also underway, with some of the technology options approaching maturity. Balzhiser (*ref. 21*) summarizes a recent Fluor report to EPRI which estimates costs for gasification-combined cycle plants to range from $711 to $937 per kW, compared to conventional coal-fired-plant (with stack gas scrubber) costs of $838/kW. These plants consume coal and produce ash, adding a significant increment to the total cost of power.

Other electrical energy production systems are also under development or review. These include the solar-thermal powerplant, now proceeding to the 10 MW pilot-plant phase at Barstow, California (*ref. 22*). A number of small (< 100 kW) solar-thermal systems are also in various states of development. These smaller systems enjoy an advantage for many applications by eliminating the costs involved in delivery of electricity from a centralized plant to the small remote user.

Of the dispersed solar conversion systems, the photovoltaic cell program may have the potential for making the largest contribution by the turn of the century, because the photovoltaic cell has no moving parts which will require maintenance. Periodic cleaning may, however, be necessary in some environments.

The EPRI cites a number of advantages for photovoltaic solid-state solar cells for the generation of electricity (*ref.18*).

"Cooling water is not required for nonconcentrating systems because the light is converted into electricity at or near ambient temperature."

"The systems can function with diffused sunlight. . ."

"Solar cells are direct conversion devices with no moving parts."

The deterrent to widespread application of photovoltaic cells is the current high cost of single-crystal silicon cells, about $15 000 per peak kW, according to EPRI. Because of costs, EPRI does not expect photovoltaics to make a significant contribution to the electrical power generation mix by the year 2000, but qualifies that forecast with the statement that technological breakthroughs may occur.

Henry Kelly of the Office of Technology Assessment, U. S. Congress, reviewed photovoltaic alternatives and the current and projected market/costs (*ref. 23*). He states that the most recent government purchase of photovoltaic cells was $11 000/kW, but that it is technically possible, with known approaches, to produce solar cells for $1000 -$2000 per kW during the next 3 to 5 years.

Goals of the Department of Energy photovoltaic program administered by the Jet Propulsion Laboratory are for costs of $2000/kW by 1982, $500/kW by 1986 and $100 to $300 per kW by the 1990's. Confidence is building that these goals will be met (*ref. 24*). A major step being taken by the government is in providing a market of sufficient size to stimulate mass production techniques. The 1976 world market for photovoltaic cells was about 380 kW, with 1977 sales of about twice that amount. As the production rate increases, the prices fall and the market expands. To catalyze and accelerate that reaction is the purpose of the DOE photovoltaic program. A number of firms worldwide, including the major oil companies, recognize the market potential for low-cost photovoltaic cells and are engaging in proprietary pilot plant as well as research activities.

Dr. B. L. Welch of Johns Hopkins University cites a 1977 Federal Energy Administration (FEA) report suggesting government purchase of 152-MW peak output photovoltaic solar arrays by 1983 with an estimated cost of $240 million, or an average of $1570/kW (*ref. 25*). He cites FEA data estimating the maximum size of the photovoltaic market at 27 GW peak per year if the open market price is reduced to $750/kW.

Photovoltaic cells are only part of an electrical energy delivery system. The costs of structural support and installation, tracking systems (if used), energy storage, and power conditioning must also be considered in determining the cost of photovoltaic electricity. In addition, the comparison of capital cost per kilowatt of peak capacity of photovoltaic systems with conventional powerplants must include consideration of the attainable duty cycle; i.e., a coal-fired plant can produce useful power around the clock, whereas a solar array on the surface of the Earth can produce power for 6 to 8 hours per day, and then only on relatively clear days. A daily average ac powerload of 10% to 15% of peak solar-array output may be the best that can be sustained by a terrestrial photovoltaic system with battery storage.

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Despite the uncertainties and reservations stated previously, it is clear that photovoltaic cell production is rapidly increasing and that costs are following the downward trends experienced in prior years with other solid-state electronic devices. Also apparent is a large amount of work in progress on processes and production techniques for the mass production of a variety of potentially low-cost photovoltaic solar cells.

To put this forecasted contribution of terrestrial photovoltaic cells to the electric power generation mix in perspective, if an annual photovoltaic cell market of 27 GW peak is realized in 1986, if all installations are within the United States and if the capacity factor is 15%, solar electricity could constitute an increase of approximately 1% in the 1986 U.S. capacity to generate electrical energy. To achieve this production rate will require that more than a threefold increase in production and market development must occur each year for 10 consecutive years.

The solar power satellite can employ an expanded production capability for photovoltaic cells more effectively than can centralized ground-based electric plants. The high-orbit vantage point of the SPS eliminates the day-night cycle, detrimental weather influences, and the need for energy storage systems with their inherent inefficiencies. A solar power satellite capacity factor of approximately 90% can be achieved. This potential increase in capacity factor can permit a given production rate of photovoltaic cells to provide more than 6 times the contribution to U.S. generating capacity than if they were deployed on Earth.

These benefits of the SPS, however, remain latent until the technical feasibility of each element of the system is demonstrated and present uncertainties in cost and capacity factor are narrowed.

Solar Power Satellite Cost Estimates

The solar power satellite was suggested by Dr. Peter Glaser of the Arthur D. Little Company in 1968. It has been subjected to several studies and reviews by NASA and DOE for the past 5 years. The tempo of this study activity increased in 1976 when NASA study groups rendered a qualified endorsement of technical feasibility of the concept. In the past 2 years, major "systems studies" have been accomplished by Boeing Aerospace Company for the Johnson Space Center and Rockwell International for the NASA George C. Marshall Space Flight Center. The emphasis in these studies has been on the engineering definition of all elements of a large, commercial powerplant for initial operation after 1990. Their purpose has been to confirm the availability of key technology, to produce conceptual design for a representative system, and to determine the development and unit costs. As is the case for other advanced energy sources, these costs must be considered as preliminary estimates.

Capital costs for the SPS were estimated by four independent study teams in the 1976-77 interval. Estimated costs ranged from $1400/kW to more than $7000/kW. The primary contributors to this wide variance were different estimated costs of the photovoltaic cells (from $130/kW peak to $921/kW) and construction time (from 1 year to 6 years).

Improved definition of the satellite, ground receiver, space transportation system, and construction process resulted in a December 1977 estimate by the Boeing Company of $2700/kW (*ref. 26*). A parallel study done by Rockwell International produced an estimated capital cost of about $2000/kW (*ref. 27*).

These costs do not translate into electrical energy cost in the same proportion to their capital costs as do conventional plants. Solar power satellites do not require fuel, produce no wastes, promise high capacity factors because of their passive nature, and appear to be inexpensive to maintain and operate in the space environment. Because of these factors, the SPS-generated electricity cost at the ground receiver output is now estimated at about 5.5 cents/kWh.

Studies are continuing with emphasis on reducing the uncertainties in capital cost, construction time, and capacity factor. Other studies are examining the alternative strategies for development of the required technology, and demonstration of the concept to clear, measurable criteria in several steps, and are reviewing potential favorable and unfavorable environmental impacts of the system.

Innovative approaches to improving the "reference configuration" SPS are yielding significant potential candidates for system cost savings. Studies of the next 2 years should better define the system and its expected costs.

Improved definition of costs is vital to the evaluation of SPS and of other advanced energy sources. If the EPRI projection of electrical demand in the year 2000 is correct, each 1 cent/kWh variance in electrical energy cost will alter the U.S. electrical bill by almost $6 billion per month. This cost leverage will tend toward conservative decisions by the utility industry and may lead to delay in decisionmaking on advanced energy sources. During the intervening years, coal and nuclear fission plants will provide the growth in capacity. Also during this interval, increased understanding must be gained of the technical status and dependability of cost estimates for nuclear fusion, breeder reactors, terrestrial solar (photovoltaic and thermal) collection, and the solar power satellite. Within these cost estimates should be included the costs of producing fuels, safely disposing of wastes, alleviating detrimental environmental effects, and accommodating socioeconomic dislocations.

The selection of electrical generating plants by the utilities has historically been governed almost exclusively by economics over the plant life. In recent years, the selection process has become more complex because of several factors. New environmental protection measures have been developed and required. Increased timespans for site approval, plant licensing, and construction have added to the costs of interim financing. Inflation in the cost of labor and materials has increased estimated plant capital costs during the preconstruction and construction phases. Prediction of fuel costs is required over the interval from initial consideration to the end of plant life—a span of 40 years or more—which in turn requires that predictions be made on future supplies, demand, and regulatory policy toward the intended fuel.

For these reasons, it is essential that any proposed power generation system be assessed as early as possible on the bases of environmental, health, safety, and other societal impacts. NASA is accustomed to this analysis process with its programs and issued, in April 1978, the "Environmental Impact Statement (EIS) for the Space Shuttle Program." Assessment of the solar power satellite to these criteria has begun by NASA, using the Shuttle EIS as a model, and these preliminary assessments are under review and are being refined by the Department of Energy.

The three primary environmental concerns of the SPS relate to the microwave power transmission beam, the influence on the atmosphere of launch operations during construction, and the safety of workers in the space environment. Related areas under investigation are the requirement for critical materials, energy "payback time," water consumption, land area required, and employment/skills-mix questions.

The microwave-beam concerns are in three areas: interference with rf communications, heating effects on the upper atmosphere, and biological effects on life forms near the ground-based receiver. Each of these areas is under investigation and tests are in the planning stage for determination of the possible effects. Arndt and Leopold (*ref. 28*) summarize the current state of knowledge of the potential microwave effects. The SPS downlink frequency of 2450 MHz is in the midrange of a frequency band reserved for industrial, medical, and scientific uses.

The radiofrequency-interference (RFI) effects due to spurious noise of the space transmitter tubes are expected to be held below current CCIR (International Radio Consultative Committee) requirements by the use of phase-lock loops and multiple-cavity filters. A significant development and test program will be necessary to confirm that candidate elements of the SPS rf system meet the RFI requirements.

Atmospheric heating by radiofrequency beams is of interest primarily because of possible disruption of communications dependent on ionospheric reflection. Radiofrequency heating of the ionosphere has been analyzed and limited, comparatively simple studies to date indicate that maximum safe energy density in the "E" and "F" regions of the upper atmosphere (110 km and 200 to 300 km, respectively) is 23 mW/cm^2. The SPS beam has been designed to observe this limit and additional tests are planned at heating power levels representative of the SPS beam (*ref. 29*).

Several comprehensive reviews of the effects of microwave radiation on humans have been completed. Most researchers and all U.S. standard-setting agencies agree that microwave effects on humans are limited to thermal effects, and continuous exposure at 10 mW/cm^2 does not produce detrimental thermal effects. Eastern European researchers, however, suggest that central nervous system effects can occur at lower levels. Consequently, microwave energy exposure guidelines in Eastern European countries are currently much lower than limits in the United States. The SPS receiving station size results in exposure levels at the boundary of no greater than 1 mW/cm^2. This level could be lowered by increasing the size of the "buffer zone" around the ground receiver, should future research indicate that the U.S. exposure standards should be lowered.

Launch-vehicle emissions are of interest for two reasons. First, the large increase of launch-vehicle size and rate of use necessary to construct the SPS network, when compared to past launch-vehicle use, frequently leads observers to the incorrect assumption that the fuel burned will be a significant part of the total U.S. hydrocarbon combustion. Current launch-vehicle designs require about 1500 tons of methane and 300 tons of hydrogen for each launch. Each launch places about 400 tons of useful payload into low Earth orbit. For the current SPS design weight and transportation system to geostationary orbit, the construction of each 10-GWe SPS will require about 400 flights of the launch vehicle. The resulting combustion products of 600 000 tons of methane and 120 000 tons of hydrogen for each SPS are primarily carbon dioxide and water vapor and would be produced by fossil-fired powerplants of equal capacity to the SPS in about 7 months of operation. During that time, about 5 billion kWh would be generated—less than 0.25% of the 1977 production of electricity. Other comparisons of the combustion products produced by SPS launch activity may be drawn with automobile use, flaring of gas in the production of oil, industrial boiler use, etc., which will show that the maximum expected SPS launch activity is not a significant contributor to total combustion products generation of our economy.

Second, the launch vehicle, unlike ground sources, traverses the atmosphere and injects a portion of the exhaust products into the upper atmosphere. The methane-fueled first stage operates to about 50 km altitude and the hydrogen-fueled second stage completes the insertion into orbit at an altitude of about 120 km. Water vapor and hot hydrogen exhaust products are therefore injected into the lower ionosphere (D and E layers) but not into the sensitive "F region" at 200 to 300 km altitude. Studies of the effects of this launch activity on the atmosphere are now underway by the Argonne National Laboratories for the Department of Energy.

Construction activities in space lead to the need for protecting personnel from the natural environmental hazards. Provision of a life-supporting pressure environment, and protection from solar thermal and ultraviolet radiation are well-understood engineering problems. Protection from the energetic particle fluxes (cosmic rays, geomagnetically trapped energetic particles and solar proton events) require that more knowledge be gained on the expected dynamic range of these phenomena and that engineering measures such as shielding be applied to meet exposure standards yet to be established for space workers. Daily, monthly, and career dose limits must be established to determine the necessary investment in protective measures (suits, pressure cabins, and "storm shelters"). The Apollo lunar missions and the Skylab missions provide NASA a familiarity with these trade-offs and the necessary design methodology.

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The additional hazards of collision with micrometeoroids and with manmade orbital debris also require analysis, test, and the selection of protective measures for personnel and vital equipment. Again, the background gained in past space operations indicates that adequate protective measures may be provided for reasonable costs. "Space cleanup" of past manmade orbital debris may become desirable during the SPS construction phase, and meticulous housekeeping during construction will be imperative.

Other evaluation factors include energy "payback" interval, use of critical materials, land use, and water consumption. The Jet Propulsion Laboratory of the California Institute of Technology has provided a preliminary assessment of the SPS to these measures (*ref. 30*). Their findings illustrated by Figure ***15*** were that the SPS energy payback time is 0.6 to 1.6 years; and that life-cycle water consumption is about 1% and land use about one-fourth of equivalent capacity coal-fired plants. Further analysis and assessment of these factors is underway by the Department of Energy. Presumably, similar data will be produced by the DOE on other advanced energy systems so that these important non-economic factors may be compared.

Energy Research and Development Indirect Economics

A large portion of U.S. present and projected energy must be obtained from imported oil. The costs of energy research and development must be considered with the limited insight which is possible into the process by which the Organization of Petroleum Exporting Countries (OPEC) establishes the price of their energy exports. Hazelrigg of ECON, Inc. (*ref. 31*), addressed this topic and concluded that rational self-interest of the oil producers will lead to a variation in the price of oil as a function of their perception of prospects for replacement sources of energy. Figure ***16*** *(p. 21 of ref. 31)* illustrates the results of the ECON analysis. The price of oil to optimize the benefits to the producers is shown by ECON to be about $1.00 per barrel greater if the producers expect replacement sources for oil to be 100 years away rather than 25 years into the future.

Acceleration of energy research and development (R&D) may therefore have a net annual cost to the United States of much less than the budgetary figures if this activity leads to a more optimistic view of the future by the oil producers in other nations. Another way of viewing the situation is that the United States is going to pay, in the short term, for an aggressive long-range energy R&D program *even if it is not conducted!*

No proof of this relationship is possible in advance, and since the alternative routes cannot both be followed, history will not be able to directly quantify these indirect economic trends. The trend is both intuitively and mathematically sound, however, and may be recognized as a major factor in the Federal decisionmaking process toward energy research and development.

Figure **16** ►
Optimal Consumption Patterns with Energy Research and Development

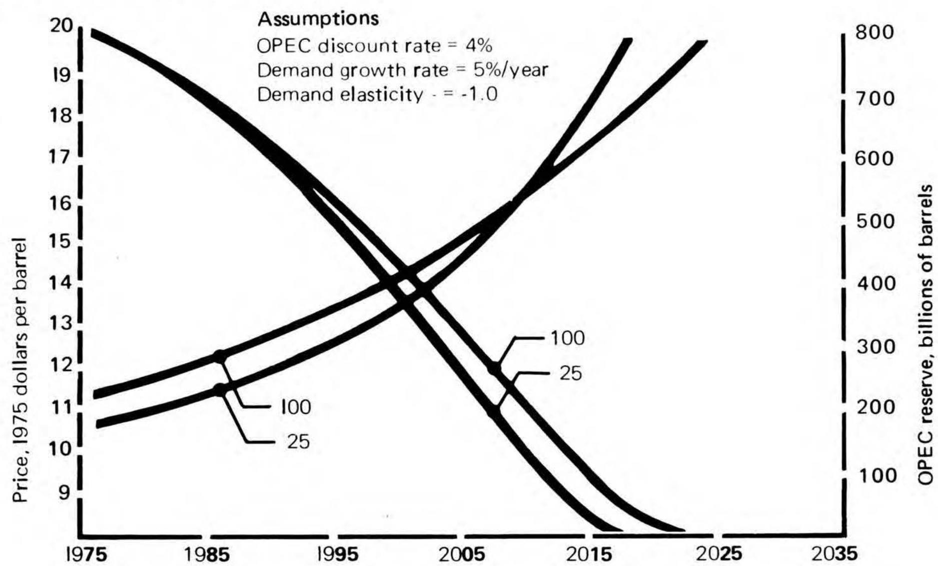

Figure **15** Solar Power Satellite Resource Requirements

* Resource Requirements	Solar Power Satellite	Coal
** **Life Cycle Fuels** Metric tons/MW - year	13.3	3500
Water consumed Metric tons/MW - year	7.7	800
Land area requirement M^2/MW - year	673 - 1018	3600
*** **Manpower** Years/MW - year	3.36	?
Energy payback time in years	0.6 - 1.6	?

* Produces 48 - 10 GWe plants by 2025 which generate 480 GW . . . U S generating capacity in 1973 was 495 GW. Costs to acquire this network averaged $48.4 billion/year in 1976 dollars or about 3% of the 1976 Gross National Product.

** Terrestrial solar thermal or photovoltaic plants require 10 - 20% fossil-fired backup, or 350 to 700 MT/MW year. Reference: JPL report 900-805, rev. A - SPS Preliminary Resource Assessment

*** Solar Power Satellite produces over 1.48 million jobs.

Development Program

The present NASA/DOE SPS program (Fig. ***17***) is intended to reach a major plateau in the evaluation of the SPS by 1980 against the criteria of technology readiness, potential cost effectiveness, and environmental effects (*ref. 32*). Significant progress has already been made in this evaluation process. This plan now excludes technology development and testing of the space elements of SPS.

In August 1978, O. C. Boileau, President of the Boeing Aerospace Company, related to the U.S. Senate the results of the NASA-supported SPS systems study recently completed by his company (*ref. 33*). He stated: "We have carefully weighed systems requirements against existing technologies and have found—on paper, at least—that solar power satellites appear to be technologically, environmentally and economically promising." He advocated a 5-year, ground-based technology development necessary to confirm key analyses.

The program recommended by Boileau is approximately 6.5 times the funding rate of the current 3-year joint DOE/NASA SPS study program and includes significant technology development activities. Bills were introduced in both Houses of Congress during the past session (*ref. 34 and 35*) to accelerate the SPS evaluation program with an FY79 authorization of $25 million. The House bill passed by an overwhelming margin but the Senate bill was not acted upon. The near-term future pace of the SPS definition and evaluation program is therefore not yet resolved.

● **Objective**

To develop by the end of 1980, an initial understanding of the economic practicality and the social and environmental acceptability of the Solar Power Satellite concept.

● **Funding**

$ thousands

Program Components		1977	1978	1979	1980	Total
NASA	Systems Definition definition	2500	1700	1300	800	**6300**
DOE	Environmental, health, safety	220	1940	2050	1740	**5950**
	Societal assessment	164	537	537	322	**1560**
	Comparative assessment	95	376	754	565	**1790**
		2979	**4553**	**4641**	**3427**	**15600**

• Program Milestones	1977	1978	1979	1980
Program initiation	●			
Baseline concept selection				
preliminary		●		
final		●		
Program recommendation				
preliminary			●	
updated			●	
final				●

Figure **17** NASA and U.S. Department of Energy Solar Power Satellite Concept Evaluation Program

Conclusion

The solar power satellite is an opportunity for the application of the space technology and engineering competence of the United States toward a partial solution to the imminent shortage of primary energy. The elements of the SPS are logical extensions of the photovoltaic cell development program and of our space capabilities. Significant advances in knowledge of the component efficiencies, costs, and weights and of environmental effects may be obtained within the next 5 years by an aggressive program of analysis and technology development, including limited testing in the space environment with the Space Shuttle.

The SPS is not *the* answer to our future energy requirements but it may well be one important ingredient in the future energy systems mix and may help to minimize economic dislocations. It needs to be accelerated, along with the distributed solar energy systems, to ensure that the energy potential of the Sun may be applied to drive our industrial complex as well as to provide warmth for our buildings. Current programs are making progress in understanding of the SPS, but much more rapid progress is both possible and desirable.

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