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OVERVIEW OF SYSTEMS DEFINITION ACTIVITIES FOR SATELLITE POWER SYSTEMS

F. Carl Schwenk
NASA Headquarters - Washington, D. C.

The Satellite Power System, as shown in the first viewgraph (Figure 1), is a means to gather energy in space and transmit that energy to earth in useful form. The concept shown is merely one of many possibilities for this concept. The Satellite Power System, invented in 1968 by Dr. Peter Glaser of the Arthur D. Little, Inc., has been the subject of design studies, symposia, program reviews by committees and, since 1977, the center of the activity known as the Concept Development and Evaluation Program. The purpose of this paper is to review what has been done during the last three years in the systems definition effort which has been the prime responsibility of NASA. In doing so, it is wise to refer to the total SPS effort conducted by NASA, which began in 1972, because the present lore of SPS is the summation of all past work.

Prior to the Concept Development and Evaluation Program, the scope of SPS activities were as described on the next viewgraph (Figure 2). This chart, taken from a Table of Contents of a report on SPS prepared in early 1977, shows that the studies conducted by NASA included considerations of the role of SPS as an energy system, space technology, ground systems, environmental concerns, and comparisons.

During these pioneering efforts many versions of SPS were studied and contributed to the present state of systems definition in SPS. Both photovoltaic and thermal energy conversion concepts were studied.

One important aspect of SPS is getting it into space in the first place. Various transportation concepts for getting payloads into orbit at the lowest possible cost were studied, including modified shuttles, up-rated shuttles and a variety of advanced vehicle concepts generally known as Heavy Lift Launch Vehicles. These included ballistic single-stage and two-staged vehicles, winged two-stage vehicles for ease of recovery, and single-stage-to-orbit vehicles which could take off from conventional airports. In addition to studies of systems, the early analysis of SPS considered related activities in construction methods, construction locations and facilities, and different transportation methods in space, including chemical rockets for all orbit-to-orbit transportation, and electric propulsion systems using both nuclear energy and solar energy as the prime power source.

From all these studies, the result is a focus on the photovoltaic approaches as being the prime early candidates for an SPS configuration. The choice resulted from a combination of the many factors I've described and represents an integration of many elements of the study efforts.

It should also be noted that the microwave power transmission system has received the most attention in SPS studies. The power transmission system dominates the system design, environmental concerns and, ultimately, implementation of the program. It sets power levels and, therefore, system sizes and masses. For good penetration through the atmosphere, the carrier frequency in the range of one to ten gigahertz is desired. Because great emphasis was placed on obtaining baseload capability in satellite power systems, a frequency of 2.45 gigahertz in an available industrial, scientific and medical (ISM) band of the electromagnetic spectrum was selected for most of the study effort. Consideration was given also to frequencies of 5.8 and 8.0 gigahertz. For the 2.45 gigahertz frequency the transmitter and ionospheric thermal limits set 5 megawatts as the maximum power that could be delivered in a single beam; however, lower powers per beams are possible. It was assumed that obtaining the maximum power level for a given size of transmitter system would result in the most economical power plant.

Though we have the example of the Goldstone test as one experiment related to the satellite power system, it is significant to realize that nearly all of the efforts on SPS have been studies based on assumptions and projections of where the technology may be in the future, and ought to be in the future, in order to achieve a satisfactory power system. Supporting the SPS studies, however, are broadly based NASA and DOD space research and technology programs covering nearly all the technical disciplines important to SPS. Studies conducted outside the SPS program showed that laser power transmission could possibly be feasible in space missions and for delivering power to Earth. An output of one of these early studies of laser power transmission is illustrated in this picture (Figure 3) which shows a system where the power plant is in low Earth orbit and laser relays are placed in geosynchronous orbit in order to achieve delivery of power to a single spot on Earth.

With this background I believe you can see then that SPS has had a history of studies and relies heavily on R&T activities being conducted outside the SPS program, that are supportive of the Concept Development and Evaluation Program, which I will now discuss. In the systems definition effort, which has been the responsibility of NASA, the objective has been to define a baseline system concept or concepts to evaluate technical feasibility and to provide information required for environmental and socio-economic assessments. As time has gone on in the Concept Development and Evaluation Program, the initial objectives in systems definition were expanded to include studies of alternative approaches and to conduct critical supporting investigations where needed and as may be possible.

One of the first requirements of the Concept Development and Evaluation Program was to establish a reference Satellite Power Systems concept for use in conducting evaluations of environmental impact, societal concerns, and comparative assessments. In order to establish a reference system, common guidelines (Figure 4) were established based upon the judgment derived from the earlier studies which I have just described. Many people can and have quarreled with these guidelines; however, it was necessary to establish some basis for conducting the studies. As further work is done on SPS, it will be necessary to examine the impact of changing these guidelines to determine whether more optimal or more favorable versions of SPS might be derived from different starting assumptions.

From these guidelines and the studies which have been conducted over the years, the reference satellite power system concept was established. The general concept is outlined on this viewgraph (Figure 5). It shows a large flat structure (5 Km x 10 Km) holding solar arrays for generating DC power from the sun. The DC power is collected and delivered by means of a rotary joint to a transmitting antenna system. The transmitting antenna was set at 1 kilometer in diameter and it is formed of transmitting antenna subarrays which contain the DC-RF power amplifiers and the antenna waveguides for forming the beam. The beam is controlled in the reference system by a retro-directive pilot beam system. In travelling from geosynchronous orbit to the Earth, the microwave power beam expands in area from a circle 1 kilometer in diameter to an ellipse that is 10x13 kilometers at the 35° reference latitude. It is now a low power density microwave beam with a peak intensity of 23 milliwatts per square centimeter in the center and 1 milliwatt per square centimeter at the edge of the rectenna. The rectenna is made of a series of panels which contain an open screen ground plane with half-wave dipole antennas and diode rectifiers. DC current is collected and delivered to the peripheral rectenna where it is processed for distribution to the electrical network.

Artist illustrations of two versions of the reference system are shown on the next viewgraph (Figure 6). One version of the reference system uses silicon solar cells in a planar array without concentration of the solar energy. A silicon reference was included in the study because of the vast amount of experience available now and expected with silicon technology in the future. The gallium aluminum arsenide solar cell version was included as a reference system because the gallium aluminum arsenide solar cells have several advanced features which make them attractive for use in the satellite power system.

The next chart (Figure 7) shows the comparison of the two reference systems in terms of their mass in millions of kilograms. We see that the total mass for the gallium aluminum arsenide array option is in the range of 34 million kilograms while that for the silicon option is in the range of 51 million kilograms. If transportation costs were the determining factor, obviously the gallium aluminum arsenide version would be chosen because of its much lower mass; however, the gallium aluminum arsenide solar cells are likely to be considerably more expensive than the silicon, at least in terms of current projections. Also there are some greater degrees of uncertainty on the achievement of performance desired in one solar cell option versus the other.

In addition to the definition of the reference system, which will be covered in much greater detail in other sessions of this Symposium, the NASA activities in the Concept Development and Evaluation Program included studies in many of the critical areas of SPS and associated areas of critical supporting investigations. The next viewgraph (Figure 8) shows a table of funding of the NASA activities during FY 1977-1980, the years of the Concept Development and Evaluation Program, and shows how the funds were expended in the major areas of endeavor. As can be seen, approximately $7.9 million were expended for systems activities during the Concept Development and Evaluation Program. Of this total, $2.2 million was spent on systems definition activities which are those functions and studies which integrate all the other work into comprehensive system concepts. You can note that most of the effort was accomplished during the first two years in systems definition for the preparation of the reference system, as I have just discussed. The footnote also indicates that we have been able to put some small amount of money into additional studies of laser energy transmission as an option for the satellite power systems concept. Some results of the laser system studies will also be given later in this Symposium.

Another major area of emphasis in the systems activity has been in the area of power transmission and reception. Microwave power transmission is certainly a critical element in the feasibility of the satellite power system concept and warrants this level of attention.

I would now like to say a few things which will relate to results of some of these activities during the Concept Development and Evaluation Program. First, I would like to discuss the use of solid state microwave converters which was mentioned earlier. We conducted research on the application of solid state converters and studies of concepts which might use these devices in place of klystrons or other tube type converters because of the potential for high reliability in solid state devices. One version would be to make a simple replacement of the klystron tubes with an array of many millions of small DC-RF converter transistors. And this has been studied under the Systems Definition portion of the program. Another radical approach to using solid state converters is to create what we call a sandwich of solar cells, circuitry and solid state DC-RF converters which would be mounted on satellites as illustrated in this viewgraph (Figure 9). Here we show two versions where the microwave transmitting antenna is actually the sandwich structure. One face contains the waveguides and the DC-RF converter transistors and the other side contains the gallium aluminum arsenide solar cells, which are illuminated by a system of reflectors.

A great deal of importance in the SPS studies have been placed on the matter of construction. In fact, considerations of construction operations has played a large role in the selection of the reference system concepts. Studies have also been made of the ground operations required to support the building of the rectenna and the industrial demands of SPS.

In addition to the activities I've described, a number of significant items of work have been accomplished in the systems studies activities. Among them are the studies of variations in launch trajectories for the Heavy Lift Launch Vehicles required to deliver payloads to low Earth orbit to reduce the impact of the effluents from the rocket engines on the ionosphere. Studies are also under way to explore alternative designs for the launch vehicles in order to determine what is the most favorable concept for delivery of payload into orbit.

Studies of alternative power levels and transmitting frequencies for satellite power system have been conducted. At the reference frequency of 2.45 gigahertz, larger antenna systems with smaller rectennas and lower power outputs are economically feasible under certain conditions as shown by these studies. It was also shown that satellites operating at 5.8 gigahertz transmitting frequency instead of 2.45 gigahertz were feasible and could provide power within an economic range or costs. Studies also showed that multiple antennas on the satellite power system were feasible and perhaps desired in order to make best use of the orbital spacings available at geosynchronous altitudes.

In order to obtain expert assessment of the results of the Systems Definition studies and technology investigations that NASA has conducted during the SPS Concept Development and Evaluation Program, the NASA Centers involved sponsored five workshops addressing the major SPS technology areas. These workshops are listed on the next viewgraph (Figure 10). The results and findings of these workshops are being reported and will be discussed during this conference, but I would like to give a very brief summary of their findings as a capstone to this discussion of the systems studies effort which NASA has conducted.

In the microwave power transmission area, the workshop panel reported that there was cautious optimism that the SPS microwave power transmission system is probably technically feasible; however, a long-term R&T program will be needed in order to prove the capabilities of this complex operation of transmitting power from space to Earth. In structures and controls, the workshop panel report indicates that substantial work remains to be done in modeling and in techniques of active control for structures the size of SPS. In the construction and materials workshop, the findings were that the assembly concepts appear credible but much more R&D work is needed in this area. One important lack is the insufficient data on the long-term behaviour of composite materials in geosynchronous orbit. The panel recommended that, in addition to the composite structural materials in the reference system, aluminum structures also be given continued consideration. In space transportation it was recognized that the propulsion systems for the reference heavy lift launch vehicle are achievable without high risk. It was also thought necessary to keep open many of the propulsion options before a firm choice is made. Reusable thermal structures will require a major development program and the key issues in space transportation remain the solution of problems related to repeated operations of space vehicles. This technology will be developed, in part, through the operation of the Shuttle. Under energy conversion and power management it was noted that key technology advances are needed, for example, in the solar blankets, the solar cell encapsulants, waste heat radiators, and the high speed switch gear. There can also be a major concern in the area of operation of satellite systems at the extremely high voltages required by the reference system.

The question at this time must be, "What are the major findings of the systems studies activity in the Concept Development and Evaluation Program?" Those of us close to the program feel that the concept of transmitting power from space to Earth is not faced with insurmountable technical problems; however, this judgment is based in large part on studies that rely on assumptions and projections of critical technology disciplines. It is only through further research and experiments that we can change these assumptions to hard data, and it is only with hard data that we will be able to give an unqualified statement as to the technical and economic viability of any SPS concept.

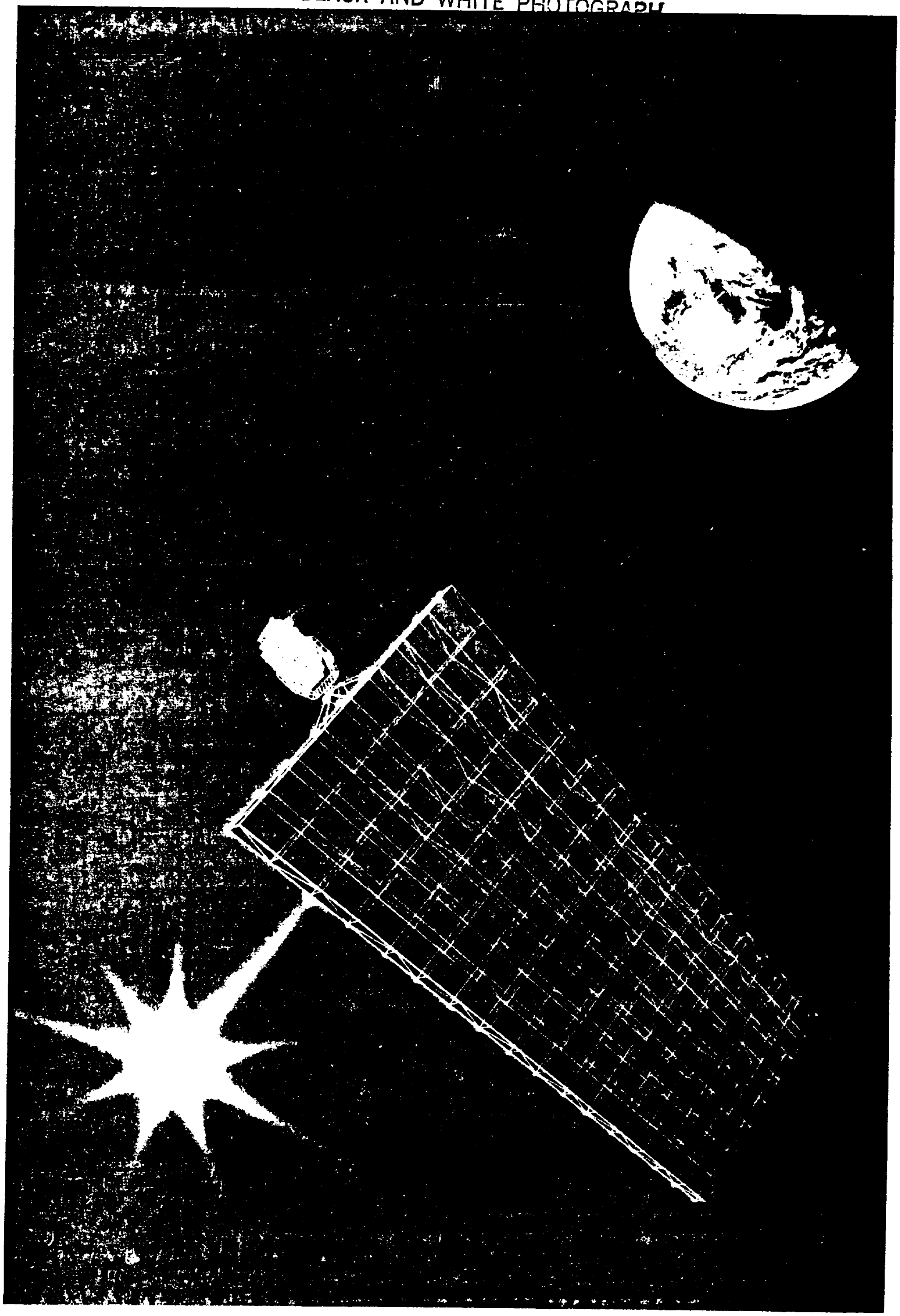

Figure 1

SCOPE OF NASA STUDY EFFORT BEFORE 1977

- PROGRAM REQUIREMENTS
- SATELLITE POWER STATION (SPACE SYSTEM)
- SPACE CONSTRUCTION AND MAINTENANCE
- SPACE TRANSPORTATION SYSTEMS
- ENVIRONMENTAL FACTORS
- MANUFACTURING, NATURAL RESOURCES, GROUND TRANSPORTATION AND ENERGY CONSIDERATIONS
- PROGRAM PLANNING AND COSTS
- ALTERNATIVE SYSTEMS COMPARISONS

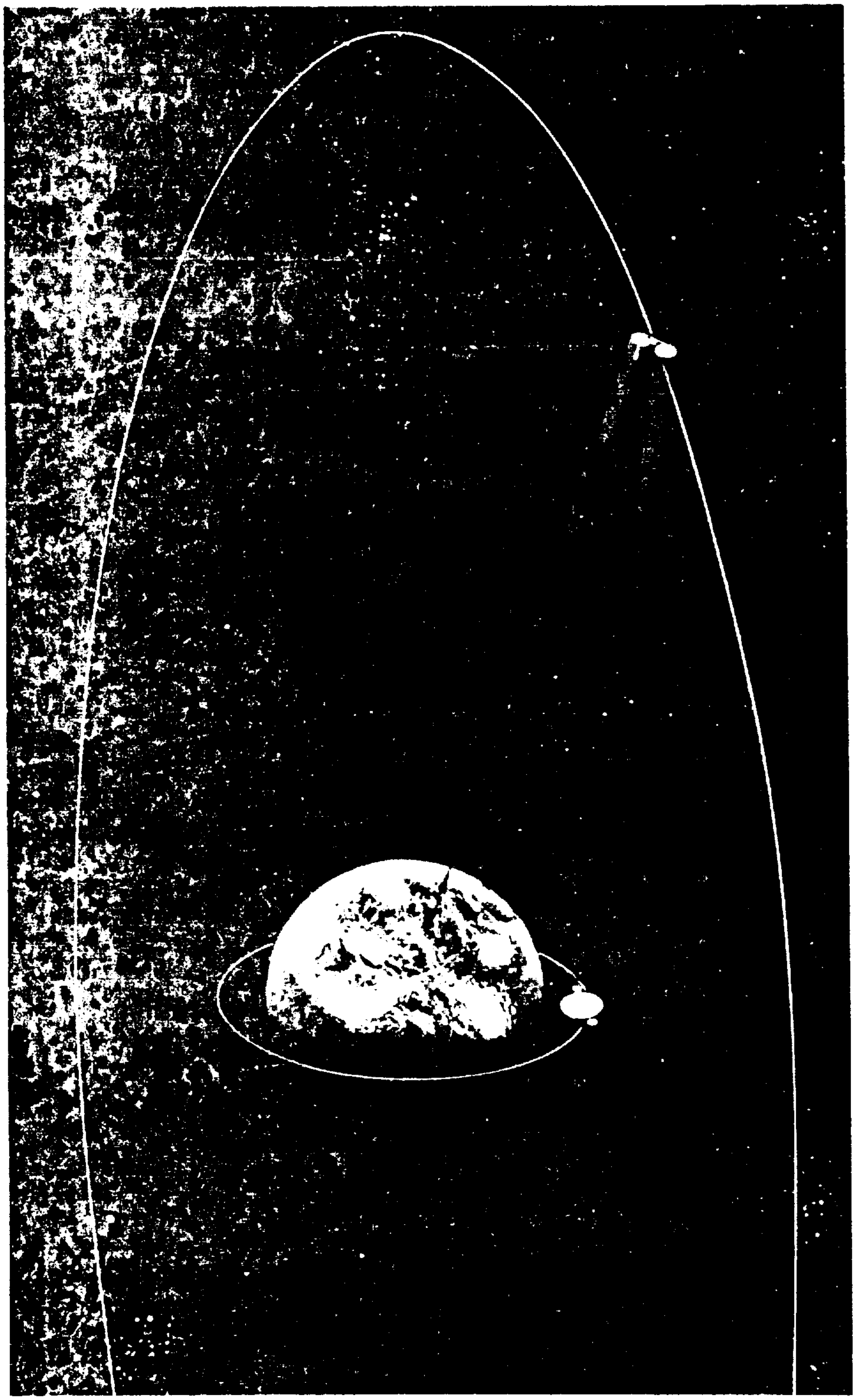

Figure 3
Initial Laser SPS Concept

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NASA Solar Power Satellite

Evaluation Study Guidelines

For the purposes of the Solar Power Satellite Evaluation Program common guidelines were established which were based upon judgement derived from earlier studies.

- Initial operational date for commercial satellites — 2000
- Technology availability — 1990
- Construction materials obtained totally from earth resources
- Operational satellite in geosynchronous orbit
- Microwave system operating frequency — 2.45 GHZ industrial band
- Microwave power density not to exceed 23 mW/cm^2 in the ionosphere
- Microwave system sized to provide 5 GW output from rectenna
- Reference implementation rate assumed to be two 5-GW solar power satellite systems per year (10 GW total)
- Solar power satellite design lifetime of 30 years

Figure 4

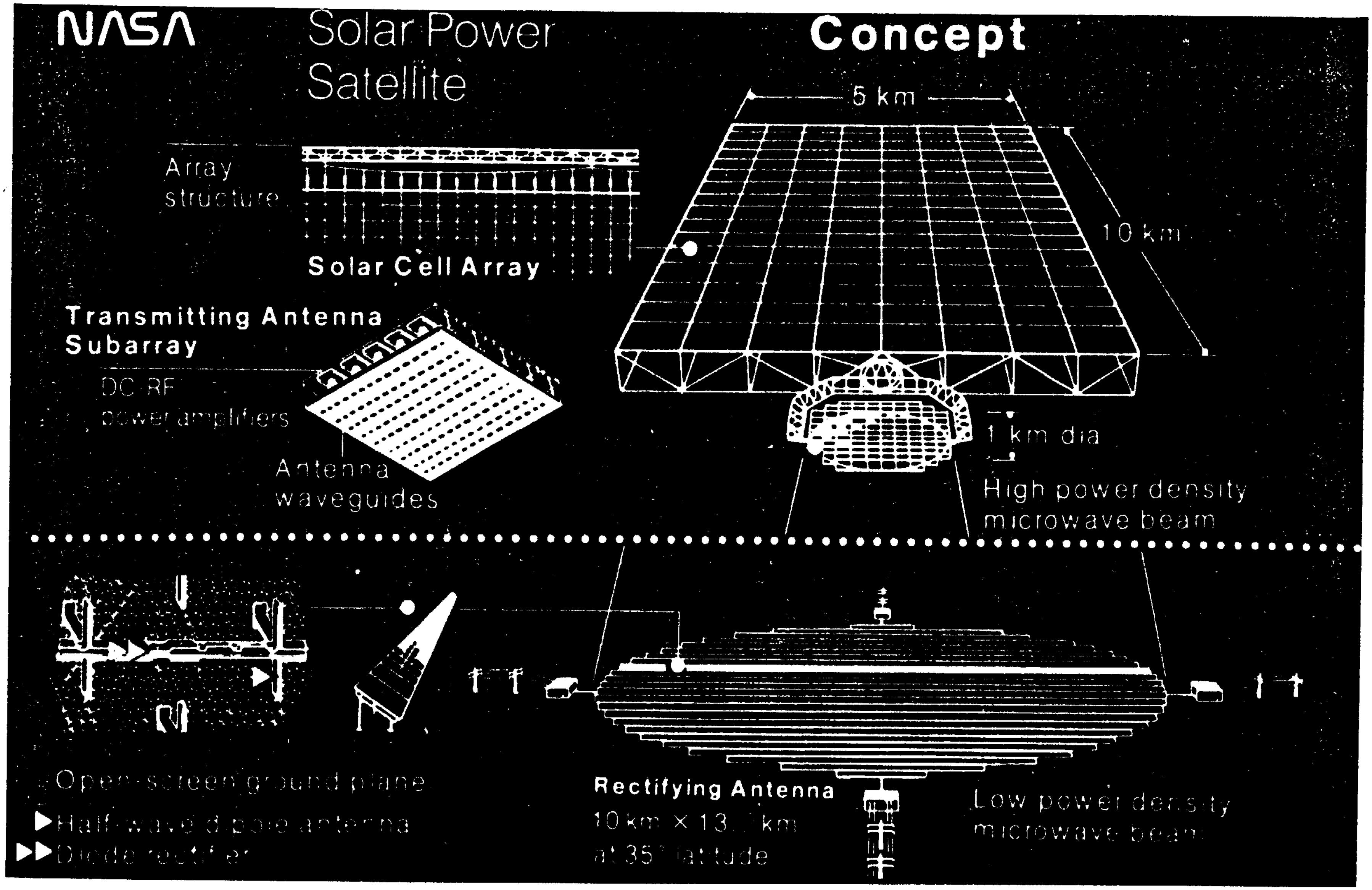

Figure 5

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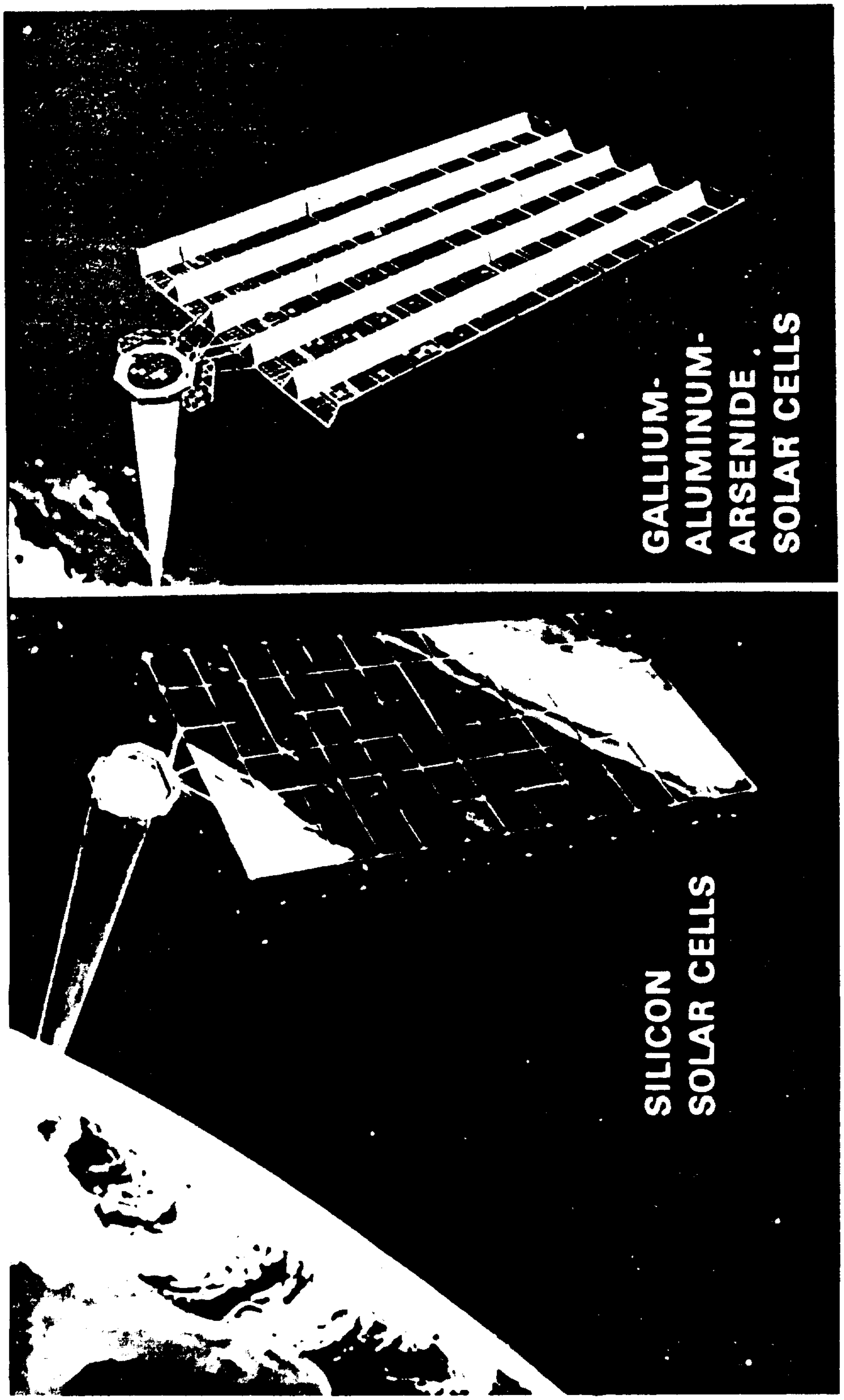

Figure 6
Reference System Concepts

NASA Solar Power Satellite

Satellite Mass Summary

Millions of Kilograms

	GaAlAs Array Option CR=2	Silicon Array Option CR=1
Solar Array	13.8	27.3
Transmitting Antenna	13.4	13.4
Array - Antenna Interfaces	.1	.1
Sub total	27.3	40.8
25% Contingency	6.8	10.2
Total	34.1	51.0

Figure 7

Figure 2

SATELLITE POWER SYSTEM
CONCEPT DEVELOPMENT AND EVALUATION PROGRAM
SYSTEMS ACTIVITY FUNDING ~ $K

	FY 77	FY 78	FY 79	FY 80	TOTAL
SYSTEMS DEFINITION	715	765	235	490**	2,205
SOLAR ENERGY CONVERSION	85	60	100	50	295
ELECTRICAL POWER PROCESSING & DISTRIBUTION	150	50	100	-	300
POWER TRANSMISSION AND RECEPTION	735	565	1,240*	260	2,800***
STRUCTURES/CONTROLS AND MATERIALS	200	165	285	150	800
OPERATIONS	150	225	490	50	915
SPACE TRANSPORTATION	165	170	150	100	585
TOTAL	2,200	2,000	2,600	1,100	7,900

* INCLUDES $400K FOR SOLID STATE SPS

** INCLUDES $125K FOR LASER SPS

*** INCLUDES $700K FOR MW AT JPL

Figure 8

NASA SATELLITE POWER SYSTEM **OAST**

PRELIMINARY CONCEPTS EMPLOYING SOLID-STATE MICROWAVE COVERTERS

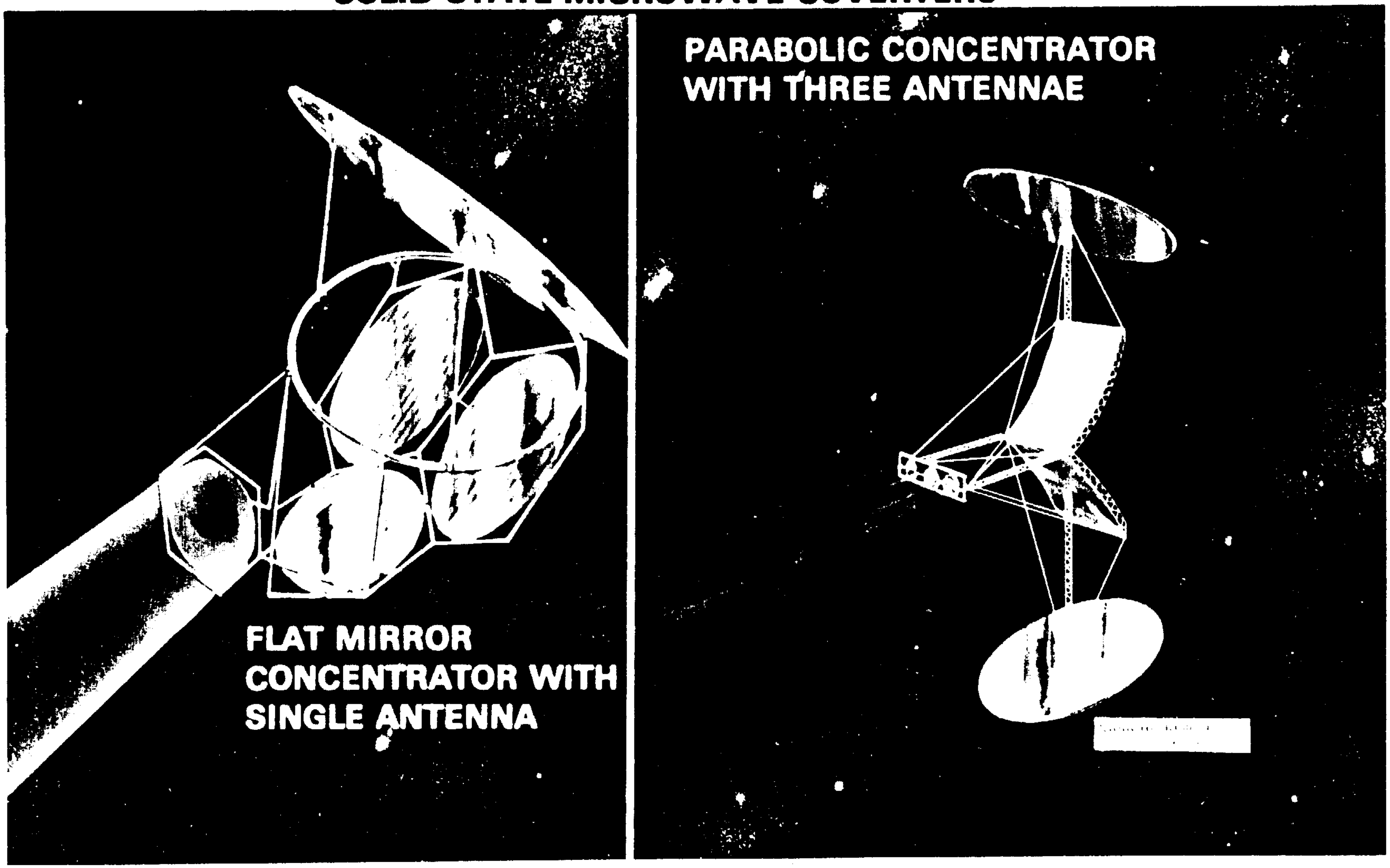

Figure 9

Preliminary Concepts Employing

Solid-State Microwave Converters

SPS TECHNICAL WORKSHOPS

JSC MANAGED WORKSHOPS

DISCIPLINE	CHAIRMAN	DATE
• MICROWAVE POWER TRANSMISSION	DR. J. FREEMAN, RICE	JAN 15-18, 1980
• STRUCTURAL DYNAMICS & CONTROL	DR. B. MINGORI, UCLA	JAN 22-23, 1980
• CONSTRUCTION AND MATERIALS	DR. R. MILLER, MIT	JAN 24-25, 1980

MSFC MANAGED WORKSHOPS

DISCIPLINE	CHAIRMAN	DATE
• TRANSPORTATION	DR. R. JAHN, PRINCETON	JAN 28-30, 1980
• ENERGY CONVERSION & POWER MGMT	DR. J. R. WILLIAMS, GIT	FEB 5-7, 1980

Figure 10