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SPACE SOLAR POWER SYSTEMS

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INTRODUCTION

Power from sunlight — a long-time dream of philosophers and inventors — is becoming an engineering reality. Solar heating and cooling is beginning to undergo commercial development. A pilot plant phase has begun for ground-based solar electric plants. The ultimate solar power plant — a power station in space called powersat — is being studied by Boeing. But why a power station in space? Isn't that prohibitively expensive and impractical? The Boeing Company does not think so, and its findings have been summarized in this report.

GENERAL DESCRIPTION

Two primary candidates for a means of converting solar power to electrical power in space exist: solar cells (photovoltaic) and thermal engines. Although Boeing is investigating both candidates with equal vigor, this report primarily deals with a thermal-engine concept called powersat.

The powersat will be essentially continuously illuminated by sunlight (no night, no weather) and will collect over six times the solar energy falling on any equivalent size area on Earth. Power beamed from the powersat can be coupled to a converter station sited in any part of the nation — or the world, for that matter — to provide continuous baseload electric power (see fig. 1). In contrast, early ground-based solar plants will produce intermediate load (i.e., only daytime) power and only in sunny regions. Continuous illumination at higher intensity offers a potential economic advantage to spacebased solar power if the transportation to space can be accomplished at a sufficiently low cost. Boeing's studies of the system economics indicate that this accomplishment is possible and that the outlook for commercially competitive electric power from satellites is promising.

The powersat envisioned by Boeing would use lightweight mirrors to concentrate sunlight into a cavity and thereby heat the cavity so that it serves as a "boiler." The heat would then be supplied to turbine generators similar to those in use at conventional powerplants. These machines convert about a third of the input heat energy to electricity; the other two-thirds (the thermal pollution of conventional powerplants) is returned to the environment. The powersat would use space radiators to reradiate this unusable heat to space far from the Earth. The electricity would be converted to a microwave beam for transmission to a receiving antenna on Earth for commercial distribution as electric power.

The powersat would be large — many square kilometers in size — but would produce great amounts of power. A typical design requires 48.6 square kilometers (12 000 acres) of mirrors for 10 000 000 kilowatts of electric output from the ground station. Most of the satellite area consists of thin, reflective plastic film, which minimizes the weight to be transported to space.

The powersat illustrated here (fig. 2) is the result of conceptual design studies performed at Boeing over the past year. The four power generation modules shown provide a reasonable compromise between the simplicity of a single large module and the practical considerations of transportation and operation.

Each module consists of a mainframe structure formed from fold-out trusses, a spiderweblike fill-in structure to support the plastic film mirrors, 10 000 to 12 000 1011.71-square-meter (0.25 acre) mirrors and their spreader frames, a cavity heat absorber surrounded by twelve 300-megawatt helium turbogenerators, and a heat radiator. Attached to one of the modules on a rotating joint are the microwave generator and antenna. The electric power produced by the turbogenerators is routed to the microwave generator for conversion and transmission.

The parts of the satellite are designed as subassemblies for transportation by the space freighter. For example, one turbogenerator with its heat exchangers and accessories can be packaged on a pallet for a single-launch delivery; the pallet forms a portion of the wall of the cavity heat absorber. Hexagonal plastic film mirrors can be folded and rolled so that many reflectors can be launched together.

Located in a stationary orbit 35 405.6 kilometers (22 000 miles) above the Earth, the powersats will be illuminated by sunlight more than 99 percent of the time. They will appear to hang motionless in the sky, and a simple fixed-position array of antenna elements (dipoles) will serve as the ground-based converter for the power beam. The converter array will be approximately 8.0 kilometers (5 miles) in diameter. Its construction and appearance will resemble cyclone fencing.

ECONOMIC CONSIDERATIONS

Cost and economic analyses have indicated promise of commercially competitive electric power costs even if the development of the powersat is amortized by operational revenues. A busbar cost of 6.9 mills ($0.0069) per megajoule (25 mills ($0.025) per kilowatt hour) has been used in the Boeing studies. This rate is about equal to projected busbar costs for nuclear power in the 1990's; it is slightly more than that for most current coal-fired electric power generation but is cheaper than that for current oil-fired power. The 25-mill busbar cost enables an allotment of $60 billion for development and $13 billion per satellite, with use of an 8-percent discount rate, an investment horizon of 30 years beyond beginning of service of the first satellite, and addition of one satellite (10 000-megawatt ground output) per year to the system. Cost studies indicate that the $13 billion per satellite should be divided roughly as $8 billion for satellite hardware (including orbital assembly costs), $4 billion for space transportation, and $1 billion for the ground station. Preliminary estimates of powersat system costs fall within these targets.

Technical feasibility of the powersat concept is not in question. It could undoubtedly work. The issue is implementation at an acceptable cost, such that an economically feasible project is the result. Boeing's studies have outlined practical approaches to an economically promising system (see fig. 3).

Closed-cycle turbogenerators offer efficiency, compactness, light weight, and low cost for conversion of heat energy to electricity. Helium turbines are under development for Earth-based applications — the largest yet operated has a 50-megawatt rating. Scale-up to the projected powersat size of 300 megawatts would be a straightforward development; this size has been studied for nuclear reactor applications. The closed-cycle helium gas turbine provides compatibility with desirable cycle-limit temperatures and enables use of high temperatures without corrosion or oxidation.

A simple geometric principle was used by Boeing to construct and test intrinsically flat mirrors of metallized plastic film during a heliostat research project for ground-based solar power. These mirrors are very light in weight and do not require precision parts. The test mirrors had 2.5 square meters (27 square feet) of reflector and weighed approximately 453.6 grams (1 pound) each. The powersat would use thousands of mirrors and similar design, approximately 1114.8 square meters in size (12 000 square feet or approximately 0.25 acre). Each would be individually steered by a small servo system to direct its energy to the central cavity. The use of steered, flat mirrors provides the requisite high concentration of sunlight at light weight and low cost and eliminates the need for a large, massive high-precision structure. In space, the protective plastic bubble is not needed.

The 54 431.1-megagram (60 000 ton) satellite cannot be transported to orbit in a single flight. It will be assembled in space from subassemblies of manageable size. The National Aeronautics and Space Administration (NASA) Skylab program demonstrated the effectiveness of men working in space. The space assembly job is analogous to the construction of powerplants on Earth, with transportable elements at a field location.

Transmission of the converted power to Earth was early recognized as a key problem. Microwave transmission studies and experiments by the NASA, Jet Propulsion Laboratory (JPL), and Raytheon have demonstrated the principle of efficient transmission. Efficiencies of about 90 percent for each of the three transmission steps (electric-to-microwave conversion, antenna-to-antenna transmission, and microwave-to-electric conversion) are indicated, and these values lead to a predicted transmission link efficiency of 70 percent or better.

System economics are dependent on low-cost space transportation. Flight to orbit is not intrinsically expensive; that is, the basic energy cost is not high. The cost of propellants for a large rocket (Saturn or the projected space freighter) is less than $11.02/kg ($5/lb) of payload. The history of rocket development from Vanguard to Saturn shows reduced cost through increased efficiency and size. By partial reuse, the shuttle will eliminate a large part of the highest cost element of Saturn. Through complete reuse, efficiency that results from large size, and efficiency that results from using launch crews at high launch rates, the space freighter can keep costs below $44.09/kg ($20/lb), according to Boeing studies.

SETUP AND OPERATION METHODOLOGY

The size of the powersat is awesome, primarily because normally space payloads are throught of as being fully assembled on Earth and then launched into space. Skyscrapers, dams, or nuclear powerplants would be equally awesome if they were thought of as being transported, fully assembled, from one place to another on Earth.

Powersat parts and subassemblies would be transported to a low Earth orbit, similar to the Skylab orbit, in hundreds of flights of a low-cost space freighter, shown in comparison with the Apollo-Saturn moon rocket in fig. 4. The freighter would burn nonpolluting hydrogen fuel as did the Saturn upper stages. Its "fat Albert" shape provides a large-volume payload bay and enables controlled aerodynamic return to Earth and a rocket-arrested soft landing. The freighter shown has been sized for 226 796.2 kilograms (250 tons) of payload and would use space shuttle engine technology and a water-cooled heat shield to achieve total reusability and a ground handling time between flights of less than 1 day.

The destination of the space freighter is an assembly station in space, manned by a construction crew. In the zero gravity of orbit, the lightweight structure of the powersat can be safely deployed with a minimum of effort and all the parts can be installed, connected, and checked out.

Completed power generation modules would be efficiently transferred to a stationary orbit at 35 405.6 kilometers (22 000 miles) by electric rockets drawing electric power from the modules. The low thrust of the electric rockets would not overstress the lightweight structure and could effect the transfer in about 3 months. Small conventional rockets would assist the electric rockets in keeping the power module pointed at the Sun. The electric rocket engines and their controls would be returned to the assembly station to be used again and again. Final assembly of the powersat occurs in the operational orbit by joining the modules together and attaching the microwave transmitter, transported by one of the power generation modules, at its operating position.

The power transmission system must efficiently move the electric energy obtained from the Sun over 35 405.6 kilometers (22 000) miles of space to the Earth's surface for use. Efficiency is critical. To maintain the same useful power output on the ground if transmission efficiency is reduced 10 percent, the entire powersat must be made 10-percent larger.

Wireless transmission of power, rather than just signals, has been foreign to our thinking. However, the possibility was originally recognized by Nikola Tesla about 75 years ago. Recent experiments at Raytheon and the JPL have demonstrated overall link efficiencies greater than 50 percent. Still to be accomplished are the major engineering developments of precision electronic phase control for beam forming and further conversion element efficiency improvement to reach the projected 70-percent transmission efficiency.

The transmission system would use amplitron radiofrequency generators much like microwave oven tubes, and a wavelength of approximately 12.7 centimeters (5 inches). Maximum beam strength at the center of the receiving antenna is approximately 484.4 W/m^2 (45 W/ft^2). At the antenna edge, the beam strength is well below public exposure standards.

SPACE TECHNOLOGY HISTORY AND POTENTIAL

It is instructive to contemplate the history of space technology when one is attempting to imagine the potential of its future. Still vivid are images of the early space vehicles of the late 1950's climbing into the Florida sky, all too often ending in a brilliant display of flames, fragments, failure, and frustrations. And just a decade later, the ponderous Saturns rose slowly into the same sky on Earth-shaking thunder carrying men to leave ageless footprints in the sterile dust of another world.

The history of "modern" space technology really goes back to Goddard's early experiments, beginning with his first liquid-rocket flight in 1926. The stage was quickly set for development, over the next 15 years, of the basic liquid rocket, which culminated in the 10.9-megagram (12 ton) German V-2 war rocket of 1942 to 1945. The next 15 years saw performance improvements, increases in size, and implementation of staging, all of which resulted in vehicles that could attain orbit. Early Russian spectaculars in space led to the American Apollo program. Steady improvements in reliability and safety, increases in size and complexity, and use of high-energy fuels put man on the Moon only 12 years after Sputnik I was launched.

Costs, as well as the achievements of space flight, became spectacular. The current thrust of space technology is toward lower costs through reusable hardware and cost-optimized design. This trend is on the path to economic practicality of the powersat. But a powersat program cannot be moved up to in one big all-encompassing step. A series of steps are needed, beginning with studies, concepts, and technology experiments (see fig. 5). Space tests onboard the shuttle pertaining to fold-out structure, deployment devices, microwave experiments, and the like (see fig. 7) will proceed through pilot-plant prototype hardware ground tests and design studies of a space freighter. An orbiting subscale pilot-plant powersat will prove out the technical features and capabilities needed to make the full-size powersat an economically practical reality. Then we will be ready for the big step to an operational powersat program.

DEVELOPMENT PROGRAM

How long would it all take? Is this a next-century solution to a this-century problem? Boeing's preliminary studies have indicated that an orderly three-phase development program (see fig. 7) could place the first operating powersat in service in approximately 15 years. This prediction is entirely consistent with the historical fact that significant advances in aerospace technology require from 12 to 15 years to reach fruition.

The first phase is a detailed engineering analysis and design-to-cost optimization study. Supported by tests and experiments in critical areas, this phase would yield selection of most design features, and higher confidence in system economics and would provide firm direction and guidelines to the succeeding advanced development phase.

The second or advanced development phase would develop and prove out, by subscale flight demonstration, all the critical elements and features of the entire system except the space freighter. Flight experiments and pilot-plant assembly and operation could be a principal mission for the space shuttle in the early- to mid-1980's.

The third phase or full-scale development program would begin with design definition and long-lead development of the space freighter. High confidence in its performance, cost, and operational characteristics would be available when results from the advanced development program merited a final decision to proceed with the entire powersat system. The development phase includes design and construction of the ground and space facilities required to deploy one 10 000-megawatt satellite per year.

Forecasts indicate that by the 1990's the United States will need to add between 30 000 and 70 000 megawatts of new generating capacity per year (see fig. 8). The Boeing powersat economic analyses conservatively assumed capture of about one-fifth of this market. A greater powersat addition rate could be implemented if needed.

CONCLUDING REMARKS

Solar energy has bathed the Earth throughout its history. The ancient Greeks had begun to recognize some of its potentials for man. Small machines using solar energy were built and exhibited during the 19th century, but they were mostly curiosities. Solar energy powered Skylab; it has powered most of the United States spacecraft. Now, in the latter part of the 20th century, its potential value is beginning to be perceived as a limitless, permanent source of energy.

Coal, "combustible rock," was known to antiquity. Its use on a commercial scale began in England during the 16th century. Petroleum was discovered in the 19th century, and petroleum-based liquid fuels soon came into commercial use. During the 20th century, fossil sources of energy have been being depleted a million times faster than their creation rate. As a result, the age of petroleum is ending; but coal will be a principal source of fuel until at least well into the 21st century. Also during the

20th century, development has been initiated on two alternative sources of energy representing "permanent" solutions — nuclear (particularly fusion) and solar. The need for energy to provide power for civilization is so critical that all promising sources should be pursued.

Boeing's studies of the powersat have resulted in their consensus that the most practical way to use solar energy for electric power on a large scale may well be to collect it in space, without hindrance by darkness and weather. It is believed that the powersat should be considered as a promising long-range energy system and that current technology is sufficiently mature to initiate the beginning steps toward its development.

The time for a decision of major commitment is not now. The decision recommended now is to begin in-depth engineering and economic study of power from space. Many incremental decision points, each dependent on successful accomplishments, will lead to full-scale deployment. The promising long-range potential of the powersat is there; now is the time to take first steps.

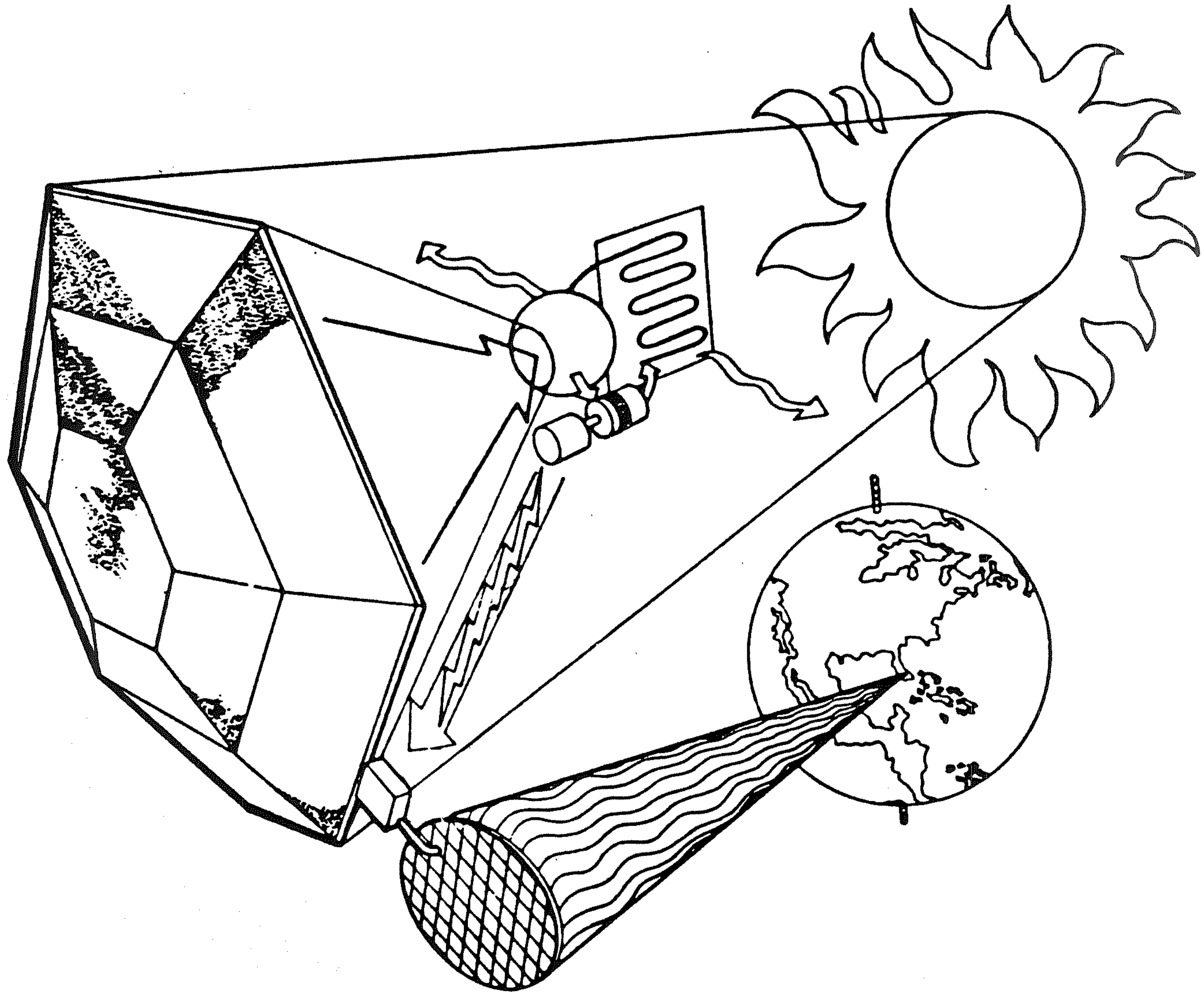

Figure 1.- Powersat in geosynchronous orbit beaming energy to Earth.

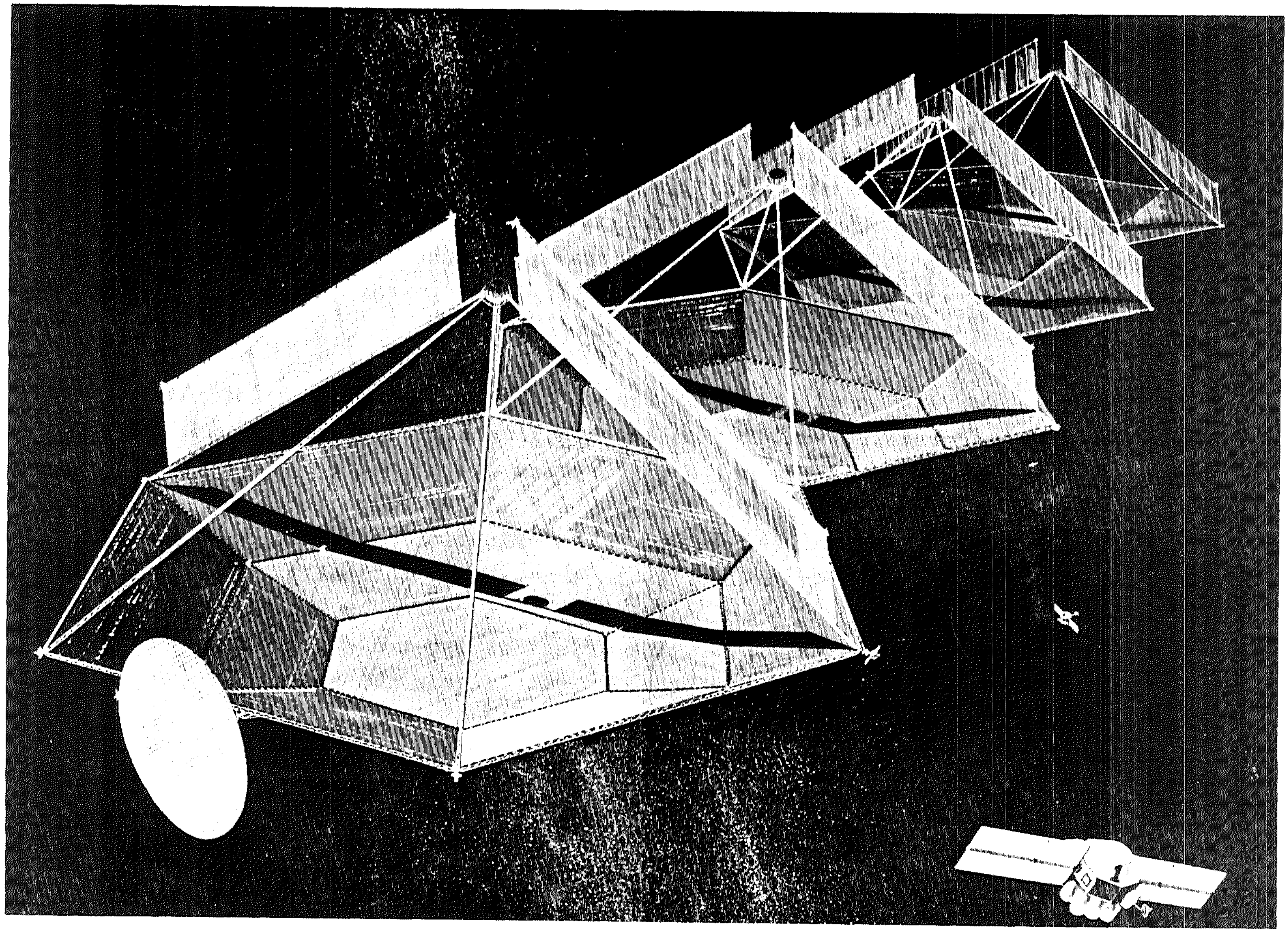

Figure 2.- Powersat configuration.

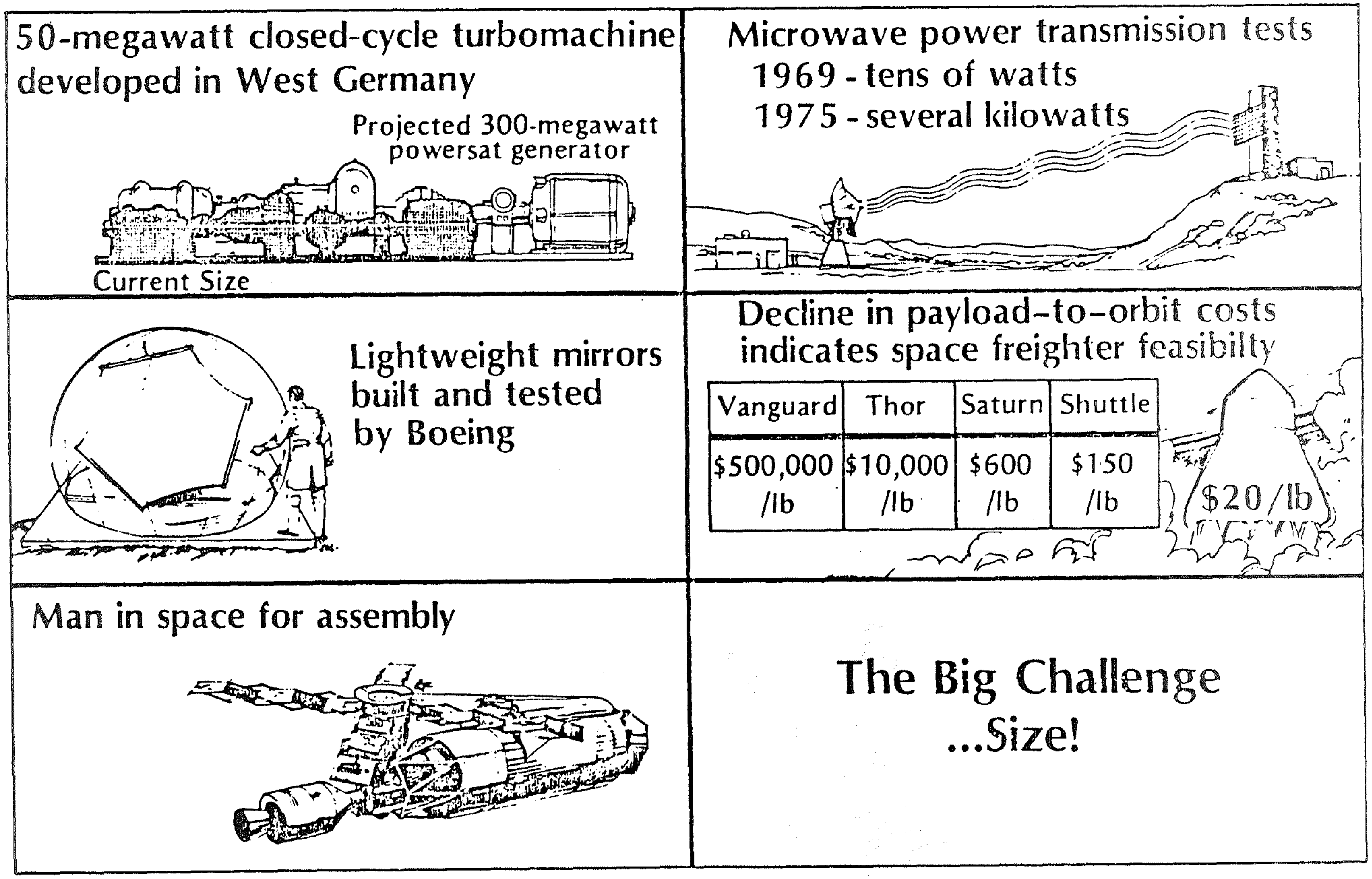

Figure 3.- Feasibility based on existing technology.

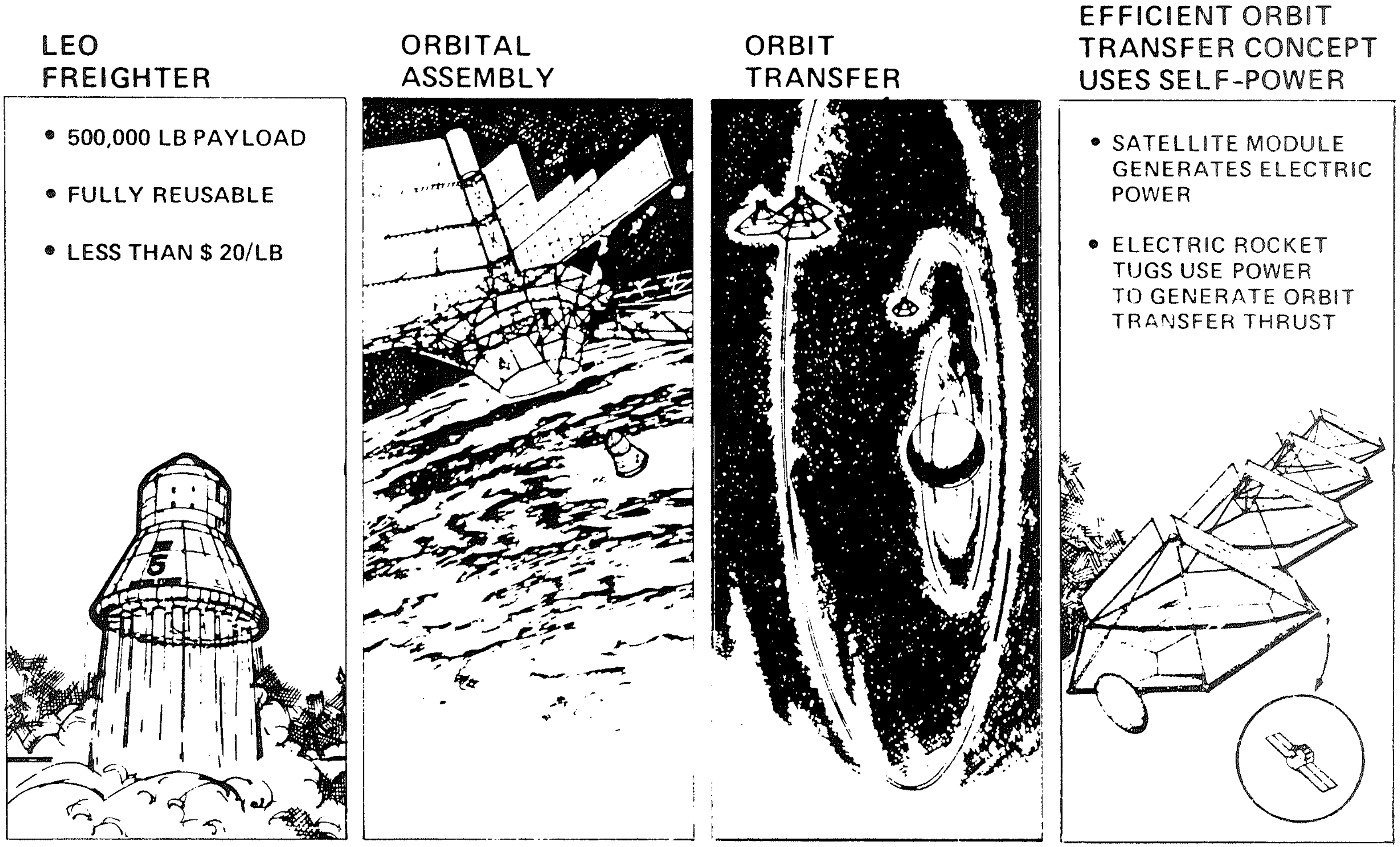

Figure 4.- Critical elements of power from space (common to any space-based system).

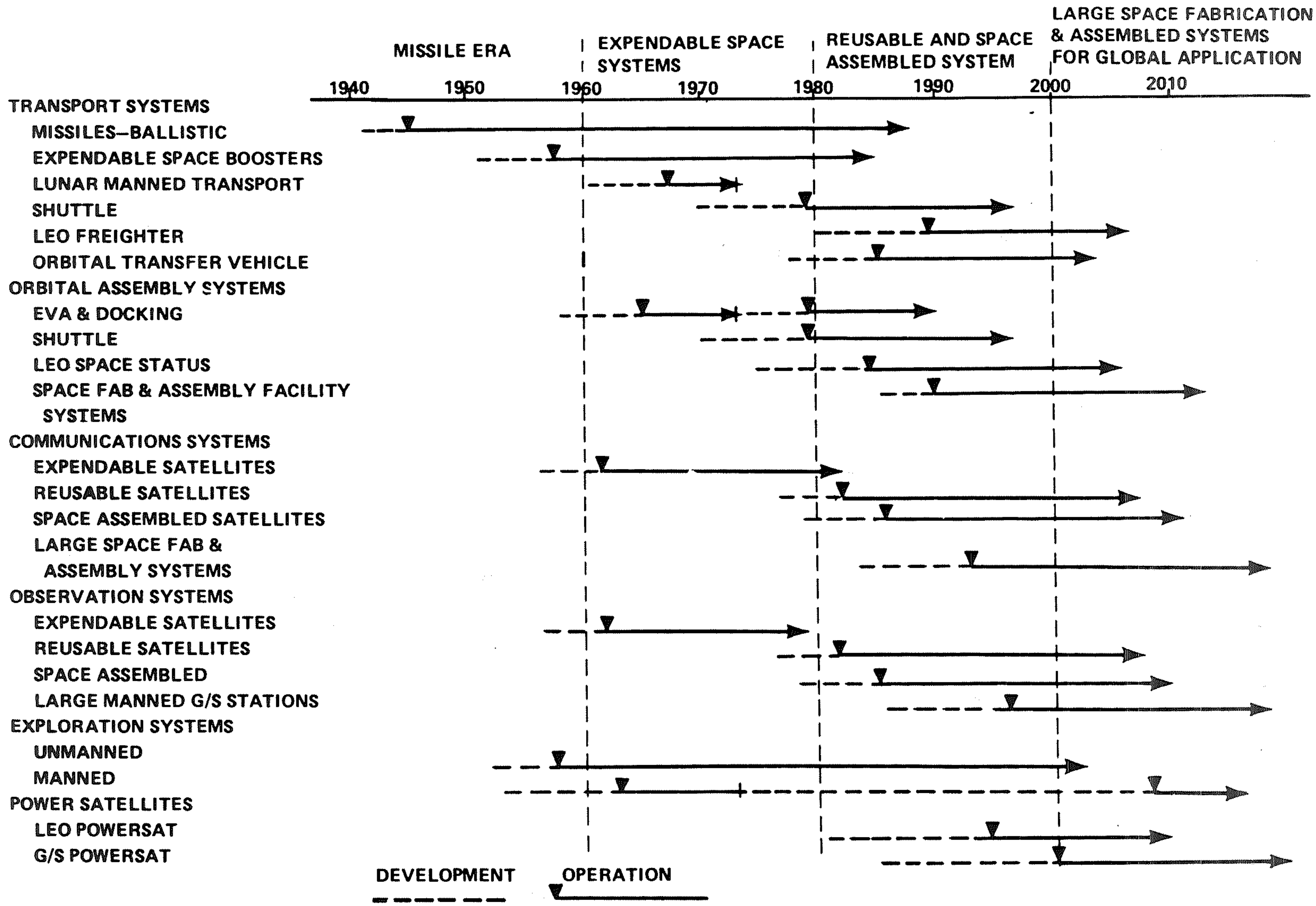

Figure 5.- Global space systems evolution.

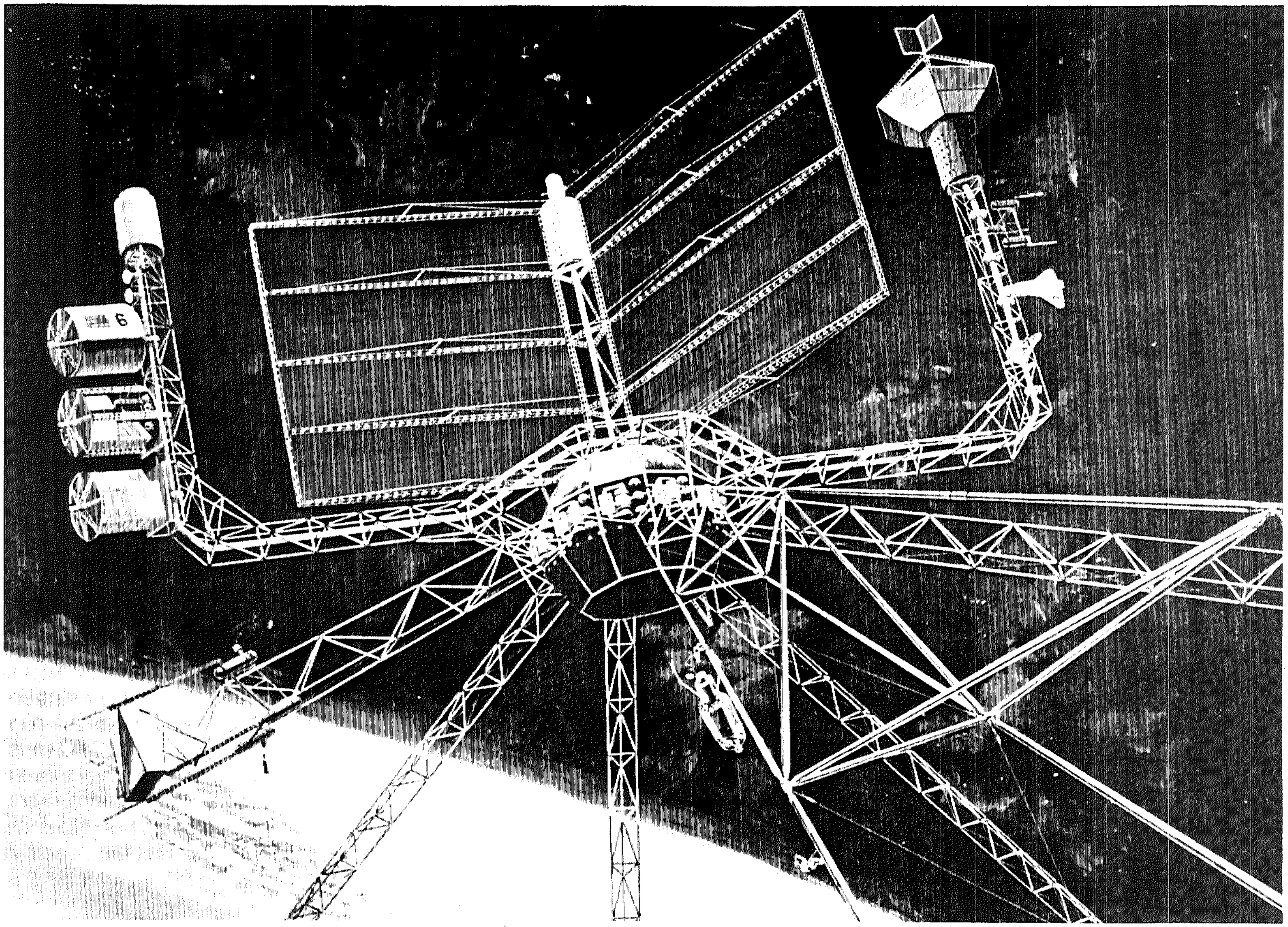

Figure 6.- Space Shuttle: key to space solar power.

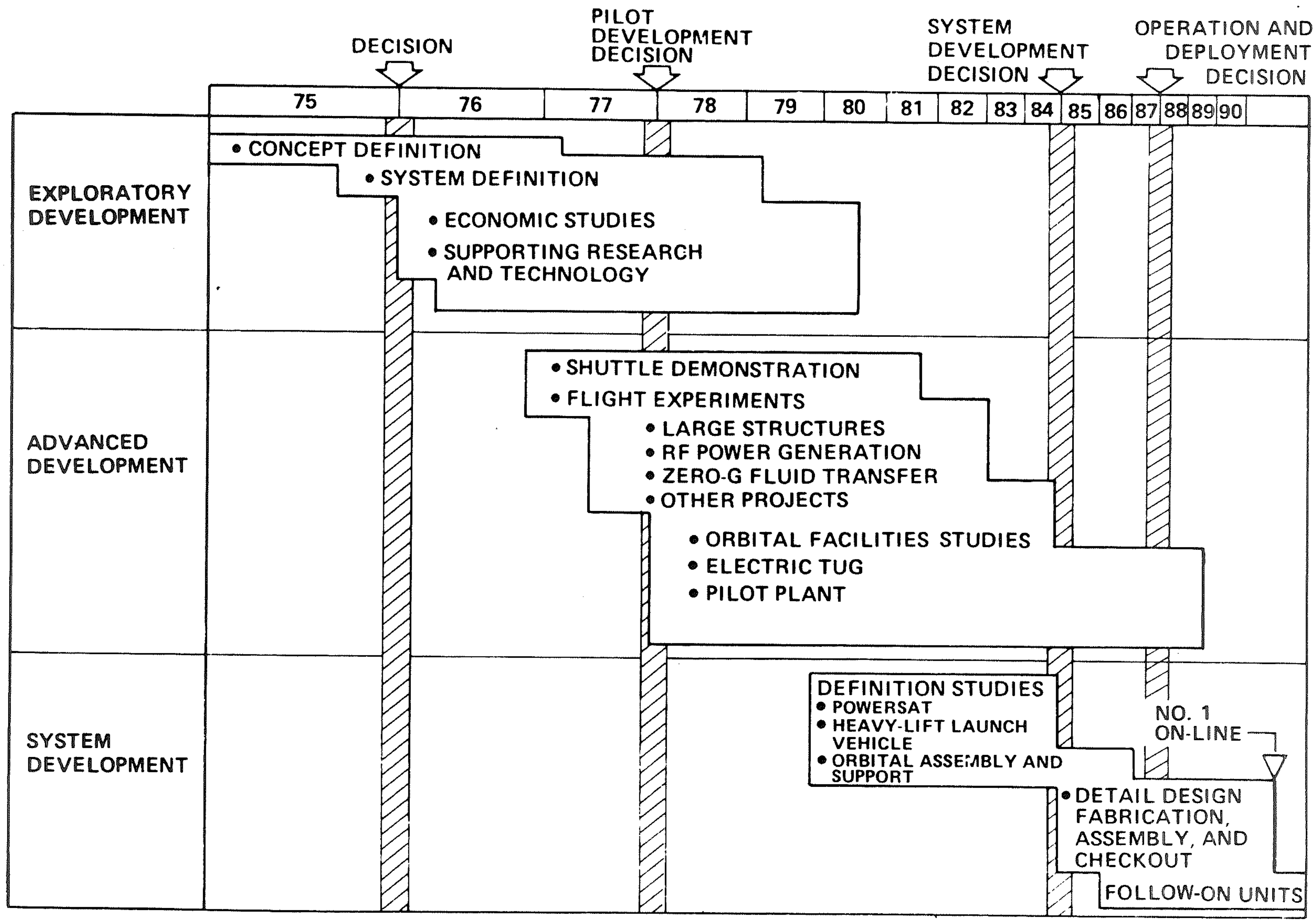

Figure 7.- Three-phase powersat development.

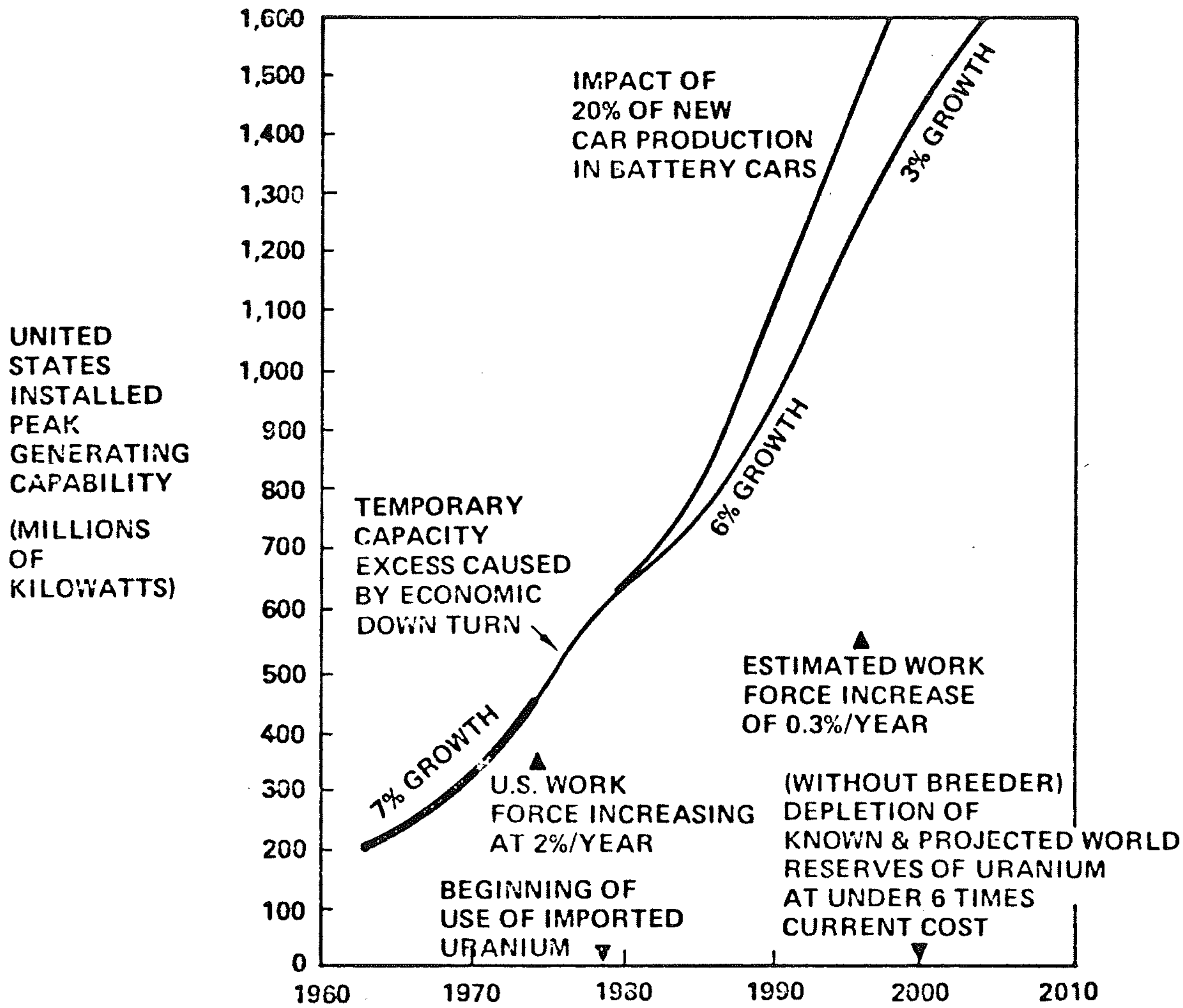

Figure 8.- Projected U.S. electrical power demands.