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# Space Solar Power

(NASA-TM-79436) SPACE SOLAR POWER.

N78-21611

DESCRIPTION OF CONCEPT, RESULTS OF  
PRELIMINARY STUDIES, REQUIREMENTS FOR  
EVALUATION (National Aeronautics and Space  
Administration) 21 p HC A02/MF A01 CSCL 10A G3/44

Unclas  
15186

Description of Concept

Results of Preliminary Studies

Requirements for Evaluation

March 30, 1977



## **INTRODUCTION**

To support a growing population and to improve the quality of life for that population, the requirements for energy in the U.S. and world will continue to increase. Projections indicate that U.S. requirements may grow by a factor of two to three between now and 2000.

The nation is actively pursuing alternate sources of energy because of the problems or concerns related to obtaining required energy for the future from oil, gas, nuclear, and coal sources. Solar energy is an obvious candidate for consideration. Solar energy is inexhaustible and clean. Its use in the past has been limited by the relative cost of collecting and converting solar energy into electrical power. The increasing costs of other energy sources will make solar energy more attractive.

During recent years a new concept for the collection of solar energy has been developed. This concept involves the location of solar power stations in space. This brochure presents the concept, results of preliminary studies, and requirements for space evaluation.

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## **A SPACE SOLAR POWER CONCEPT**

The space solar power concept is illustrated in Figure 1. A large solar collector is located in a geosynchronous orbit that is approximately 22,000 miles above the earth. In geosynchronous orbit there is no day or night, clouds, or atmosphere to interfere with the solar energy reaching the collector. Six to fifteen times as much solar energy will be received in space as on the ground in a given period of time for a given size collector. Equally important, it will be continuously received. The geosynchronous location of the solar collector means that it remains fixed over the same spot on the earth and can provide continuous power to a given location.

The solar energy collected in space is converted into microwave energy by devices such as klystrons or amplitrans. Energy is beamed to earth by using a transmitting antenna as illustrated by the circular device at either end of the large collector. The energy is received at the earth's surface by a "rectenna" (rectifying antenna). The received microwave energy is converted to conventional forms of electrical power and transmitted to nearby cities and industries. It should be noted that the receiving rectenna can be located in the area where the power is to be used and does not have to be located in areas of the country where there is a high percentage of sunlight. This is because the microwave beam is not affected by day, night, or clouds, and only by the atmosphere under particularly adverse conditions.

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# SPACE SOLAR POWER CONCEPT

GEOSYNCHRONOUS ORBIT

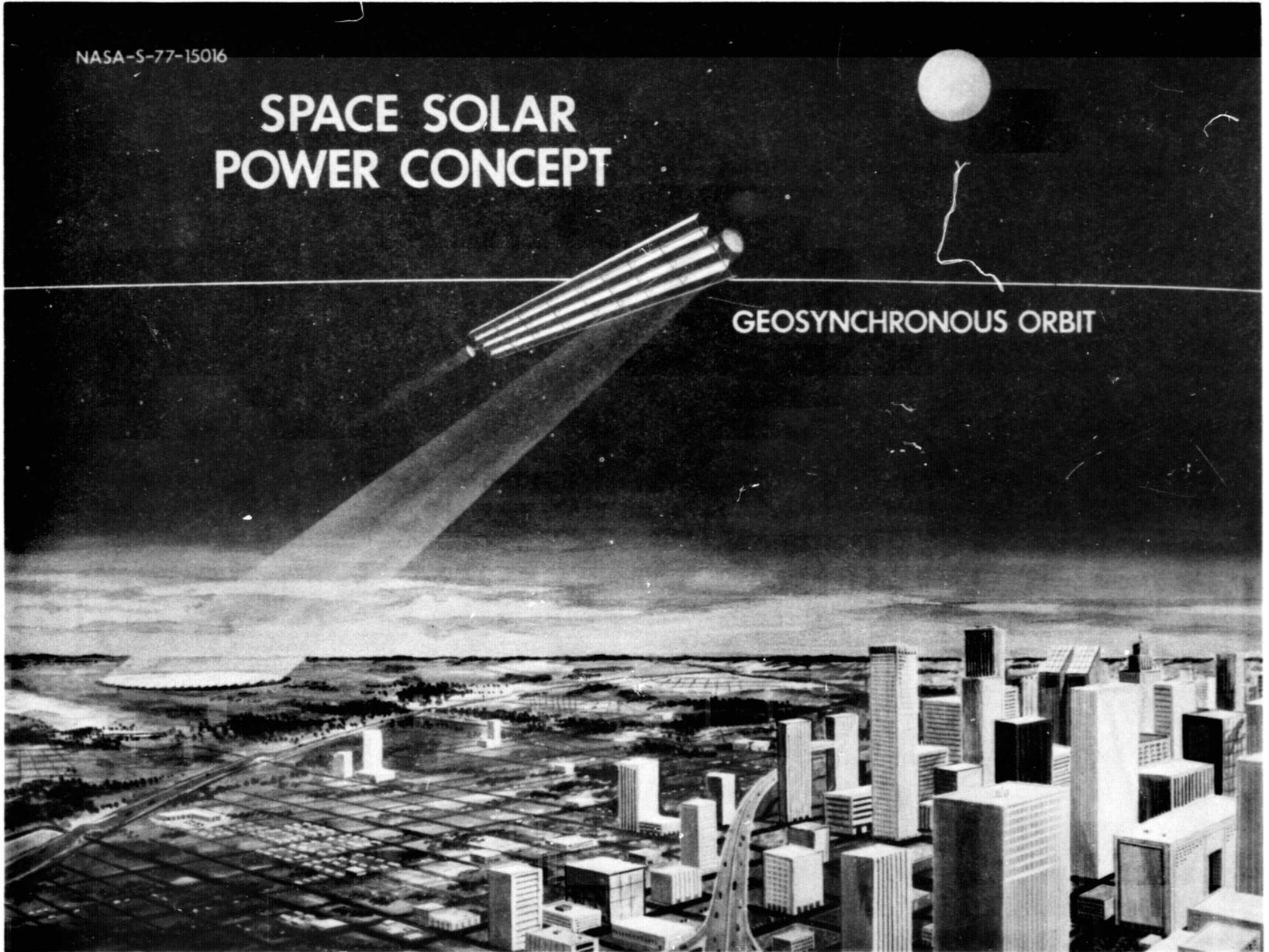


Figure 1

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## **APPARENT ADVANTAGES AND NEW REQUIREMENTS**

The apparent advantages of the concept and related requirements for new or improved technologies are summarized in Figure 2. Due to the day-night cycle, clouds and atmospheric effects, and relative earth-sun positions, the solar collector in space will be exposed to 6 to 15 times more sunlight over a period of time than an equal-sized collector located on earth. The location in geosynchronous orbit provides near continuous access to sunlight and allows the system to operate as a baseload plant.

Essentially, the microwave beam is unaffected by weather. This independence from weather results in location of receivers to meet power demands rather than obtain optimum sunlight conditions.

The concept appears to offer a number of advantages; however, for the system to be viable it requires new or improved technologies. Solar cells or other energy collection techniques need to be improved in efficiency while simultaneously reduced in weight and production costs. Transmission of large amounts of power by microwave techniques needs to be explored and systems optimized. Techniques for constructing large structures in space need to be developed and demonstrated. Cost of moving men and materials to orbit needs to be significantly reduced. Preliminary studies indicate the possibility of these technology advancements.

# Why Consider Space Solar Power?

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## Apparent Advantages

- Greater insolation (6-15x)
  - Base load capability
  - Minimal day/night and weather concerns
  - Geographical independence
- 

## New Requirements

- Power conversion
- Microwave power transmission
- Space construction
- Space transportation

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## TYPICAL RESULTS OF INITIAL STUDIES

Preliminary studies of the space solar power concept have been conducted by industry and government.

The results presented in Figure 3 are considered typical of results from a number of studies. The studies considered a silicon solar cell system, although at the present time other photovoltaic and solar thermal systems are possible options.

The "range of estimates" presented reflects optimistic and conservative projections of the required technology. It should be noted that each of the weight estimates includes an allowance of 50 percent for growth or underestimation. The range of cost estimates is a reflection of these projections. The difficulties of projecting costs for a system 15 to 20 years in the future should be recognized. The primary intent of the present estimates was to determine whether the cost estimates would be in the tens of mills as compared to hundreds or thousands of mills per kilowatt-hour. The resulting estimates of 30-115 mills/kWh indicate that the potential costs are in a range where the concept is worthy of further investigation.

The significance of the cost of solar cells and space transportation is described later in this brochure. The environmental effects of the system are generally favorable, particularly in terms of minimal air and thermal pollution. Studies will be required to provide definite answers to questions related to the microwave beam.

The study indicated that the aerospace industry represents a base of knowledge, capability, and organization required for the development and implementation of the space power concept. In general, the requirements of the system represent extensions of capabilities developed and exercised during the past 20 years.

It was concluded that the space concept appeared competitive with other advanced power generation systems when a variety of factors were considered, including technological feasibility, cost, safety, natural resources, energy payback, environment, baseload characteristics, location flexibility, land use, and industrial capability.

# SPACE SOLAR POWER CONCEPT

## TYPICAL RESULTS OF INITIAL STUDIES

- TECHNICAL FEASIBILITY - AN ENGINEERING PROJECT OF MAJOR PROPORTIONS BUT NOT REQUIRING SCIENTIFIC BREAKTHROUGHS
- TECHNICAL DATA - RANGE OF ESTIMATES
  - ENERGY CONVERSION-TRANSMISSION EFFICIENCIES - 8 TO 4%
  - 10,000 MW PLANT - SIZE - 90 TO 180 km<sup>2</sup>  
WEIGHT - 50 000 TO 100 000 TONS
- ESTIMATED COST OF ELECTRICITY - 30 TO 115 MILLS/kWh
- MAJOR COST DRIVERS - SOLAR CELL PERFORMANCE AND SPACE TRANSPORTATION
- SIGNIFICANT ENVIRONMENTAL BENEFITS, AND QUESTIONS TO BE ANSWERED
- ENERGY PAYBACK RATIO PROMISING - 1 YEAR
- NATURAL RESOURCE REQUIREMENTS REASONABLE
- EXISTING TECHNOLOGICAL AND INDUSTRIAL BASE
- "COMPETITIVE" WITH OTHER ADVANCED SYSTEMS

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Figure 3

## A TYPICAL CONFIGURATION

Figure 4 presents a typical system configuration resulting from an initial study. The dimensions and weights are approximately midpoints of the ranges presented in Figure 3.

This configuration produces a total of 10,000 megawatts of power at the ground rectenna(s) for introduction into the electrical grid. Five thousand megawatts are available from each of two rectennas which operate with the same satellite. This particular two-antenna-rectenna combination is not required but is convenient to "balance" the Space Solar Station.

The large size of the satellite is related to its large power output capability. Additional studies will be required to determine the optimum size for the solar power stations, although they are expected to be quite large for reasons of economy. An additional consideration of utilizing this size for the study was the projected requirements for large electrical parks of this size in the period 2000 and beyond.

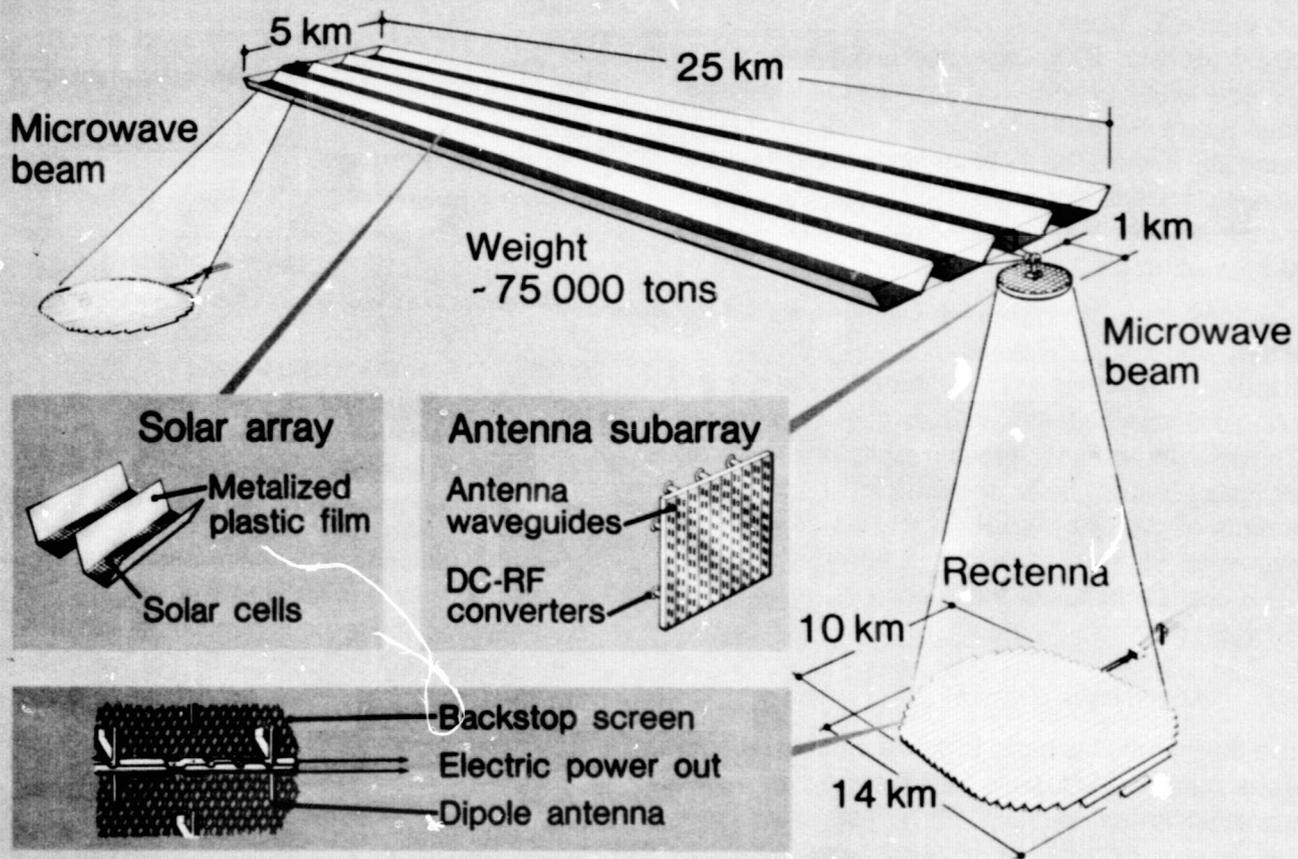
This configuration assumes silicon solar cells operating at a conversion efficiency of 10.3 percent at 100° C. Reflectors are used to concentrate the sunlight on the solar cells. The energy from the solar cells is converted to microwave energy and transmitted to earth at a frequency of 2.45 GHz. The efficiency of this conversion and transmission is estimated to be 58.3 percent, resulting in an overall collection-conversion-transmission efficiency of 6 percent. The transmitting antenna consists mainly of microwave generators, in the form of klystrons or amplifiers, and waveguides.

The ground-based rectenna or rectifying antenna collects the microwave radiation from space and rectifies this power into direct current. The rectenna elements consist of a half-wave dipole antenna and a half-wave rectifier (Schottky barrier diode).

The weight of the configuration is estimated to be 75,000 metric tons. This total estimate was made by estimating the weights of each component in the system and adding a 50 percent growth allowance.

# A Typical SPS Configuration

(2 x 5000 Megawatts Output)



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Figure 4

## GROUND-BASED ACTIVITIES

### Solar Cells

The Energy Research and Development Administration embarked on a program to reduce the cost of solar cells for terrestrial applications. This work, in which the Jet Propulsion Laboratory is playing a key role, has a goal of achieving solar cells with a cost of \$500 per kilowatt by 1986 (see Figure 5). Costs of \$100-300 per kilowatt are projected by the year 2000 based on a demand of 50 gigawatts equivalent power. The implementation of a commercial Space Solar Power Program would increase this demand still further. The technical data and cost estimates presented herein assume a cost of solar cells varying from a conservative \$500 per kilowatt to an optimistic \$100 per kilowatt in the 1995-2025 period.

Present studies have emphasized silicon solar cells because they are technically the most advanced. In addition, our space experience has been limited to the silicon cells. Solar cells from materials such as gallium arsenide show considerable promise. Recent results of laboratory tests (see Figure 5) indicate an improvement in efficiency of these cells of over 50 percent in the last 2 years. If further projected improvements are achieved, the size, weight, and cost estimates of the space system may be reduced by as much as 40 percent.

### Microwave Transmission

Microwave transmission is basic to space and other communications systems. Microwave transmission of power in large quantities is less familiar. Early tests were conducted from a helicopter to ground. More recently, preliminary tests have been conducted within the context

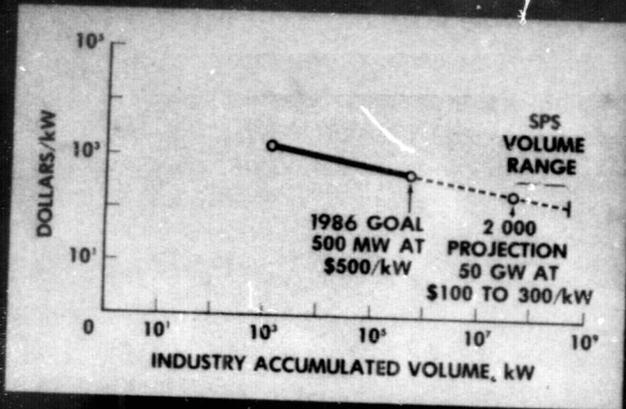
of the space solar power concept. Tests have been conducted using the microwave radiation capabilities of the large space tracking system located at Goldstone, California (see Figure 5). In these tests, 30 kilowatts of power were transmitted via microwave to a receiving antenna located at a distance of 1 kilometer from the transmitting antenna. Laboratory tests have also been conducted which have successfully demonstrated a number of concepts and components contained within the system.

The use of microwave transmission immediately raises questions as to its characteristics and effects. The characteristics of the full scale beam are shown in Figure 5 as a function of the power density at the receiving antenna and the surrounding area. The maximum intensity at the center of the rectenna is  $23 \text{ mW/cm}^2$ . The intensity at the edge of the rectenna is  $0.9 \text{ mW/cm}^2$ . For reference, current U.S. standards for old and new microwave ovens are 10 and  $5 \text{ mW/cm}^2$ , respectively. Radiation beyond the edge of the rectenna is less than  $0.1 \text{ mW/cm}^2$  or 1 to 2 percent of the allowable limit.

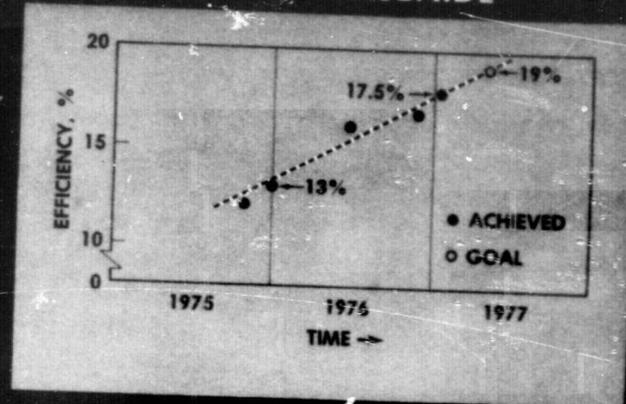
The earth rectenna and space satellite represent an integrated microwave transmission system. Failure of this system would not result in a movement of the beam "off" the rectenna, but a "defocusing" of the beam such that the level of dispersed radiation would be  $0.003 \text{ mW/cm}^2$ . It is recognized that, while the beam intensity beyond the edge of the rectenna is very low, research is required to conclusively establish that exposure to these levels would have no significant effects on humans, animals, or vegetation.

# GROUND BASED ACTIVITIES SOLAR CELLS

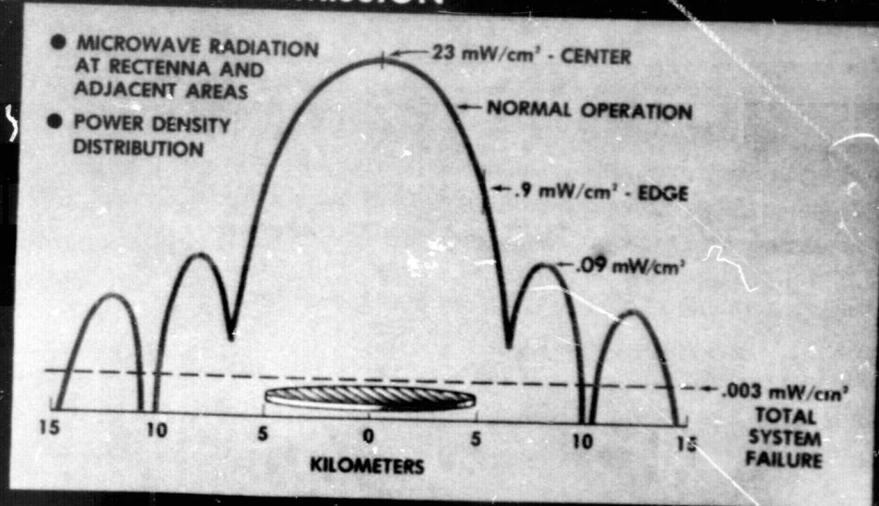
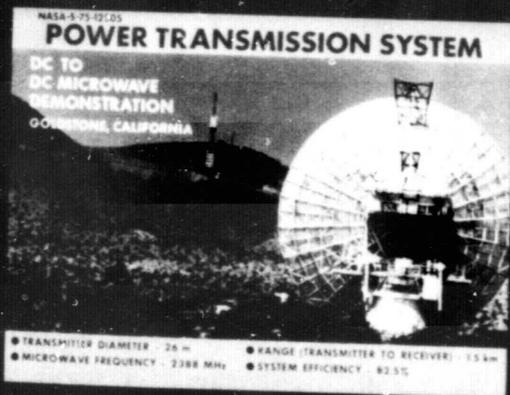
## SILICON



## GALLIUM ARSENIDE



## MICROWAVE TRANSMISSION



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Figure 5

## SPACE PROJECTS FOR EVALUATION OF CONCEPT

A complete evaluation of the concept will require continuing analysis, ground testing and development, and a series of space projects. Ground tests and development related to solar cells and microwave transmission have been mentioned. Also, ionospheric heating tests and electric propulsion devices should be pursued. Experiments should be conducted to develop techniques for beam fabrication, performance of "unjacketed" microwave power tubes, and properties of materials in space. In conjunction with ground development and space experiment activity, a series of space projects is required to synthesize the results of the smaller individual projects that lead to systems results on which future decisions and activities can be based.

Figure 6 illustrates a series of possible projects that will provide pertinent information and, if implemented, will lead to a large scale power generating capability. The initial project would consist of the construction in low earth orbit of a 500-kilowatt solar array and transmitting antenna. The project will allow evaluation of construction techniques and microwave transmission tests. Such a space power system would have continued use for other space applications.

Subsequent space projects require definition during the next several years. Conceptual projects are shown in Figure 6. The second project might be the construction of a larger 2- to 10-megawatt solar array in low earth orbit to allow construction productivity analyses and an antenna of a scale adequate to provide "proof of design concept."

The third project might involve the use of a test article at geosynchronous orbit to conduct phase control tests to earth, as well as to demonstrate manned and unmanned operations including refueling between low earth orbit and geosynchronous orbit in support of deployment/assembly of the test article.

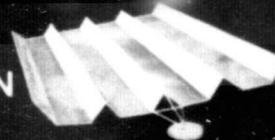
A series of space projects plus ground development and space experiments would provide the basis for a complete evaluation of the space solar power option in the 1985-1990 time period. If the decision was made to proceed, a possible sequence of events would include the deployment of a 1000-megawatt prototype station utilizing previously developed transportation systems. This system probably would not be economically competitive. It would be a useful technical and demonstration activity prior to bringing on the large scale 10-gigawatt systems in the mid-1990's with requirements for large new transportation systems.

# SPACE SOLAR POWER CONCEPT MAJOR SPACE PROJECTS

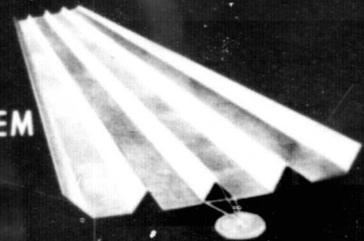
- CONSTRUCTION TECHNIQUES
  - MICROWAVE TRANSMISSION
  - 500 kW
- 
- CONSTRUCTION PRODUCTIVITY
  - STRUCTURAL PROOF
  - 2-10 MW
- 
- INTER ORBIT OPERATIONS
  - MICROWAVE CONTROL



LARGE SCALE  
DEMONSTRATION  
1 000 MW



FULL SCALE SYSTEM  
10 000 MW



1981 82 83 84 85 86 87 88 89 1990 91 92 93 94 95 96 97 1998

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Figure 6

## AN INITIAL FLIGHT PROJECT

The initial flight project is designed to achieve a number of related goals for the evaluation of the space power concept. The implementation of a 500-kW solar array represents an increase by a factor of 15-20 over past space power systems (Skylab - 30 kW). The antenna would provide the capability to assess the phased array techniques by measuring the beam pattern with a receiving antenna device located some 15 kilometers away (see Figure 7). The antenna would also allow assessment of a critical heating problem related to the microwave generators and the structure. The instrumented solar array would provide a test article for structural measurements to assess computer models.

One of the most important aspects of the test would be to evaluate various construction techniques. The figure illustrates the construction sequence. Structural members are fabricated with a beam builder and held in place by an appropriate jig. The latticework of beams is then passed through the jig, at which time the solar array blankets are attached to the structure. The antenna is taken to orbit in modules and assembled by using a remote manipulator.

The last illustration in the sequence shows the deployment of the receiving antenna which is located some distance from the solar array. This device is built on the ground and then packaged to be deployed in space with a minimum of manned assistance. Consequently, the overall project exercises the three basic construction techniques of fabrication (solar array structure), assembly (antenna modules), and deployment (receiving antenna).

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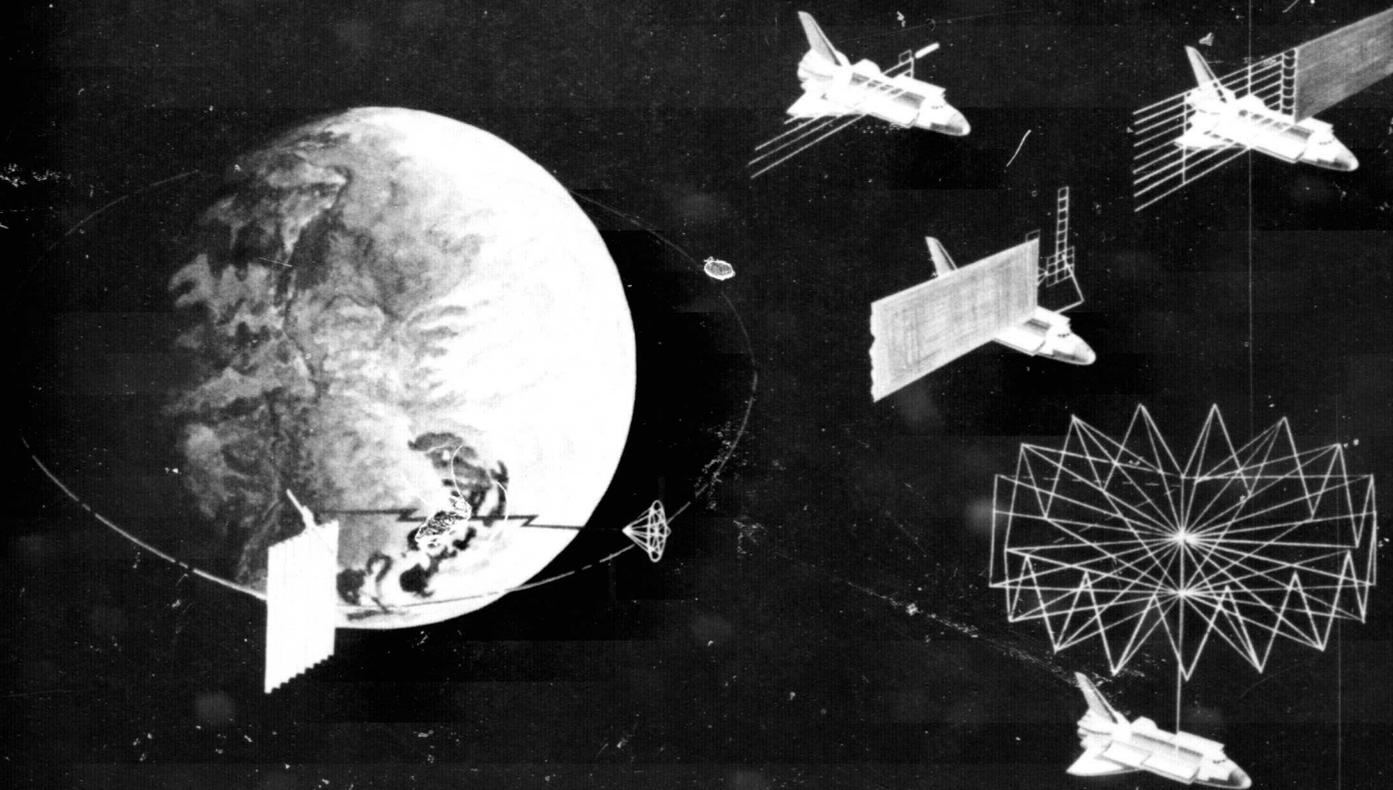
# SPACE SOLAR POWER CONCEPT

## AN INITIAL PROJECT

500 kW

MICROWAVE TRANSMISSION

CONSTRUCTION TECHNIQUES  
(TYPICAL)



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Figure 7

## SPACE CONSTRUCTION

The size of the solar power systems will require their construction in space. The space location, however, offers a number of advantages related to the zero gravity environment and the relatively small loads placed on the structures by the various environmental and systems forces involved.

Figure 8 presents an interesting comparison between a typical earth structure and a space structural beam such as might be used in constructing the solar power station.

Structural beam building machines for space use have received considerable study related to the space solar power concept. It appears that existing concepts used on earth may be applicable to space fabrication in a relatively straightforward manner.

### Space is an ideal location for large structures

Typical space structure  
segment of 20-meter (66 foot) beam

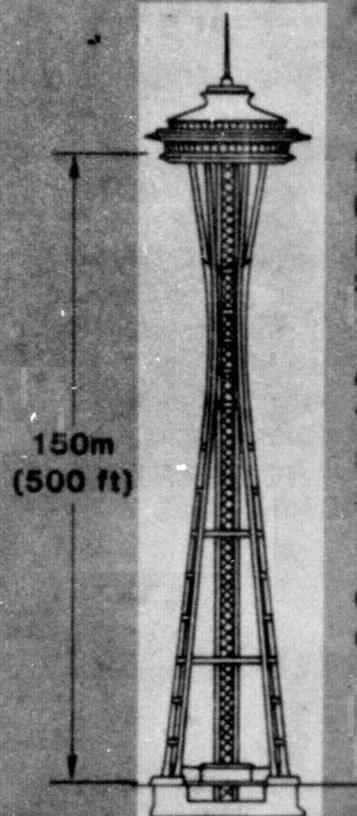
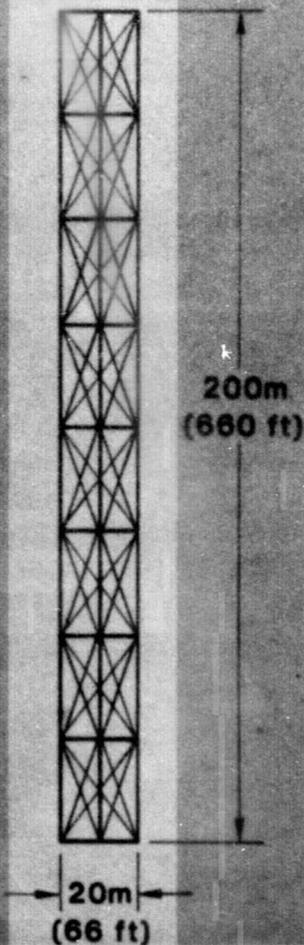
Typical earth structure  
Space Needle Tower in Seattle

MASS = 1.5 TONS

CONSTRUCTION  
TIME = 3 HOURS  
(NO SITE PREPARATION  
REQUIRED)

CONSTRUCTION  
CREW = 2 MEN

(NO WIND OR RAIN)



MASS = 8,660 TONS  
(INCLUDING FOUNDATION  
BUT NOT RESTAURANT  
STRUCTURE ON TOP)

CONSTRUCTION  
TIME = 6 MONTHS  
(INCLUDING SITE  
PREPARATION)

CONSTRUCTION  
CREW = 50 MEN

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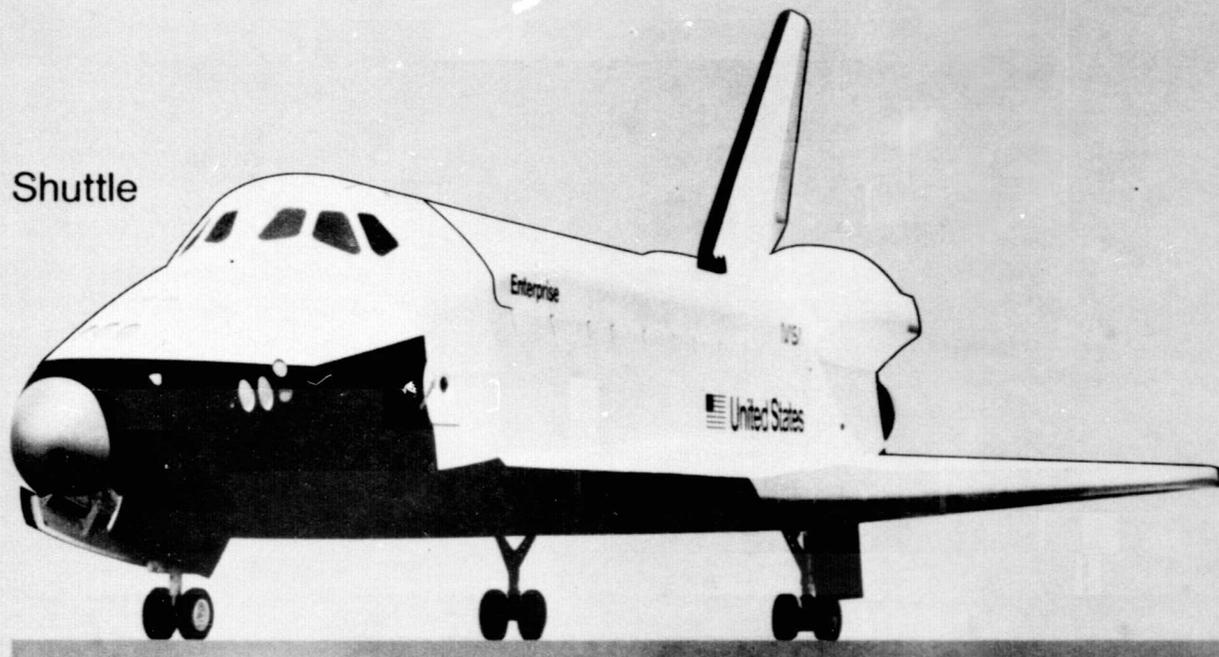
Figure 8

## SPACE TRANSPORTATION

Low-cost transportation is a key to the economic viability of the space power concept. Very large systems would ultimately be required to achieve minimum cost of electricity. The Shuttle system, however, which is now under development, will be adequate for initial space experiments and major low earth orbit space projects. The phase of space projects to be conducted at geosynchronous orbit would require an extension of the Shuttle system to provide greater payload capability and an orbital transfer vehicle to transport the test article to geo-

synchronous orbit and, also, to transport a small crew of men for short periods to assist in the deployment/assembly of the test article. This orbital transfer activity would require and demonstrate a refueling capability in low earth orbit, travel to geosynchronous orbit, and return to a low earth orbit base for transfer to the Shuttle and return to earth. Development and demonstration of this capability (low earth orbit to geosynchronous orbit and return) with its space facility and operations requirements is considered a desirable prerequisite to commitment to the large scale program activity

# Space Transportation



Provides transportation for initial space project

Shuttle use (1980-85) will provide basis for future transportation cost estimates

Geosynchronous testing may require augmented transportation capability