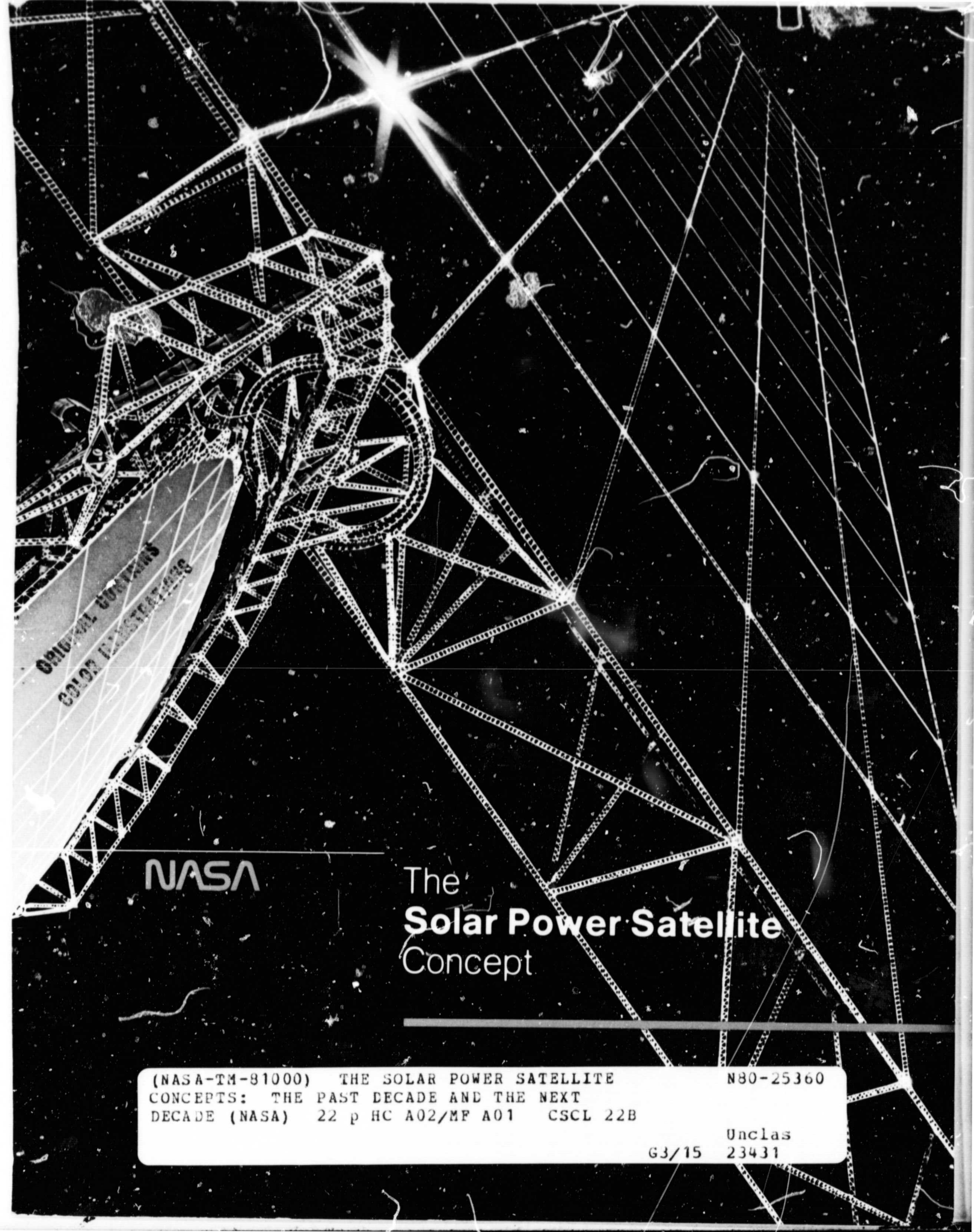

The
Solar Power Satellite
Concept

The Von Karman Lecture

Fifteenth Annual Meeting
of the
American Institute
of Aeronautics and
Astronautics

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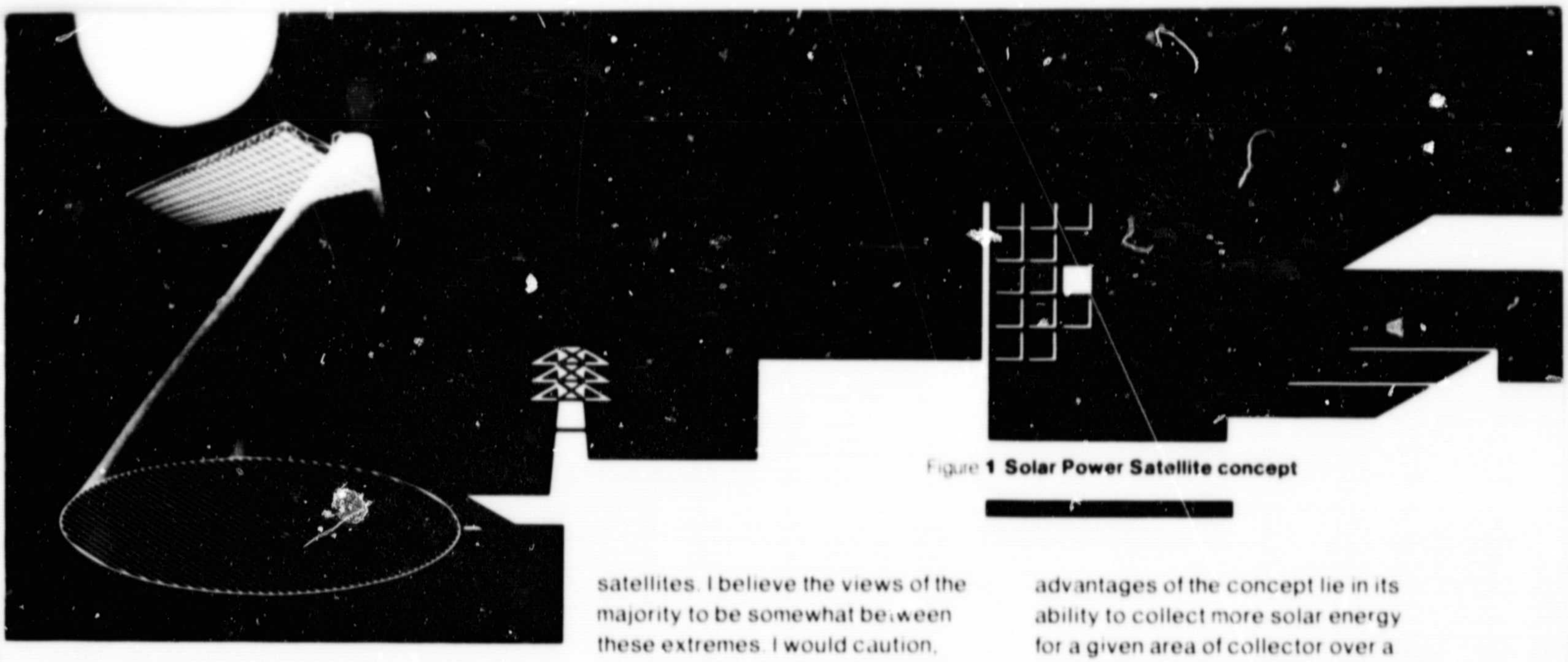


Figure **1 Solar Power Satellite concept**

Introduction

The invitation to present the Von Karman lecture included a suggestion that I discuss the Solar Power Satellite concept. I found this suggestion most satisfactory, since this concept (and the manner in which it is handled) is as important a question as exists in the aerospace community today. I believe the concept to be visionary in its application of space technologies to world needs at the turn of the century. It thereby offers a focus and a goal for technological programs, the success of which would firmly embed the use of space in the mainstream of society by providing that most fundamental of all material resources, energy. *No other space concept has been presented that offers rewards of such magnitude and importance while simultaneously involving such difficult questions of feasibility and practicality.*

In view of the potential, however, it is crucial that we of the aerospace community carefully evaluate the concept and thoughtfully advise the nation on a proper course of action.

I fully realize that there are both proponents and opponents of the concept. The positions of these two groups, in the extreme, range from complete abandonment of the concept to immediate development of full-scale energy-producing satellites. I believe the views of the majority to be somewhat between these extremes. I would caution, however, that "benign neglect" or "tolerance" of the concept without positive support and interest is tantamount to its abandonment.

I would now like to discuss the concept and the results of associated studies and in doing so illustrate my thoughts on what I believe to be a rational approach. This approach is certainly not unique. The recent AIAA policy paper on Solar Power Satellites and the views of many others coincide closely with my own thoughts. I would hope that the aerospace community could reach a consensus of views on the subject and proceed to pursue the concept in a positive manner at whatever budget level the nation can afford, and we all realistically must recognize the many pressures that exist on the Federal budget at the present time.

The Solar Power Satellite concept was first presented in 1968 by Dr. Peter Glaser of the A. D. Little engineering firm. The basic concept as illustrated in figure 1 is straightforward. It involves placing a large solar collector at geosynchronous orbit. The collected solar energy is transmitted to an Earth receiver utilizing microwave techniques. The location of the collector in geosynchronous orbit provides access to the Sun's energy nearly 100 percent of the time, and the microwave transmission allows the immediate and continuous transfer of energy to Earth. The advantages of the concept lie in its ability to collect more solar energy for a given area of collector over a given time, and to provide energy continuously without regard to the day-night cycle and cloud cover.

The concept was analyzed by a number of industrial groups and NASA in the early 1970's. In 1976, the Department of Energy and NASA initiated a concept evaluation program which will be completed in 1980.

The objective of the concept evaluation program is to develop an initial understanding of the economic practicality and the social and environmental acceptability of the Solar Power Satellite system concept by the end of 1980. The program is divided into four major components:

- System definition
- Environment, health, and safety
- Socioeconomic issues
- Comparative assessment

NASA is responsible for the conduct of the systems definition activity, and the Department of Energy is responsible for the other three activities.

The largest effort to date has been directed toward the systems definition activity and associated cost studies. The other areas are now receiving increased emphasis under the direction of the Department of Energy.

Systems Definition and Exploratory Research

Within the systems definition activity, a number of approaches have been explored. There is obviously more than one way the system could be implemented, and technology programs will be required to provide definitive data in order to select an optimum system. The studies to date have been valuable in helping to identify the strengths and weaknesses, or questions, related to various approaches and thereby to define the needs of research and technology programs.

In order to illustrate the systems definition activity and the emerging research requirements, I would like to discuss four major elements involved in the concept. These are

- *Energy Conversion in Space;*
- *Power Transmission to Earth;*
- *Space Transportation; and*
- *Space Construction.*

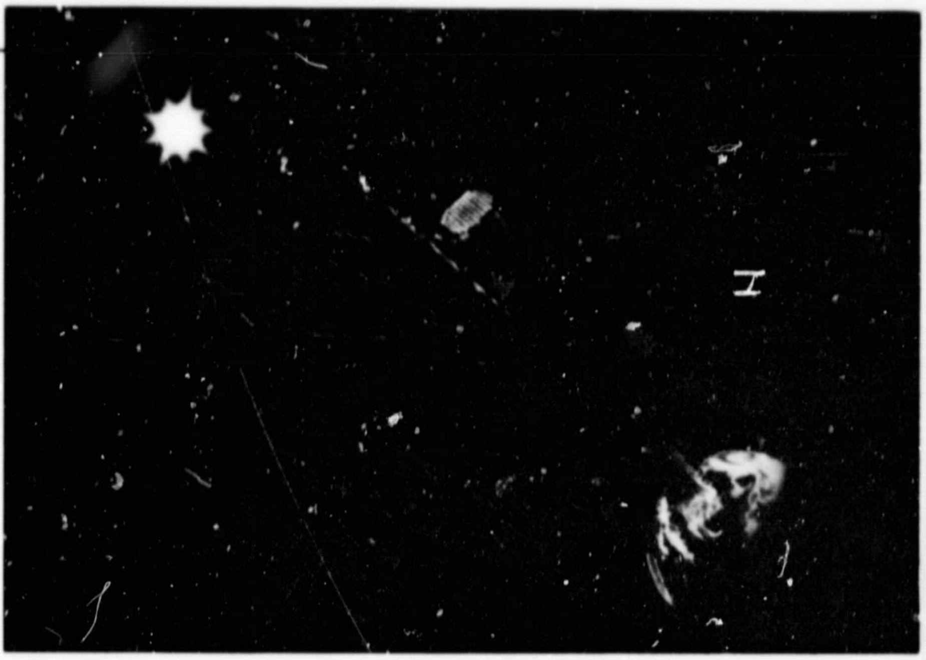
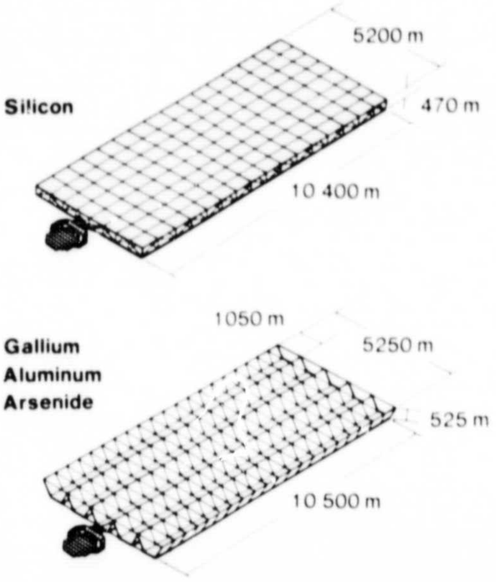


Figure **2 Typical system configuration**

A typical system configuration for the Solar Power Satellite is presented in figure **2**. This configuration provides 5000 megawatts of electrical power to a ground receiving station for introduction into a commercial electrical power grid. The mass of the satellite is estimated to be 50 000 tons, with a solar collector area of 50 square kilometers. This large size is directly related to its large power output. It will require multiple launch vehicle flights and construction in space.

Figure **3 Photovoltaic energy conversion studies**



	Silicon	**Gallium Aluminum Arsenide**
Solar blanket area	52 km^2	26 km^2
Total area	54 km^2	55 km^2
C.R.	1	2

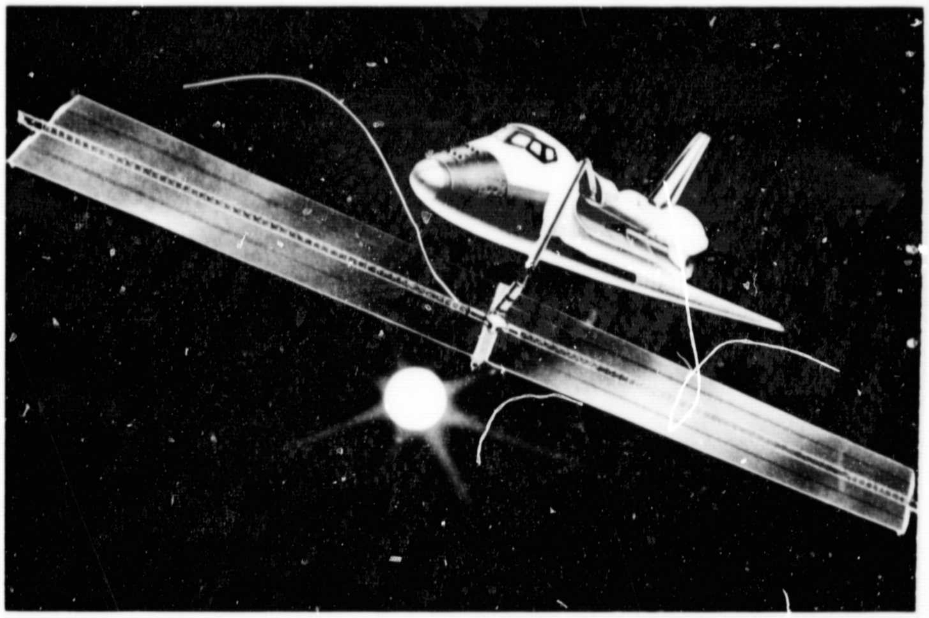


Figure **4 Shuttle Power Extension Package**

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Energy Conversion

A number of energy conversion approaches have been studied. Photovoltaic devices — specifically silicon and gallium aluminum arsenide — have received considerable attention. These two approaches are shown in figure **3**.

The solar collector illustrated on the left utilizes single-crystal silicon cells with a basic cell efficiency of 17.3% at 25° C and a concentration ratio of one.

A system employing gallium aluminum arsenide cells is depicted on the right of the same figure. This approach utilizes concentrators to focus the solar energy on the cells. Consequently, while the overall size of the two collectors is approximately the same, the area of the gallium aluminum arsenide cells is one-half the silicon cell area. This reduced cell area is achieved at the expense of a somewhat more complex construction arrangement involving the use of the concentrators.

The gallium arsenide cell offers the potential of higher efficiency, less degradation of output at high temperatures, and less susceptibility to damage by the natural radiation in space than the more common single-crystal silicon cell.

The disadvantages of gallium arsenide cells are less certain 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 both gallium and silicon to produce a composite cell that may achieve a conversion efficiency between 30% and 40%.

In the last several years, research and development programs to improve solar cell performance and to devise low-cost manufacturing techniques have been greatly expanded with gratifying results. The programs emphasizing low-cost technology are oriented toward the production of solar cells to be used on Earth; consequently, these specific cells and techniques may not be completely applicable to space requirements. These programs, however, do provide an expanded technological and industrial base on which to build the space capability and consequently are of critical interest to the Solar Power Satellite program.

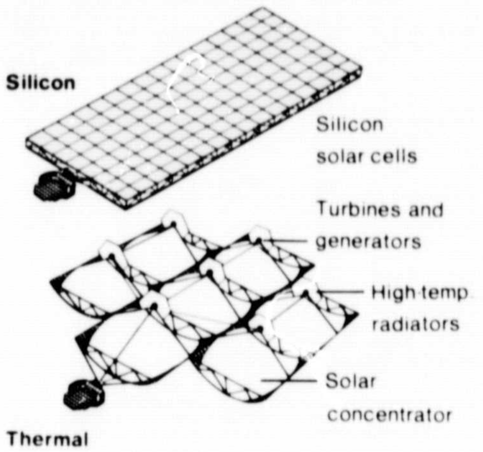
While these ongoing solar cell programs are important, we need to specifically assess the applicability of present research to Solar Power Satellite requirements and possibly to augment it in areas such as automated fabrication techniques, radiation degradation, annealing techniques, stowage and deployment techniques, concentrator material evaluation, and assessment of large-scale gallium recovery from bauxite.

Concurrent with the laboratory research and development activities, new solar arrays are being developed for near-term space use. Figure **4** illustrates one such array which is now being considered to increase the Shuttle capability to support its payloads. While these arrays are small in comparison with Solar Power Satellite requirements, they represent a continuing development of technology and space experience in this critical area.

Other energy conversion systems have also been considered for the Solar Power Satellite, including thermal cycle heat engines which use large solar reflectors to concentrate the sunlight on a boiler surface integral to the spacecraft. These engines are coupled to turbine-driven generators and space radiators.

A thermal Brayton system and the silicon cell system are illustrated in figure **5**. The photovoltaic system offers the advantages of space construction simplicity and potentially higher reliability due to its lack of "moving parts." The economic viability of the photovoltaic system, however, will depend on the ability to develop low-cost high-volume manufacturing techniques.

Figure **5 Thermal/Silicon cell satellites**



	Silicon	Thermal
Conversion efficiency	13.4%	12.3%
Area	55 km²	60 km²
Mass	49 500 T	51 000 T

· Power Transmission

The energy collected and converted to electricity aboard the satellite requires a high-efficiency system to transfer the power to Earth. The 2.45-gigahertz microwave power transmission link described in current studies is depicted in figure **6**. The system has direct-current-to-radiofrequency (DC-to-RF) power amplifiers feeding a 1-kilometer-diameter phased-array transmitting antenna. The antenna is designed to provide a tapered illumination across the array surface. It is composed of 7000 subarrays, each about 10 meters on a side, having slotted waveguides as the radiating surface. The DC-to-RF power amplifiers are mounted on the back 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 rectifying antenna (rectenna) system.

The rectenna has an active panel area of about 75 square kilometers (29 square miles) consisting of a series of panels constructed perpendicular to the incident beam. Each section is composed of a structural support system, a wire mesh screen ground plane which is opaque to microwave energy but has 80% optical transparency, and many half-wave dipole antenna elements which collect the microwave energy and feed it to Schottky barrier diodes for conversion to DC power.

The DC-to-RF efficiency of this microwave power link has been the subject of highly detailed analyses, and the efficiency of this link is now expected to exceed 60%. The transmitter employs high-power klystron tubes. About 100 000 such tubes are required for a transmitting antenna of a 5000-megawatt satellite.

As in all elements of the Solar Power Satellite concept, a variety of technical approaches is available. I have described a system employing klystron DC-to-RF converters. Other converters such as amplitrons and magnetrons should continue to receive attention. Solid-state converters are also receiving serious consideration. They would offer the great advantage of very low failure rates and thereby eliminate a major maintenance consideration. In addition, it appears that a solid-state system would "optimize" at a lower power level, on the order of 2500 megawatts, with an attendant reduction in Earth rectenna size. It may be that such a power level and size would offer more flexibility in integration with commercial utility grids.

The parameters of the microwave beam were established by

Thermal limitations of the 22-kW/m^2 output of the transmitter array
Peak power in the ionosphere of 23 mW/cm^2 to preclude nonlinear heating of the ionosphere
RF power levels incident on the rectenna which are sufficient for efficient reception
Power levels at the edge of the rectenna not to exceed 1 mW/cm^2.

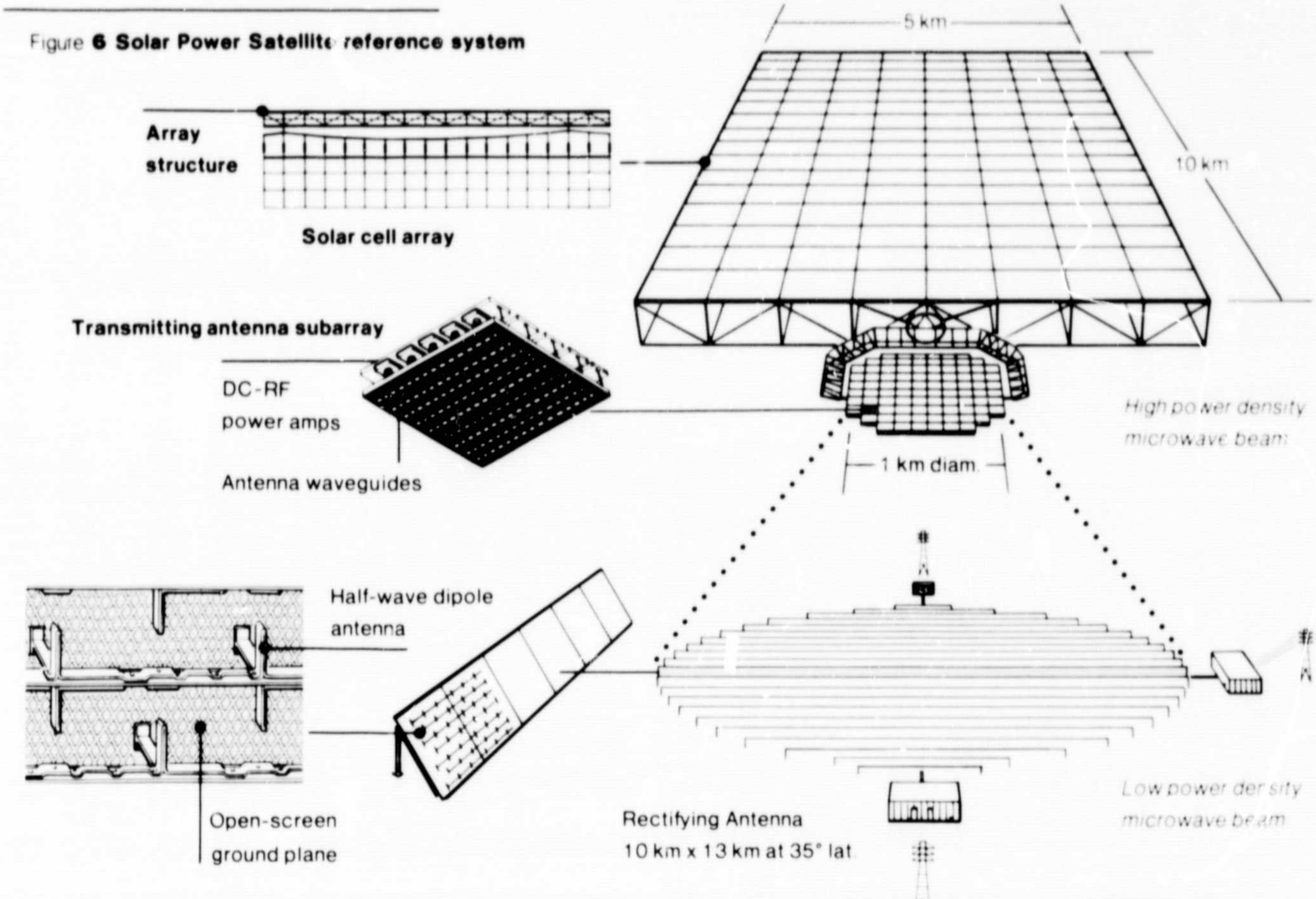


Figure **6** **Solar Power Satellite reference system**

The characteristics of the microwave beam are illustrated in figure **7**. The 1-mW/cm^2 level at the edge of the rectenna is an order of magnitude below the U.S. continuous-exposure standard of 10 mW/cm^2. For comparison, microwave oven door seals are permitted external leakage as great as 5 mW/cm^2.

If a total failure occurs within the Solar Power Satellite phase control system, the total beam will be defocused and the power level reduced to 0.003 mW/cm^2. The RF power-transmission system, therefore, is inherently fail-safe and under control from the ground.

A series of detailed experiments has been designed to develop the data base to remove the uncertainties that now exist.

In order to obtain information on these questions, exploratory research projects are being defined within the current concept evaluation program. One approach would involve the laboratory development and testing of an antenna subarray and its various elements. The transmitting antenna located on the satellite and shown in figure **8** consists of a large number of 10-meter subarrays. Each subarray consists of waveguides, microwave power amplifiers, radiators, and phase control electronics.

The subarray would be tested in an electronic systems test laboratory, a large anechoic chamber with antenna range, and a thermal-vacuum chamber. A test setup involving the anechoic chamber and test range is shown in figure **9**.

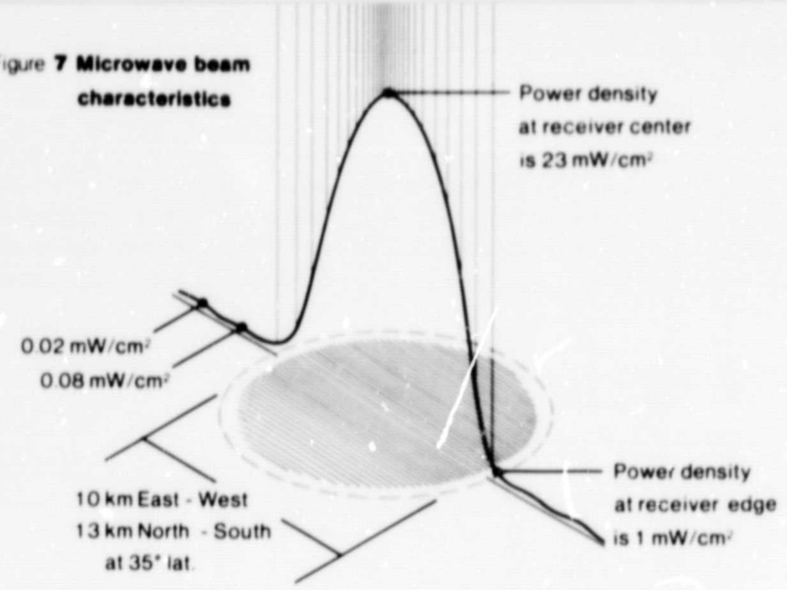


Figure **7** **Microwave beam characteristics**

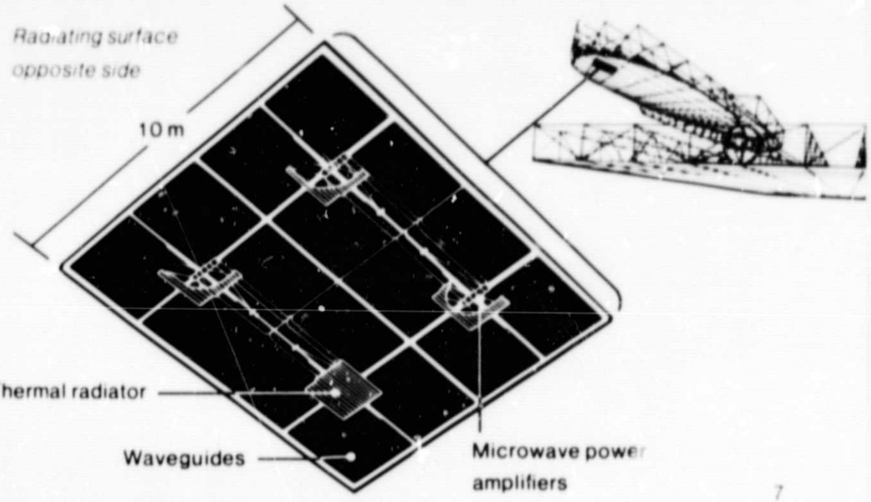


Figure **8** **Transmitting antenna subarray**

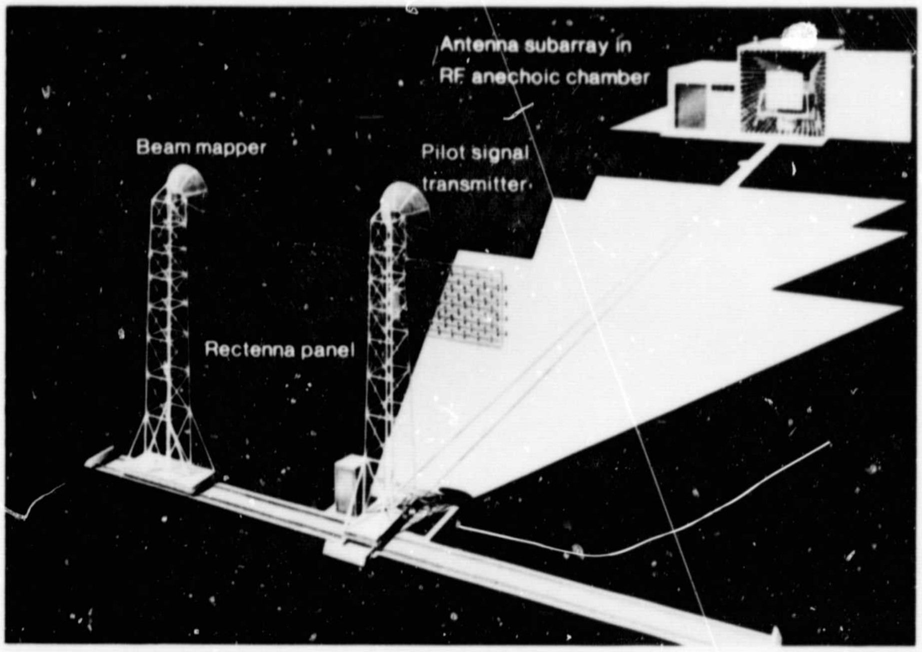


Figure **9** **Subarray test site** rendering

The subarray is mounted in the anechoic chamber and is radiating to a rectenna panel mounted at the end of the antenna range. The total microwave test project would provide quantitative data on critical parameters such as

Transmission/receiving efficiency
RF-to-DC conversion efficiency
Beam forming and steering accuracy
Thermal control characteristics
Mechanical alignment and tolerance effects
Component failure effects
Radiofrequency-interference (RFI) characteristics

Such a project is considered a critical element of a continuing Solar Power Satellite exploratory research program.

The microwave beam environmental concerns are in three areas: *(1) interference with RF communications, (2) interaction with the ionosphere, (3) biological effects on life forms near the ground-based receiver.* The RFI effects due to spurious noise of the space transmitter amplifier tubes are expected to be held below current 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 satellite RF system meet the RFI requirements.

The microwave beam/ionospheric interactions depend on the microwave beam intensity, its frequency, the altitude (D, E, or F regions of the ionosphere), and the angle between the beam and the Earth's magnetic field lines. At some threshold power density level, nonlinear interactions between the power beam and the ionosphere have been predicted to occur. These nonlinear effects could possibly degrade communications and navigation system operations.

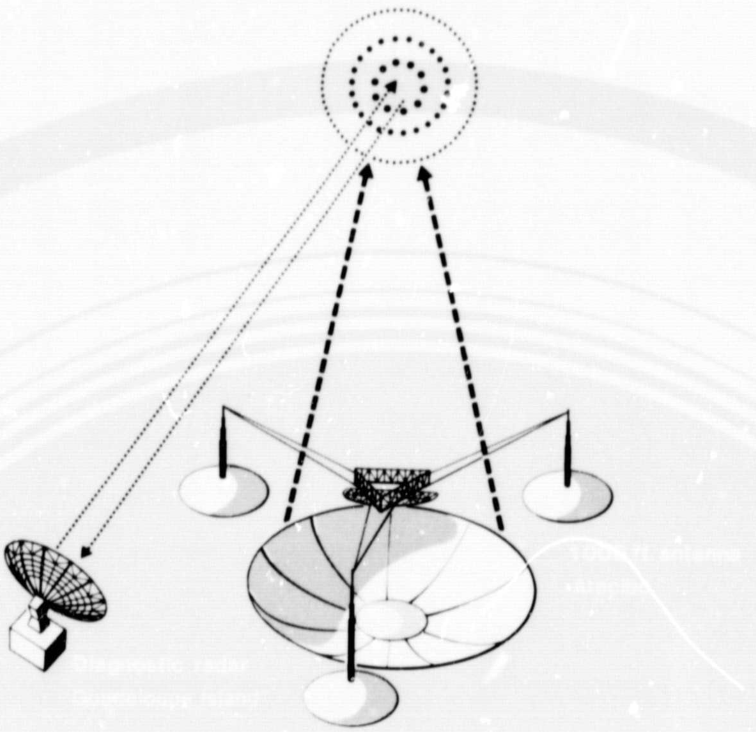
Theoretical studies to date indicate that adverse interactions may occur at power densities greater than 23 mW/cm^2. This level has been used as the design criteria for the microwave system studies. Experimental studies have been initiated to measure the threshold heating levels.

A series of tests, illustrated in figure **10**, were performed at the Arecibo Observatory in Puerto Rico in June 1977 to heat the ionosphere and to look for possible communications effects. Using the existing facilities at Arecibo, the heat input levels to the ionosphere were below the equivalent Solar Power Satellite levels and the heated volume was smaller. For these conditions, no nonlinear heating was observed and no communication effects were detected.

Tests using higher power to equal or exceed the equivalent Solar Power Satellite heating levels are now being defined. These experiments, which will involve communications and diagnostic tests at several facilities over the next several years, will determine the extent and magnitude, if any, of the microwave beam/ionospheric interactions.

Proposed biological studies of microwave beam effects include both intermittent exposure at levels greater that 1 mW/cm^2 and chronic long-term exposure of less than 1 mW/cm^2. The proposed studies have been developed after a literature survey of more than 1000 published documents dealing with the potential effects of microwaves. Unfortunately, there have been very few investigations relating to long-term low-level effects, and, while there is no hard evidence to indicate that significant adverse effects will occur, some controversy does exist. The proposed research will hopefully provide definitive information in this area.

Figure **10 Arecibo Observatory ionospheric heating test**



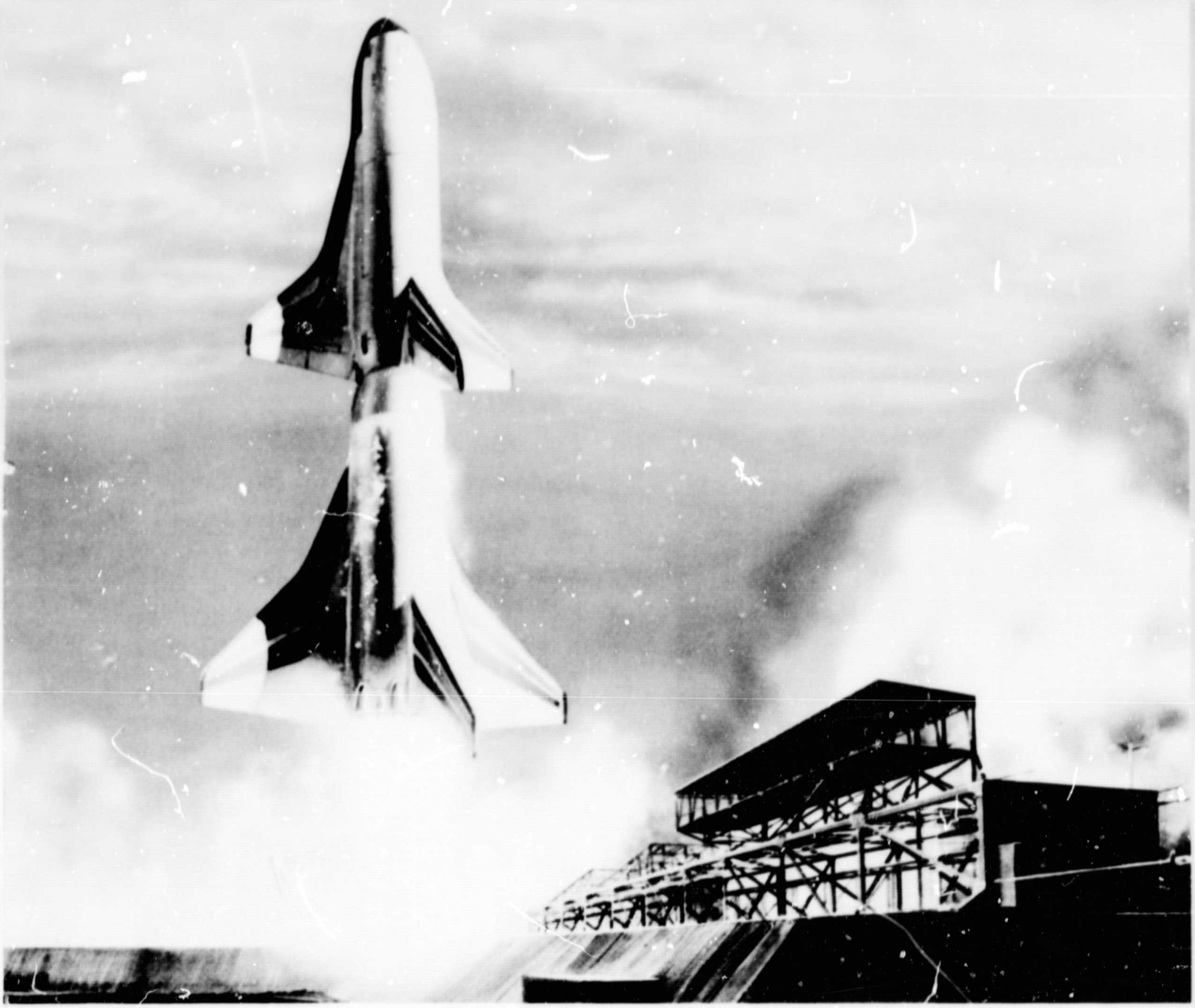


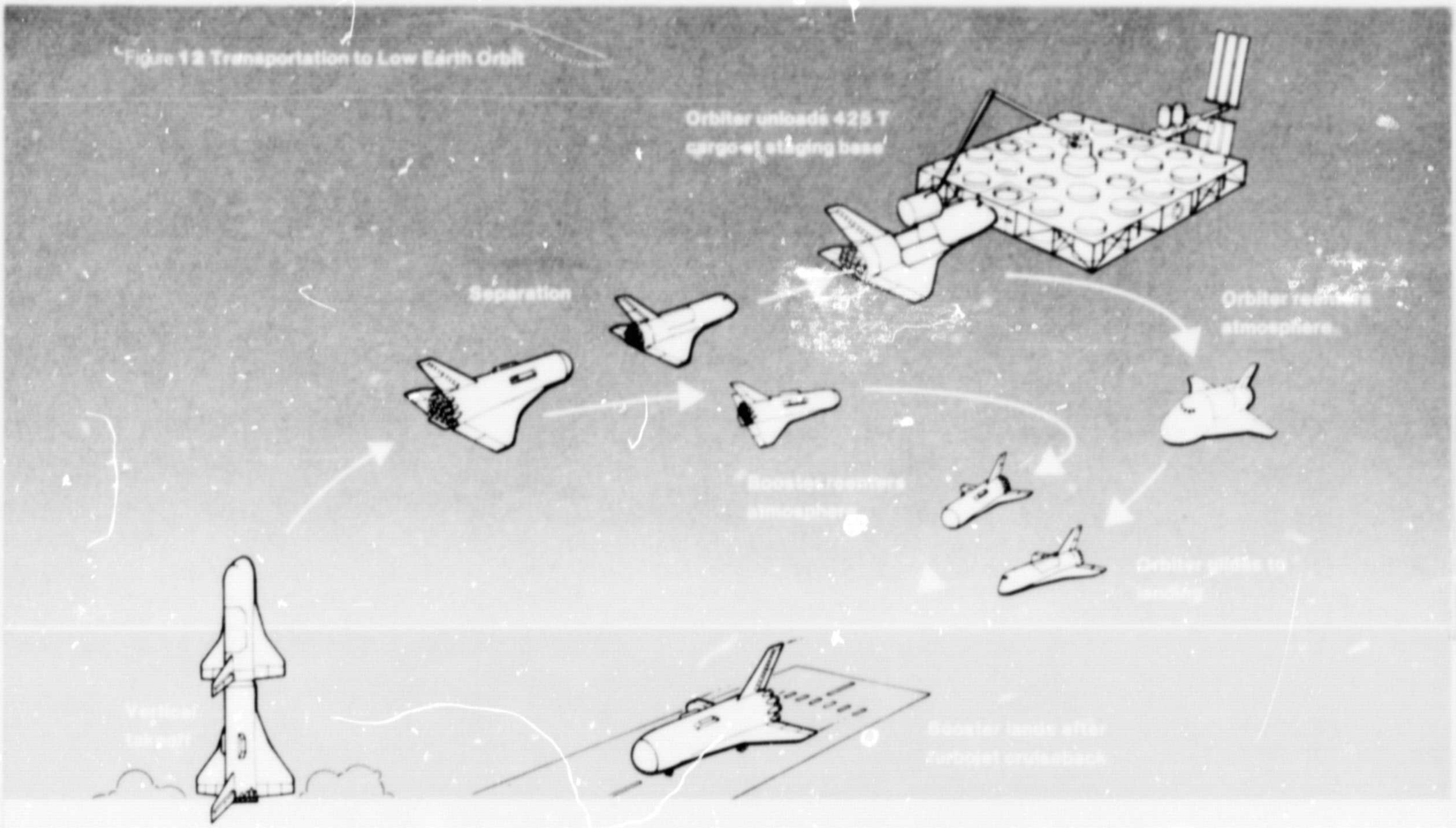
Figure **11** **Space Freighter launch** *rendering*

· Transportation

The development of a commercial satellite network of Solar Power Satellites will require a new, tailored launch system to achieve the economies of scale and to preserve for reuse all vehicle elements, including propellant tanks. A vehicle design capable of a single-mission delivery of about 425 metric tons to low Earth orbit is illustrated in figure **11**. It has a height of 500 feet and has wings on both stages for intact recovery of the vehicle. Landing weight of the second stage, the Orbiter, is about 850 000 pounds, twice the landing weight of a Boeing 747. 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 as the oxidizer.

Each Solar Power Satellite launch-vehicle flight, as shown in figure **12**, will make delivery of 425-ton payloads consisting of satellite components, building materials, construction equipment, and expendable supplies to a low-Earth-orbit staging base. Both stages return to an Earth landing strip to load cargo for the next flight.

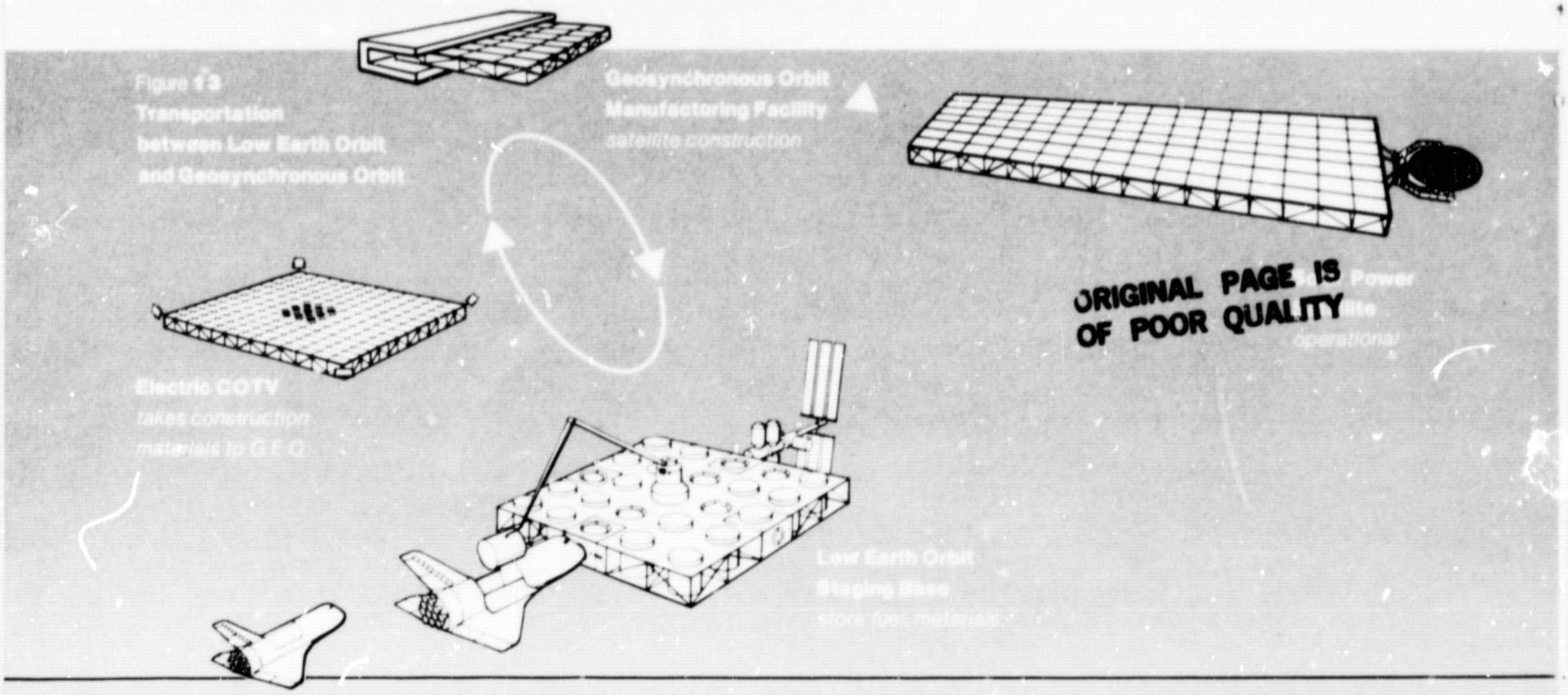
Figure 12 Transportation to Low Earth Orbit



The low Earth orbit to geosynchronous orbit transfer employs electric propulsion with an independent ion-drive transfer stage (figure **13**). The ion engines use argon as the propellant. The solar array to produce the necessary electrical power would remain a part of the vehicle and be returned to low Earth orbit for reuse. This approach combines the opportunity to perform construction at the final geostationary orbit with the propellant economy of electric propulsion. Repeated flights of a solar array through the inner Van Allen Belt will constitute 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 using a laser beam may demonstrate that this radiation damage can be reversed between missions. Gallium arsenide cells in laboratory tests indicate a "self-healing" characteristic when operated at temperatures which might be generated using concentrators.

Conventional chemical rockets using hydrogen-oxygen propellants may also be employed to transfer launch vehicle cargo to geostationary orbit, permitting construction at that

Figure **13**
Transportation
between Low Earth Orbit
and Geosynchronous Orbit



location. Because of the relatively poor efficiency of chemical rockets compared to that of 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 a Solar Power Satellite in operation.

If Solar Power Satellite modules were fabricated at the low-orbit altitude, completed modules could be "self-powered" to geosynchronous orbit. The electrical output of less than 20% of the satellite module solar array would provide sufficient electrical power to panels of ion-driven electric propulsion rocket engines. The remaining 80% of the array on the satellite module would remain protected from the Van Allen Belt radiation. While this approach might be estimated to be cost competitive with the independent electric orbital transfer vehicle, it does require construction in low Earth orbit with its attendant problems.

The possible environmental effects of the launch vehicle emissions are primarily related to the launch vehicle size and rate of use necessary to construct a Solar Power Satellite network.

The construction of a 5000-megawatt satellite will require about 200 flights of the heavy-lift launch vehicle to low Earth orbit. The resulting combustion products of 300 000 tons of methane and 60 000 tons of hydrogen are primarily carbon dioxide and water vapor. For perspective, an equivalent amount would be produced by fossil-fired powerplants of equal electrical generating capacity to the satellite in about 7 months of operation.

If the combustion products predicted for Solar Power Satellite launch activity are compared with those produced by automobiles, gas flaring in oil production, industrial boiler use, etc., it is apparent that a large Solar Power Satellite launch activity would not be a significant contributor to the total combustion products generated by our present economy.

The launch vehicle, unlike ground sources, traverses the atmosphere and distributes its exhaust products over a range of altitudes. The methane-fueled first stage operates to about a 50-kilometer altitude and the hydrogen-fueled second stage completes the insertion into orbit at an altitude of about 120 kilometers. Water vapor and hot hydrogen exhaust products are therefore injected into the lower ionosphere (D and E layers) but not into the "F" region at 200 to 300 kilometers altitude.

Specific environmental studies are now underway to further identify and quantify the effects of launch vehicle and orbital transfer vehicle emissions.

All systems studies conducted to date have shown that the cost of the transportation of construction material to space from Earth will be a significant cost element of a commercial system. Because of cost considerations, this new system, illustrated in figure **14**, must be designed and operated in a manner to greatly reduce transportation costs. The approach to achieving this goal involves total reusability and a high utilization rate of the space transportation system in a manner similar to commercial aircraft operations.

Figure **14 Space Transportation System to Low Earth Orbit**

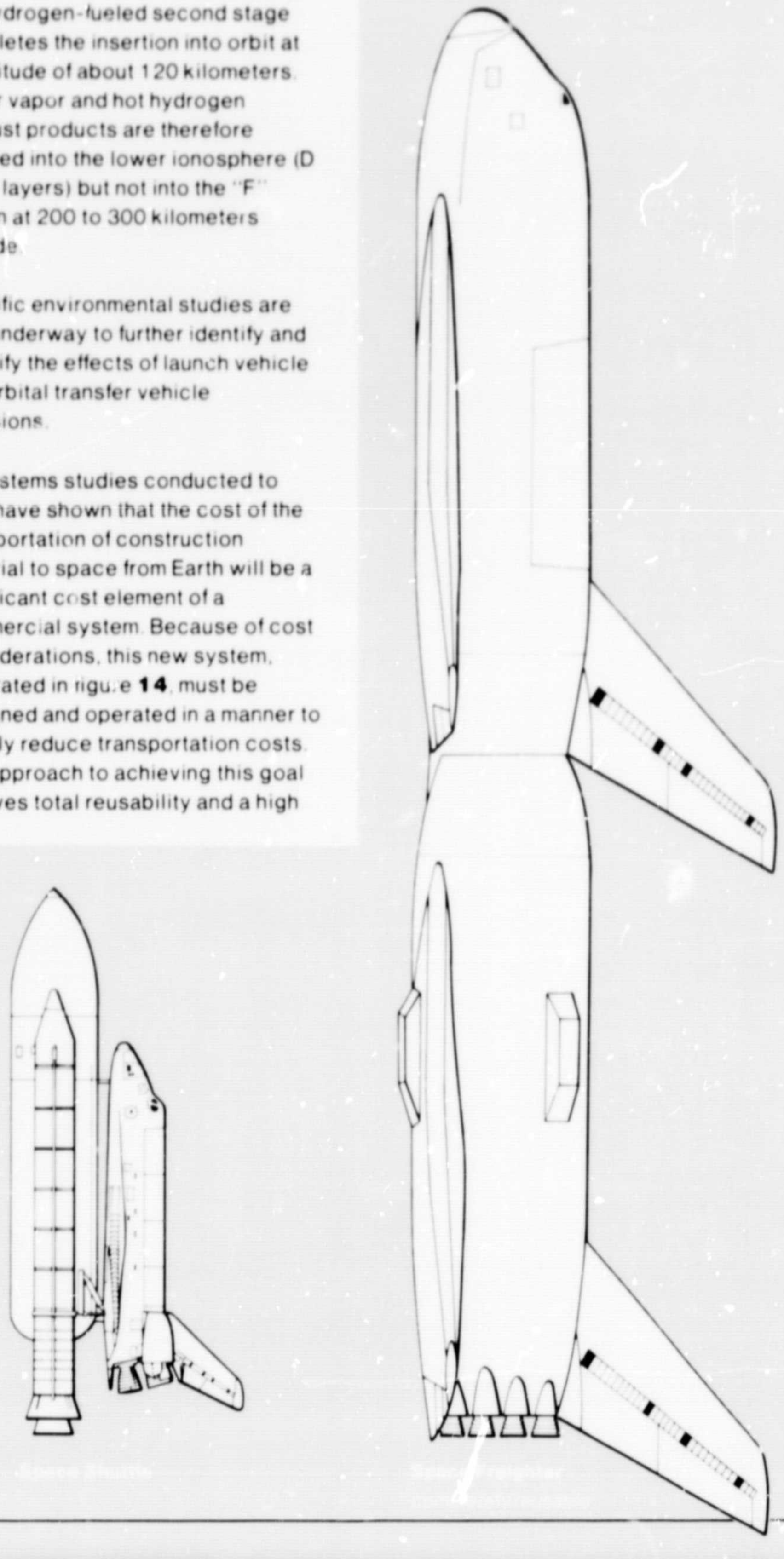


Figure **15 Space Shuttle Orbiter landing** photograph

Fortunately, the nation has already embarked on a program of space transportation system reusability. The reusable Shuttle Orbiter (figure **15**) has been in development for the last six years. A major goal of this program is to reduce space transportation costs, and the approach to this reduction is recovery and reuse of the Orbiter component of the Shuttle system. The Shuttle system is scheduled for its first orbital test in late 1979. It will be the primary U.S. space transportation system of the 1980's. The Shuttle Program will provide quantitative data on the economics of reusable space systems and thus contribute valuable information for Solar Power Satellite cost assessment.

The Shuttle system with its crew of 7, its payload capability of 30 tons, and its large volume will also provide a vital capability for the development and demonstration of various Solar Power Satellite technologies, as well as providing pertinent economic information.

While the Shuttle will provide valuable information, research programs on electrical propulsion should be expanded and new efforts undertaken for the definition of engines for a Solar Power Satellite launch vehicle, accompanied by heat transfer testing and other exploratory research.

· Construction

Construction in space of the large structures required by the satellite is a task which is formidable in scale (figure **16**). Concepts have been developed, however, which are believed to be capable of constructing a 5000-megawatt satellite within 6 months. Space construction requires protection of the work force, and some materials, 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. Structural members may therefore be much lighter than terrestrial structures of the same span and stiffness. Second, *the absence of gravitational forces 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.*

In order to minimize space transportation costs, the Solar Power Satellite program will need to package its construction materials in a very dense form. The need to construct very-low-density lightweight systems from high-density materials leads to a requirement for automated fabrication techniques. Such techniques will allow the payloads to be densely packaged for launch in the form of tightly wound rolls of construction materials.

Since repetitive operations are more readily automated, regular uniform-cross-section structural members are planned for use in construction of the satellite. Figure **17** illustrates the basic structural element of the satellite. A process similar to the familiar roll forming of light sheet metal members has been adapted to produce these structural members at a rapid pace using an automated beam builder (figure **18**). This machine consists of roll-forming, heating and cooling, and ultrasonic welding components which function to "extrude" a finished beam. These basic structural members may be produced from rolls of aluminum strip stock or from a graphite fiber/thermoplastic-impregnated roll.

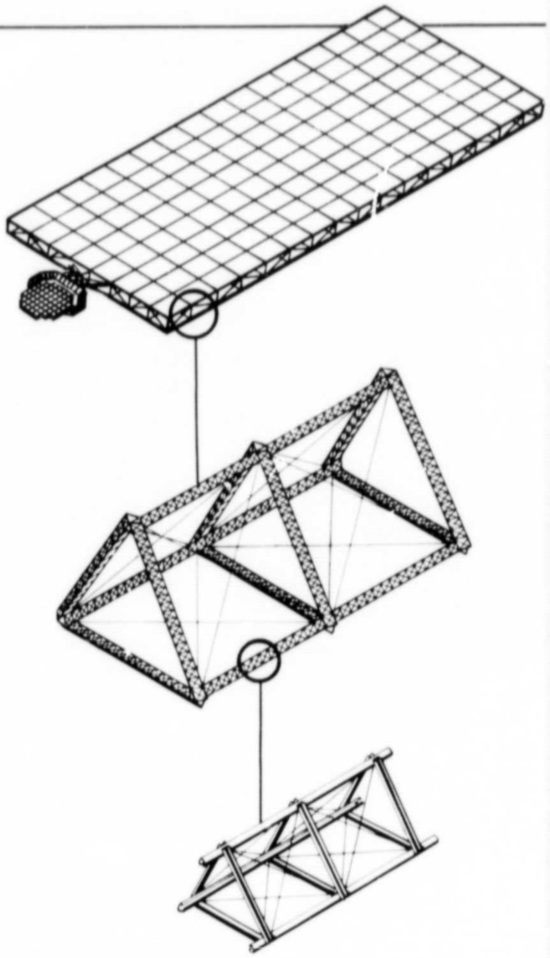


Figure **17 Basic structural element**

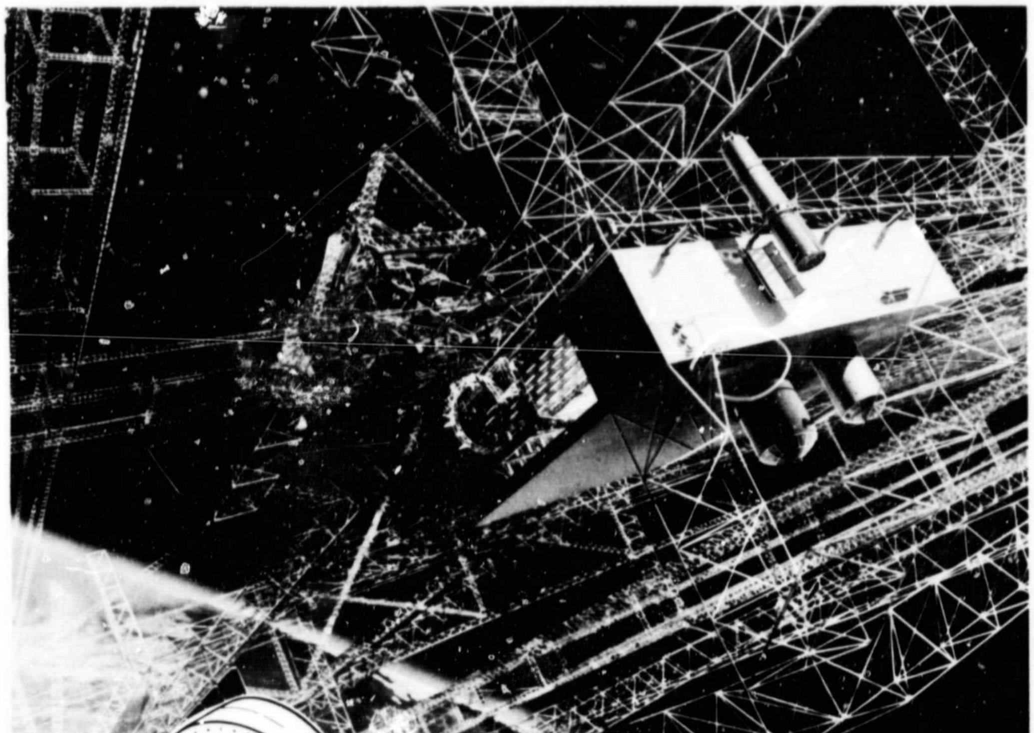


Figure **16 Construction Facility** *rendering*

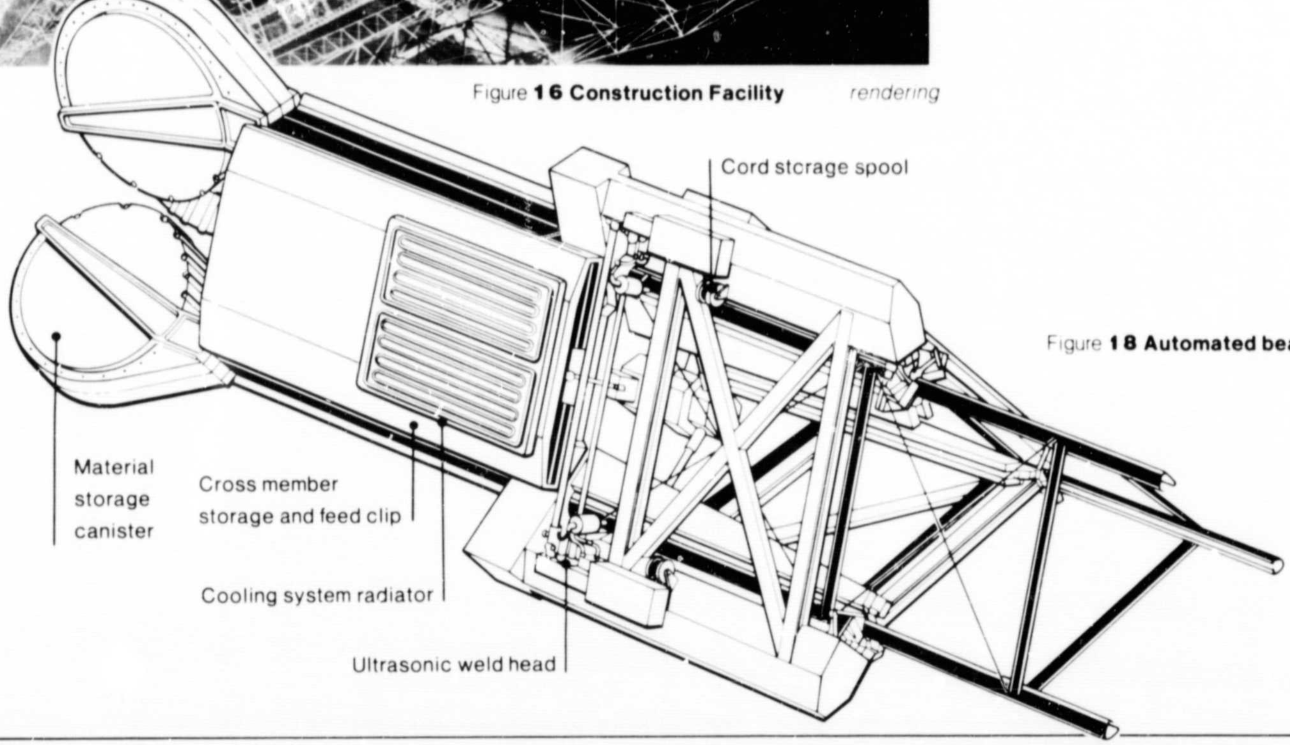


Figure **18 Automated beam builder**

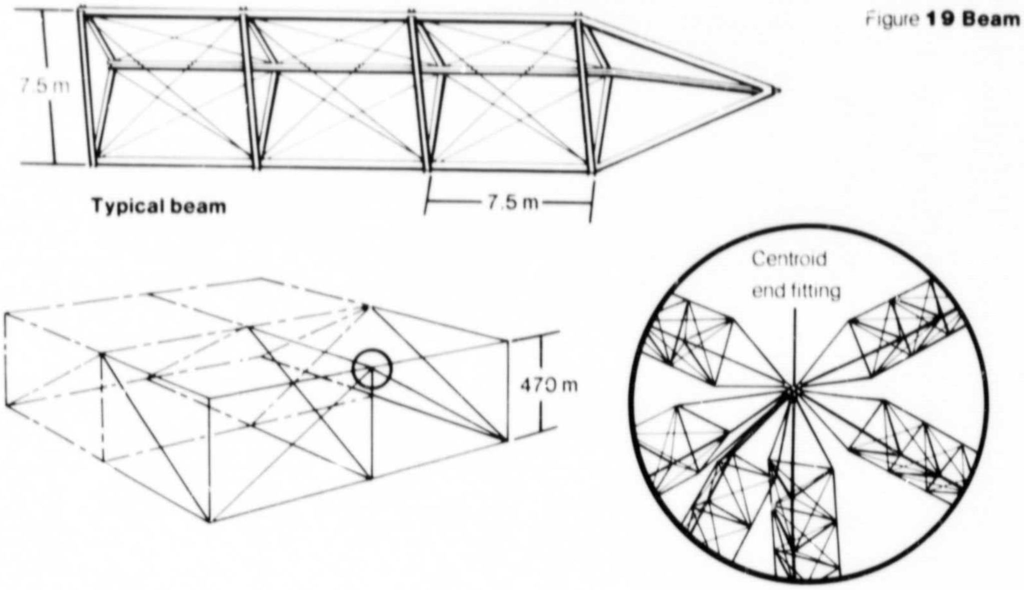


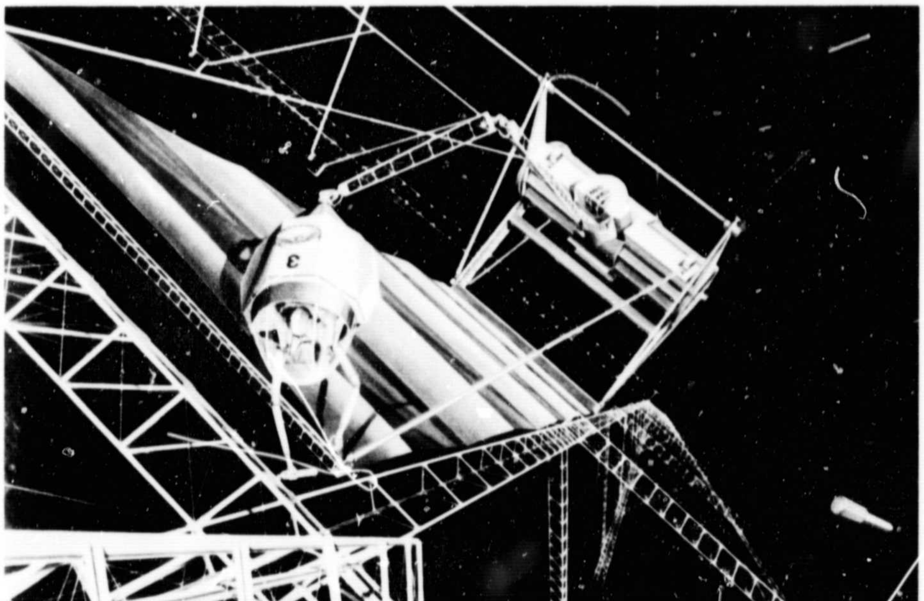
Figure **19** **Beam construction**

The latter material has the advantages of a high modulus and a low coefficient of thermal expansion. The basic structural element of the satellite, a triangular cross-section shape, may be assembled into primary-structure triangular trusses (figure **19**). These members are then assembled into a trussed box structure for the structural support of the solar-blanket membrane.

Similar elements are assembled into a heavier configuration for the microwave antenna structure in order to achieve the necessary stability and surface flatness for operation of the phased-array RF system.

A number of other specialized techniques and equipment will be required for other necessary construction functions such as the deployment and attachment of solar arrays to the basic structure (figure **20**).

Figure **20** **Installation of solar blanket tension devices** *rendering*



Two orbital locations for the primary construction activities in space have been studied. Construction in the geostationary orbit offers the advantage of continuous sunlight, which decreases the differential thermal effects on the structure during construction and reduces the need for artificial illumination of the workplace. Additionally, the construction process can be designed to produce the satellite in its final operational form, eliminating a module berthing operation. Finally, it avoids the requirement to transfer the large system from low Earth orbit to geosynchronous orbit.

The low Earth orbit approach, however, does provide the advantage of operating in close proximity to Earth and shares, 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 relatively large gravity gradient torques during construction and transit. To lessen these torques, the satellite could be constructed in low Earth orbit in modules, with final joining or berthing of the modules at the geostationary operational orbit.

The number of persons involved in the construction process is a function of the degree of automation employed. The size of the construction crew also depends on 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 construction at the rate of two 5000-megawatt satellites of new capacity per year. Contrary to intuitive impressions, cost analyses have indicated that the Solar Power Satellite system cost is relatively insensitive to crew size in space.

Construction activities in space lead to the need for protecting personnel from the natural environmental hazards. Provisions for a life-supporting atmosphere and protection from solar thermal and ultraviolet radiation are well-understood engineering problems. Protection from energetic particle fluxes requires that more knowledge be gained on the expected dynamic range of these phenomena so that engineering measures to shield space workers can be accomplished. Exposure standards must also be established to determine the necessary protective measures.

The extremely large size but very-low-density characteristics of the satellite require that it be constructed in space, or "onsite." It is anticipated that other programs of the future will also require satellites of a size that will require construction in space. For example, future communications satellites are expected to utilize platforms with multiple antennas and functions (figure **21**). Such satellites and other developing requirements, as well as the Solar Power Satellite, will require the development of the new space discipline of construction. There has been little or no experience to date in space construction.

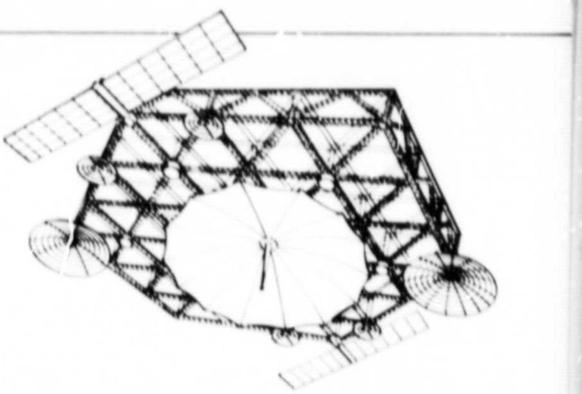


Figure **21 Multifunction communications platform**

The currently planned Shuttle Program does include a "space crane" in the form of the remote manipulator (figure **22**). This device, being funded and developed by the Canadian Government, is designed to deploy payloads from the Shuttle payload bay. Its general characteristics should make it capable of supporting construction activities. The total construction activity, however, will require a variety of tools and techniques.

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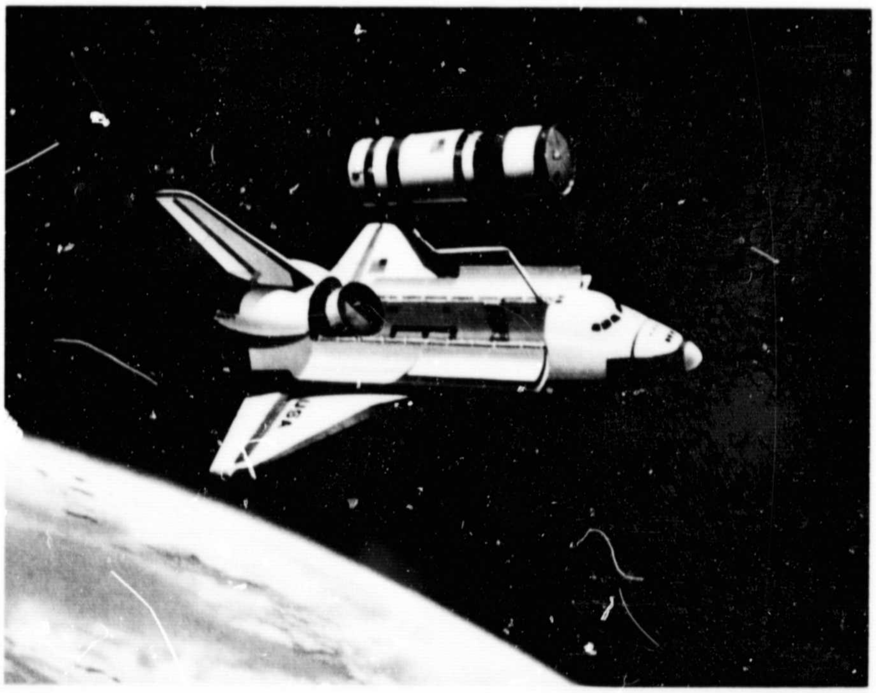
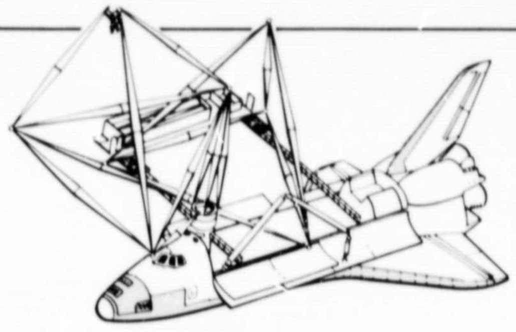
Figure **22 Remote Manipulator System** *rendering*





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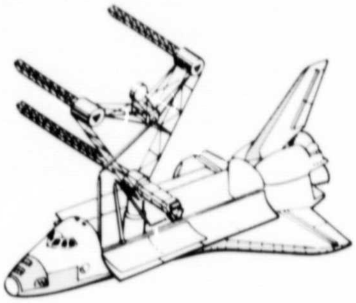
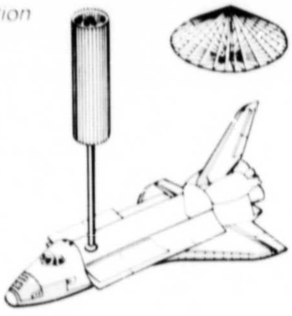


fabrication



deployment

Figure **23** **Construction techniques**

Consequently, a "Large Space System Technology Program" has been initiated to develop techniques for space construction (figure **23**). These techniques include erection, deployment, and automated fabrication methods.

Automated fabrication is believed to be a key requirement for a viable Solar Power Satellite program. Some laboratory work is underway to study such machines. Figure **24** presents a prototype machine (left) made by the Grumman Aerospace Company which is capable of producing a lightweight aluminum beam and a device (right) for forming graphite composite beam caps developed by the General Dynamics Corporation. The graphite composite material requires the use of heaters and coolers as well as the roll-forming elements required in building the aluminum beam.

In addition to the fundamental construction techniques, numerous other elements of construction systems are being identified (figure **25**), and technology activities are being initiated as funding becomes available.

Continued development and evaluation of space construction techniques is a critical area to the assessment of the Solar Power Satellite concept. Fortunately, a modest technology program is underway, and hopefully it can be expanded in the near future. At an appropriate stage of development, these techniques and devices will require evaluation in space.

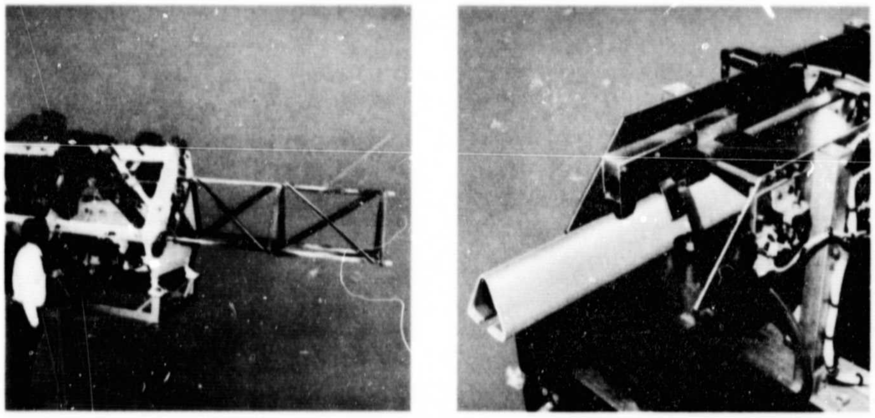
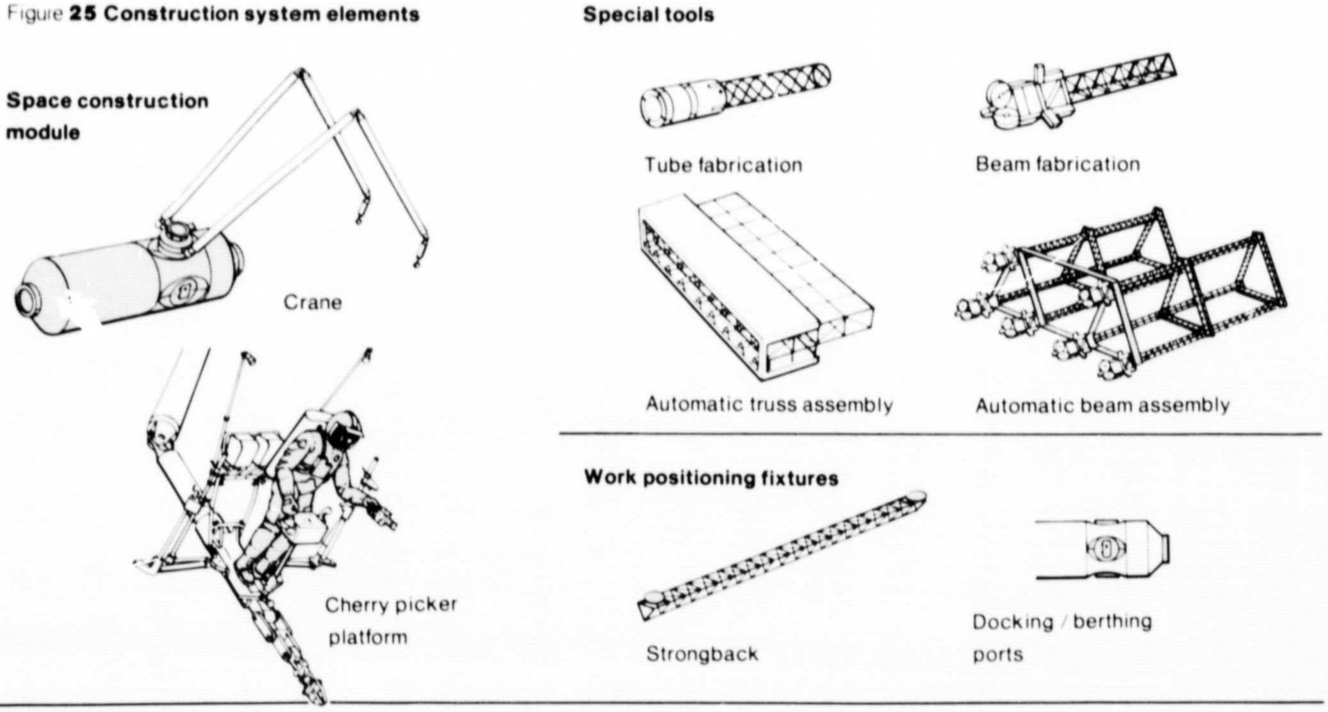


Figure **24** **Prototype automated beam builder** *photograph*

Figure **25** **Construction system elements**



Cost Considerations

Cost projections for any advanced energy system are very difficult to develop. All such estimates require assumptions related to technological advancement over an extended period of time. Nevertheless, the evaluation of a potential system requires such projections, and a number of cost estimates have been developed during the course of studying the Solar Power Satellite concept over the past several years.

Capital costs for the Solar Power Satellite 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, which varied from $130/kW to $921/kW, and construction time, which varied from 1 to 6 years.

Improved definition of the satellite, ground receiver, space transportation system, and construction process resulted in estimates of $2000/kW to $2700/kW capital costs. 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 relatively inexpensive to maintain and operate in the space environment.*

Consideration of these factors and capital costs on the order of $2500/kW result in an electricity cost at the ground receiver output of 5.5 cents/kWh.

Two of the major cost elements of the Solar Power Satellite are the solar cell arrays and the space transportation. The cost estimates for solar cells generally represent extrapolations from current programs which are directed towards the development of solar cells for Earth use. Goals of the Department of Energy photovoltaic program are for costs of $2000/kW by 1982, $500/kW by 1986, and $100/kW to $300/kW by the 1990's. Confidence is building that these goals will be met, which in turn provides a degree of confidence that estimates used in the Solar Power Satellite assessment can be achieved by the turn of the century.

Space transportation costs will represent approximately one-third of the total cost of implementing a Solar Power Satellite. The major element within this cost is the transportation of material to low Earth orbit using the large launch system previously described. Based on very high frequency of use and full reusability, launch costs for this vehicle are predicted to be similar to those for the Shuttle. The costs of fuel used in this estimate are those for hydrogen and methane obtained from the gasification of coal. The Solar Power Satellite electricity cost estimate of 5.5 cents/kWh assumed a transportation cost of $15/lb to low Earth orbit.

Obviously, this represents a significant reduction from projected Shuttle costs. Analysis indicates, however, that complete reusability and large-scale operations offer this potential.

One of the negative concerns often expressed is the "front end" money required to implement a full-scale Solar Power Satellite program. There is no question that a considerable amount of funding would be required. Estimates have ranged from $50 to $100 billion over a 15- to 20-year period. This subject certainly deserves careful consideration by individuals skilled in the appropriate fields of economics and national investment. I would suggest, however, that we should view this $100 billion in the context of a total national energy development and supply program which certainly will involve trillions of dollars between now and the year 2000.

As previously stated, the projection of costs for energy systems involving advanced technology is difficult and generally controversial. It is expected, however, that these estimates will improve as more definitive data are obtained. In the meantime, they are useful in identifying the more important cost parameters within the system and the sensitivity of total costs to changes in the cost of various system elements.

Future Activities

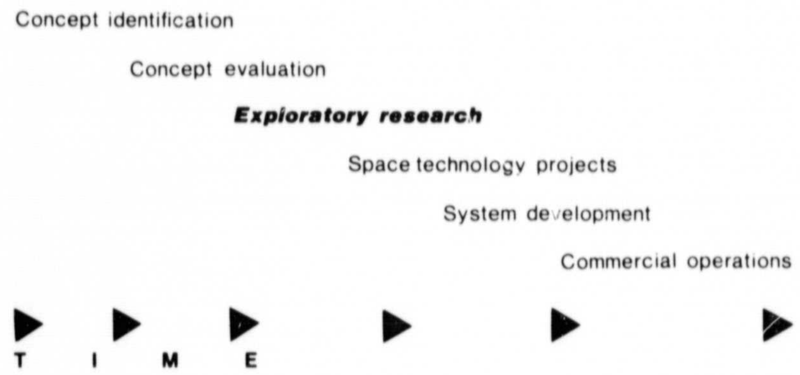
The development of Solar Power Satellites on a commercial scale would obviously be a very large undertaking. It is equally obvious that inadequate information exists at the present time to commit to a full-scale development program. For these reasons, many, if not all, of the individuals who have studied the concept would propose a phased and evolutionary activity, where each phase was based on the success of the previous phase. The succeeding phases would tend to be greater in scope and cost but would be based on increased confidence in the technical, environmental, and economic viability of the concept. Figure **26** presents typical phases which might be included in such an evolutionary plan. The phases include concept identification and preliminary studies; a concept evaluation program now underway; an exploratory research phase to answer critical questions through laboratory development and testing; and a series of space technology projects to develop operational techniques and to demonstrate key elements of the system. The combined results of these four phases of activity would provide the necessary information on which to base a decision for the very large commitment to full-scale system development and commercial operations.

Estimating the costs of electricity from a Solar Power Satellite network is a challenging task. The economic viability of the concept will depend significantly on the ability to develop techniques for the mass production of solar cells at extremely low costs, and on the ability to reduce space transportation costs through complete system reusability and high traffic volume.

Environmental considerations of the concept have focused primarily on the microwave transmission beam and its possible effects on the ionosphere, and on the low-level microwave energy that will exist outside the ground receiving antenna. Microwave energy levels in these two areas have been kept purposely low to avoid concern; however, the paucity of definitive data on microwave effects makes it difficult to provide absolute answers to all questions at the present time.

Preliminary estimates of natural resource requirements and energy payback intervals are generally encouraging, recognizing possible specific problems with particular resources and with critical assumptions within the energy payback estimates.

Figure **26 Evolutionary program phasing**



Summary of Systems Definition Studies to Date

The systems definition studies have considered photovoltaic and thermal energy conversion systems and found both to be technically feasible, with the photovoltaic approach believed to offer certain advantages. Analysis of the microwave transmission system has emphasized the development of techniques for forming and steering the beam to the required accuracy and the performance required of the various subelements of the system. Ballistic and winged launch vehicles have

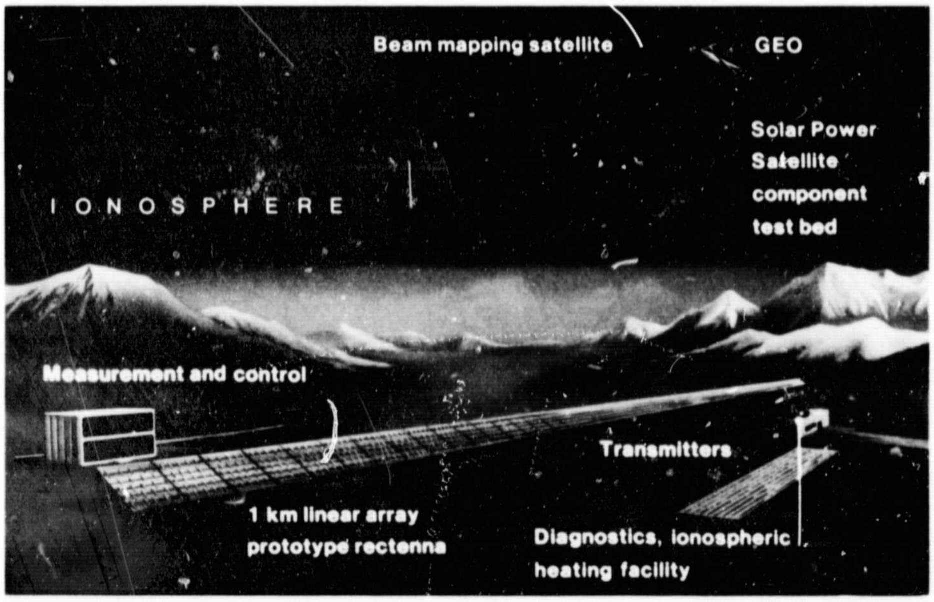


Figure **27 Large-scale inverted test concept** rendering been defined for the transportation of construction materials to low Earth orbit, and chemical and electric propulsion systems have been analyzed for the low Earth orbit to geosynchronous orbit transfer. The relative merits of constructing in low Earth orbit or geosynchronous orbit have been evaluated, and construction concepts have been defined.

Based on the various trade-off studies conducted, a reference system has been defined to provide a basis for assessing alternate technical approaches and for evaluating the concept from the standpoint of environmental and other considerations. Such a reference system should not be interpreted as a preferred or baseline design, nor should research and technology programs be limited to a single approach.

As described earlier, the concept evaluation phase of the program is currently underway. This phase is scheduled for completion in 1980. It will result in a recommendation as to whether the concept should be explored further and, if so, in what manner. The recommendation will be based on technical feasibility, economic and environmental considerations, and comparisons with other potential systems of the future.

It is premature to speculate on the conclusions and recommendations from the evaluation program as to whether or not the program should proceed to the next phase. However, the systems definition studies conducted to date have provided us with insight about the nature of technological activities that might be conducted in an exploratory research phase.

A key feature of such an exploratory research program would be laboratory development and testing to provide quantitative data concerning the microwave transmission system. Such an effort would provide not only technological data related to feasibility, performance, and transmission efficiency but also the means for critical environmental assessments. The microwave program should be complemented by efforts in other disciplines to provide answers to critical questions. We have given examples of these efforts in the foregoing discussion.

Following an exploratory research program which would be primarily ground based, a series of space projects would constitute the next phase in the development of the concept. The space project phase is not completely defined at the present time. It will require ingenuity to devise projects that will provide the required data at minimum cost. An example of such ingenuity in project planning is illustrated in figure **27**. This project is directed towards verification of the ability to electronically form and steer the microwave beam within its required accuracy. The project approach would involve constructing a "slice" of the space transmitting antenna and locating it on the Earth. A pilot beam, which normally would be transmitted from Earth, would be transmitted from geosynchronous orbit to interact with the antenna now located on Earth. The role of the Earth-based rectenna would be played by a beam-mapping satellite also located in geosynchronous orbit. To complete the simulation, a separate ground-based transmitter would be utilized to heat the ionosphere where the pilot beam passes through so that the beam would be subjected to the same conditions as in the operational case. This "inverted" test concept offers a rather complete simulation while greatly reducing the hardware that must be placed at geosynchronous orbit, thereby greatly reducing project costs.

Other projects must be defined to encompass the total requirements of a space technology program for the Solar Power Satellite. A major consideration has to do with a Solar Power Satellite "demonstration." Since the satellite was first studied, the concept of a "demonstration" has been discussed. The purpose of this "demonstrator," and consequently its technical definition, varies greatly depending on specific viewpoints. One view would look on the "demonstrator" as a device which would provide significant power, on the order of 500 megawatts, to the ground to demonstrate for technical and lay persons alike the feasibility of the concept. Variations of this approach include transmission of smaller amounts of power, down to the order of 1 kilowatt or less. In addition to variations in power, there is an option as to whether the demonstration needs to be continuous or whether it could be intermittent. If intermittent power is adequate, then the satellite could be placed in low Earth orbit at much less expense, although certain technical considerations might make such a test difficult to implement.

The timing of such a demonstration is critical. If it were done prior to a commitment to full-scale development, it would be important to limit its scope and requirements for new development, such as large-scale transportation systems. If the activity were done during the course of the development of the full-scale system, the consideration would be different since the decision for new developments would already have been made. A completely different approach to the "demonstrator" would emphasize demonstration of construction productivity rather than transmission of power to the ground.

Given this range of variables, it is apparent that the scope and cost of a "demonstration" project may vary widely. We are currently studying this range of options in order to provide a quantitative base for further considerations.

Concluding Remarks

Over the past years, various studies have defined system approaches for implementing the Solar Power Satellite concept. More important than any specific approach is the identification and quantification of the technological improvements required for the concept to be technologically and economically viable. Environmental studies now underway will soon achieve an equal degree of maturity.

There is no question that the technical and economic challenges of the Solar Power Satellite are great; however, before we discard the concept on this basis, we must give proper attention to the time span with which the concept is identified. Even the enthusiastic advocates of the concept would agree that it will take 15 to 25 years to implement a full-scale satellite. Given that time period, we might reflect on the progress in space and technology over the last 20 years as briefly summarized in figure **28**. During that time, we have effected an extensive and intensive advancement of technology in all aspects of space activities; satellites have demonstrated long life without maintenance; reliable communications have been effected over millions of miles as well as for extensive commercial application; solar cell and fuel cell energy systems have been developed and applied to space needs; space transportation systems capable of lifting 120 tons to low Earth orbit have been developed and reusable transportation systems are imminent; and, finally, we have conducted manned operations 240 000 miles from Earth and for up to 90 days near Earth.

There are many other ways of measuring our technological advances, such as computer efficiencies and the great reduction in computation costs. The question is whether we have the confidence that our young people of today can achieve the advances over the next 20 years that we have in the last 20 years. Given the proper support, I have no doubt that they will achieve even greater progress. Furthermore, I believe that the space program provides a stimulus and attraction to a type of young people that can accomplish these challenges.

During this last year, we selected 35 astronaut candidates. We expected a reasonable degree of interest; however, we were overwhelmed by a flood of 8500 applicants. The large majority of these were not pilot astronaut candidates but mission astronauts, and they came from a multitude of technical disciplines. The quality of the large majority of these candidates made a final selection inordinately difficult.

The significance of the continuing interest of these highly qualified and educated young people provides me with the confidence that the competence and enthusiasm exists to meet the challenges required to develop a viable Solar Power Satellite.

The question of financial resources is an obvious one in relation to the pursuit of the Solar Power Satellite concept. We all recognize that, at this time, the demands on the Federal budget are stringent. Many programs are competing for funds in a time when the budget must be constrained. Consequently, it is not surprising that large amounts of funding may not be able to be allocated to the study of this concept. I believe we all understand this limitation and can accept the challenge to make the most progress with limited funds. I believe, however, that a program so limited must have a proportionately larger degree of positive management support and leadership to confirm the importance of the concept's potential.

In conclusion, I would reiterate my belief that the Solar Power Satellite concept is one, *if not the only*, potential space project that appears possible within our capability that can provide a needed resource of incomparable importance. Given such a situation, can we do other than give it our most careful consideration and support?

Figure **28 Space technology** 1958 - 1978

- **Extensive - intensive technology development**
  - **Long-life satellite without maintenance**
    - **Reliable communications over millions of miles**
      - **Solar cell and fuel energy systems**
        - **120-ton payloads**
          - **Manned operations**

            240 000 miles from Earth
            ~ 90 days in space