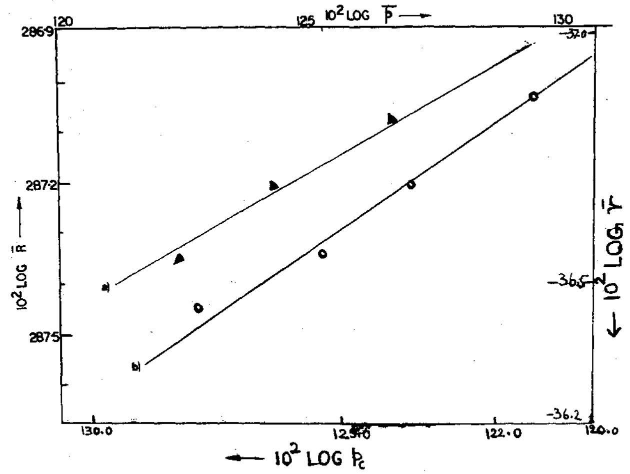

Fig. 1 a) Dependence of $\bar{r}$ on chamber pressure; b) logarithmic plot of $\bar{R}$ vs $\bar{P}$ to observe the validity of the empirical relation.

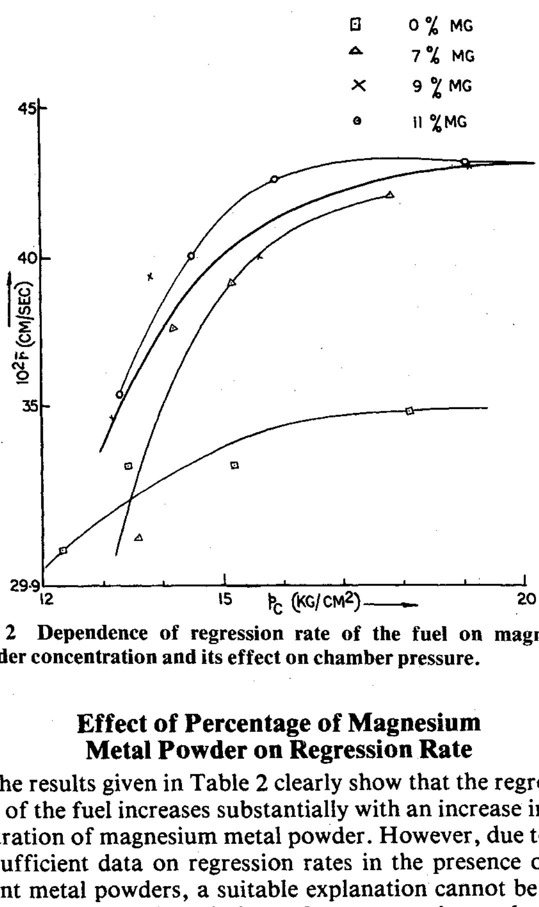

Fig. 2 Dependence of regression rate of the fuel on magnesium powder concentration and its effect on chamber pressure.

Effect of Percentage of Magnesium Metal Powder on Regression Rate

The results given in Table 2 clearly show that the regression rate of the fuel increases substantially with an increase in concentration of magnesium metal powder. However, due to lack of sufficient data on regression rates in the presence of different metal powders, a suitable explanation cannot be given for the nature of variation of $\bar{r}$ vs metal powder concentration. From Fig. 2, it is observed that with an increase of metal powder concentration in the fuel, the regression rate starts to become independent of the chamber pressure.

Empirical Relation

The empirical relation mentioned below has been developed to account for the experimental observations.

$$A\bar{R} = (\bar{G}_o + A\bar{G}_o^2)\bar{P}^N - B\bar{G}_o^n\bar{P}^{2N}$$

where $\bar{R} = \bar{r}/V_i$; $\bar{G}_o = G_o\text{max}$ and $P = p_c/p_a$. The value of G_o^{max}, which is the value of G_o beyond which the regression rate of the fuel will start decreasing due to flooding on the surface of the fuel, was calculated from the equation of the curve (a polynomial) obtained from the plot of $\bar{r}$ vs G_o (Table 2), for the case of fuel containing 9% Mg. The equation of the curve was calculated by an averaging method and is $\bar{r} = G_o - 31.7\ G_o^2$. The value for the maximum of the curve (G_o^{max}) comes out to be 0.0164 kg/cm² sec.

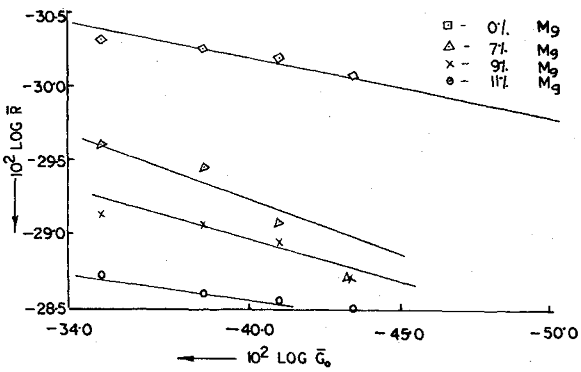

Fig. 3 Logarithmic plot of $\bar{R}$ vs $\bar{G}_o$ to observe the validity of the empirical relation.

Various plots (Fig. 3) have been shown to observe the validity of the empirical relation and the average value of exponent n comes out to be 2.6. Plots of log $\bar{R}$ vs log $\bar{P}$, Fig. 1b, when G_o is kept constant, indicate that the regression rate varies as the square root of the chamber pressure. The empirical relation also gives an idea as to the dependence of $\bar{r}$ on G_o and it is quadratic in nature.

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Evolution of the Satellite Solar Power Station (SSPS) Concept

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Rationale for the SSPS

SINCE 1968, the configuration of the SSPS has evolved as a result of a series of technical and economic feasibility studies.[1] The concept[2] requires that the SSPS be maintained

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in synchronous orbit around the Earth to provide a nearly continuous conversion of solar energy into electricity. The electricity is fed to microwave generators incorporated in a transmitting antenna. This antenna directs the microwaves to a receiving antenna on Earth, where their energy is efficiently and safely reconverted to electricity.

The conversion of solar energy via an SSPS in synchronous orbit has the following advantages: 1) The amount of solar energy available in synchronous orbit ranges from 6 to 10 times that available on Earth in areas receiving copious sunshine. 2) The solar energy in orbit is available nearly continuously except for short periods around the equinoxes, at which time the satellite will be shadowed by the Earth for a maximum of 72 minutes a day. 3) The SSPS in synchronous orbit is stationary with respect to a desired location on Earth; the microwave beam can be directed to most receiving antenna sites on low-value land or offshore. 4) Waste heat associated with solar energy conversion and microwave generation is rejected to space; no waste products are generated; the microwave beam densities meet international standards; and the thermal pollution entailed in the reconversion of microwaves directly to electricity at the receiving antenna is about one quarter of that of conventional power plants. 5) The SSPS has the potential to deliver from 2,000 to 15,000 MW of power to Earth.[1] At first the SSPS could meet incremental capacity demands and subsequently replace conventional power plants.

As originally conceived, the SSPS could have utilized thermal[3] or photovoltaic[4] approaches to convert solar energy into electricity. However, photovoltaic energy conversion by solar cells was chosen for a baseline design because it is a passive technique and it represents a demonstrated technology as a result of widespread use in the space program. In the SSPS baseline configuration using silicon solar cells, two solar collector panels provide a power output of about 8500 MW, and the effective power output at the receiving antenna bus bar is about 5000 MW.

Thermal approaches are being pursued although they require dissipation of waste heat through active systems, including radiators. This poses a major challenge because of the mass required for large-area space radiators and the problems inherent in the reliability of active systems.

Laser and microwave approaches were considered for transmitting the power generated in the SSPS to Earth. However, the microwave method was chosen because it uses state-of-the-art or achievable technology to obtain high efficiency in generation, transmission, and rectification.[5]

Consideration of the transmission of power from orbit to Earth by laser was discontinued because of the low efficiencies associated with the conversion of electricity into laser power and the reconversion of laser power into electricity. In addition, the absorption of laser beams in the atmosphere would reduce the overall efficiency of power transmission to an uneconomic level.

SSPS Technology and Costs

Photovoltaic Conversion

The key element in the photovoltaic conversion of solar energy to electricity is the silicon solar cell. The present technology is to mount the cells on rigid substrates and bond cover glasses to the cells to shield them from radiation. These cells are about 200 microns thick and about 15% efficient. Advanced "roll out" blanket designs with weight/power ratios of about 15 kg/kW have been fabricated.

With improved fabrication techniques, reduction in thickness to less than 100 microns, plastic film lamination and use of solar concentrators, solar cell array weight/power ratios of about 1.5 kg/kW are projected to be achievable in 10 years. These projections are based on improvement of the efficiency of single-crystal silicon solar cells – considered feasible even with reduced thickness – to 18%[6] and achievement of the goals of the National Photovoltaic Conversion Program being conducted by ERDA, one of which is to reduce the cost of silicon solar cells to about 50¢ per peak watt. Assuming that the same solar cell efficiency can be achieved, reducing solar cell thickness from 100 microns to 50 microns will reduce the 5000-MW SSPS mass from 15.6×10^6 kg to 12.4×10^6 kg. A 10% reduction of solar cell efficiency will lead to an increase of the SSPS mass to 13.8×10^6 kg. Solar concentrators with Kapton-film mirrors coated to reflect solar radiation onto solar cells and to filter undesirable portions of the solar spectrum will reduce the cell area required. If a 70% slope experience curve were to apply, one SSPS would require the production quantity necessary to achieve the projected solar cell cost reductions. The 30-year operational lifetime of the SSPS is based on a projected logarithmic degradation of silicon solar cell efficiency, with 6% of the orginial efficiency lost after the first five years. Micrometeoroid impacts will affect 1% of the solar cells during this period.

Baseline Configuration

A 100-m-diameter central mast and stiffened structure running through the solar collector array assembly provide structural integrity. A microwave transmitting antenna is located between the two collector panels. The collector panels will face the sun continuously while the microwave antenna will rotate once a day with respect to the solar collector. Nonconducting and conducting panel-support structures carry the power to the microwave generators via the central mast.

At the perimeter of the central mast, rotary joints – the only major continuously active components in an otherwise passive satellite – allow rotation of the microwave transmitting antenna. The continuous support structure is made of dielectric materials which are transparent to the microwave beam.

The large structure required for the SSPS will be subjected to orbital perturbations, of which the gravity gradient will be the most significant. A reaction control system based on the use of ion engines (Argon is one candidate propellant) will be required to keep the SSPS in the appropriate orbit and to assure that the solar collector panels point towards the sun within one degree, while the microwave antenna is directed towards the receiving antenna on Earth. About 50,000 kg of propellant per year will be required, depending upon specific orbital characteristics, to achieve the desired stationkeeping and attitude control for the SSPS.

Assuming that 5000 MW are delivered to the bus bar, the total mass of the SSPS is 18.12×10^6 kg, divided as follows; solar arrays, 12.37; transmitting antenna, 5.54; control system, 0.04; rotary joint, 0.17. The 3.6-kg/kW weight/power ratio of the orbiting portion of the SSPS is remarkably low compared to that of terrestrial energy conversion systems.

The baseline configuration uses a cross-field amplifier (Amplitron) to convert DC to RF power at microwave frequencies.[7] The Amplitron uses a platinum metal cathode operating on the principle of secondary emission to achieve a nearly infinite cathode life.

The weight of the Amplitron's Samarium Cobalt magnet is low compared to that of conventional permanent magnets utilized in other microwave devices. We project a 0.3 kg/kW weight/power ratio for the Amplitron. Radiating surfaces, which will be operating at 150 to 200C, are designed to reject waste heat (representing about 10% of the input power) to space. The space radiators are made of pyrolitic graphite because of its low density and high emittance. A movable magnetic shunt – the only element subject to wear – is incorporated to regulate the output if the input current fluctuates.

System weight, costs, and efficiency at specific frequencies have led to the selection of an Amplitron frequency near 2.45 GHz – within the industrail microwave band of 2.40 to 2.50 GHz – which produces a near optimum output power level. At a DC voltage input of 20 kV, with an efficiency of 85% the output power of the Amplitron is 6kW.

Space is an ideal medium for the transmission of microwaves: a transmission efficiency of 99.6% is projected for the microwave beam passing through space. About 3% will be absorbed during passage through the atmosphere. During transmission from synchronous orbit to Earth, the curvature of the phase front of the beam will be very small; nevertheless, the front must be precisely controlled to achieve this high efficiency. The geometric relationships between the transmitting and receiving antennas to achieve a microwave beam power density at the receiving antenna suitable for efficient conversion into DC indicate that the diameter of the transmitting antenna should be about 0.8 km and that of the receiving antenna about 10 km (depending on latitude).

To reduce the dimensions of the transmitting antenna, the microwave amplitudes can be tapered from the center to the edge over the range of 5 to 10dB. The advantage of transmitting-antenna amplitude taper, rather than uniform illumination, is that it reduces the intensity at the center of the beam to about 25 mW/cm^2, at which level ionospheric interactions are unlikely to occur.

To achieve the desired control of the phase front in the transmitting antenna, 18-x 18-m subarrays are arranged into sectors to provide the required center-to-edge amplitude taper. A large number of these small subarrays reduces the effect of attitude-control inaccuracies. Phase-control electronics for each subarray compensate for subarray distortions which may be induced by thermal effects. The phased-array antenna is very efficient, minimizing low-frequency cut-off and reducing RF interference.

A closed-loop command and adaptive phase-front control achieves the desired high efficiency and safety essential for the microwave beam operation. The reference beam launched from the center of the receiving antenna is sensed at each subarray and at a reference subarray in the center of the transmitting antenna. The central subarray transmits the reference signals to the subarrays over calibrated coaxial cables. The difference in phase between the signals – which may result from, for example, the displacement of a subarray from the nominal reference plane because of thermal distortions of the structure – corrects the phase of the transmitted beam at the displaced subarray so that the required beam front is launched toward the receiving antenna. The wave guides, made of aluminum, have an overall thickness of about 0.5 mm, and are divided into five-meter segments to limit wave guide deflection. The maximum radiated power of each subarray will be about 7 MW.

Microwave Reception and Power Generation

The receiving antenna intercepts, collects, and rectifies the microwave beam into a dc output to high-voltage transmission network or for conversion into 60 Hz ac. It consists of an array of halfwave dipole antennas which rectify the incident microwave beam. Each dipole has an integral, low-pass filter, diode rectifier and rf bypass capacitor. The dipoles are dc-insulated from the ground plane and appear as rf absorbers to the incoming microwaves.

Because the receiving antenna element and the microwave radiation are coherent and polarized, the effective conduction cycle of the diode rectifier circuit and the reactive energy storage combine to produce a very high efficiency. (Ninety percent of the theoretical 100% conversion efficiency has been achieved in the laboratory.)

A receiving antenna based on the principle of halfwave dipole rectification is fixed and does not have to be pointed precisely at the transmitting antenna; thus, its mechanical tolerances do not need to be severe. Furthermore, the density distribution of incoming microwave radiation need not be matched to the radiation pattern of the receiving antenna; therefore,a distorted incoming wavefront caused by nonuniform atmospheric conditions across the antenna does not reduce efficiency.

The amount of microwave power received in local regions of the receiving antenna can be matched to the power-handling capability of the microwave rectifiers. Any heat resulting from inefficient rectification in the diode circuit can be convected by the receiving antenna to ambient air, producing atmospheric heating which will be less than that over urban areas because only about 15% of the incoming microwave radiation would be lost as waste heat.

In the summer of 1975, tests of a 24-square-meter array of microwave rectifier elements were conducted at the NASA Venus antenna site at Goldstone, California, to demonstrate the effective performance of dipole rectification.[8] The transmitting antenna, which consisted of an 86-ft-diameter dish, was located about one mile from the receiving elements. At a radiated frequency of 2388 MHz, incident peak rf intensities of 170 mW/cm^2 yielded up to 30.4 kW of DC output power. An average conversion efficiency of 82% was obtained at the receiving element.

Transportation, Assembly, and Maintenance

The SSPS will require a space transportation system capable of placing a large mass of payload into synchronous orbit at the lowest possible cost. It is highly probable that a two-stage transportation system will evolve which will carry payloads first to low-Earth orbit and subsequently deliver partially assembled components to synchronous orbit or possibly to an intermediate orbital altitude for final assembly and development.

The space transportation systems being considered, starting with the space shuttle now under development, vary from the use of a modified space shuttle to the development of a fully reusable liquid oxygen/liquid hydrogen heavy-lift launch vehicle with a potential capability to deliver a payload of more than 200,000 kg to low-Earth orbit. The current shuttle or its modification can be used for SSPS technology verification and flight demonstrations and for transporting elements of the prototype SSPS into low-Earth orbit. The cost for a modified space shuttle capable of lifting payloads up to 80,000 kg to low-Earth orbits is projected to be $50-100/kg. The heavy-lift launch vehicle is expected to reduce payload delivery costs to low-Earth orbit to $10-30/kg. When an advanced space transportation system based on heavy-lift launch vehicles is used, the large mass of payloads will require 60 to 100 flights for each SSPS assembled in synchronous orbit.

Ion propulsion, using solar power sources, could be used to transport a completely assembled SSPS from low-Earth to synchronous orbit – with the option to transport it to an intermediate orbit above the Van Allen belt. Chemically powered stages would transport payloads from low-Earth orbit to this intermediate orbit, and ion propulsion would transport the assembled SSPS to synchronous orbit. The cost for each flight will be strongly influenced by the feasibility of using ion propulsion for the orbit-to-orbit transportation and by the ability to reuse most of the components of the space transportation system for a large number of successive flights. Challenges inherent in the development of a low-cost, heavy-lift space transportation system are being explored.[9] Low-cost space transportation will be essential to the commercial success of the SSPS.

The large number of components, most of them performing the identical function, and the role of man in assembling these components require that the methods of assembly, packaging of components, assembly rates, and maintenance and repair support facilities for the assembly and subsequent operational phases be carefully evaluated. There are two basic approaches to assembly:[9] 1) remote assembly using ground-controlled tele-operators; and 2) assembly of components delivered to synchronous orbit by an assembly crew operating from a space station support base as part of extravehicular activities.

The choice between manned or tele-operator assembly will depend on the cost effectiveness of each approach. Tele-operators using remote assembly techniques should achieve assembly rates in excess of about 5 kg an hour, and would appear to be more effective than manned assembly, which would have to achieve rates of about 10 kg an hour to justify the cost of space stations and recycling of crews. It is highly likely that a combination of both manned operations and tele-operators will evolve, where man's most important function will be to control the assembly process. Such a space-based manufacturing operation would permit assembly rates of about 200 kg/hr. allowing the most effective use of the high-lift capability of the space transportation system, and thus greatly reducing the number of orbital flights.

SSPS Economies

Investigations into the economic viability of the SSPS in comparison with that of other power generation alternatives indicate that the SSPS deserves serious consideration.[10] An operational 5000-MW SSPS would cost about $7.6 billion, or about $1500/kW. The largest cost element is space transportation, indicating that improvements in SSPS efficiency, particularly at the receiving antenna, and weight reduction would have significant effects.

For an operational life of about 30 years, the cost of power at the bus bar would be 27 mills/kWh. The expected life-cycle revenues will be about $35 billion for each SSPS, while operating costs will be $140 million per year (or $4.2 billion over a 30-year life cycle).

The revenues from a series of SSPS can be used to offset the development program costs – $20 billion for the development of SSPS technology and another $24 billion for the development of the space transportation system and related technology. Assuming that alternative system generation costs average 35 mills/kWhr, the SSPS development program costs could be repaid if 60 SSPS were operational by the year 2014. This number of operational SSPS will provide at least 10% of projected incremental installed generation capcity in the United States. If alternative system generation costs were less than 35 mills/kWhr, between 1995 and 2014, a larger number of operational SSPS would be required.

A 5000-MW operational SSPS will be cost-competitive with coal at the projected bus bar cost of 27mills/kWhr if, as expected, coal prices rise 2.7% per year between 1995 and 2025 because of increased production costs and costs for pollution control equipment. The relative increase in the price of oil is expected to be higher; more importantly, after 2000 it is unlikely to be available – at any price – for large-scale power generation purposes.

Projected bus bar costs of terrestrial solar thermal and photovoltaic conversion systems range from 35 to 65 mills/kWh. Both of these solar energy conversion systems would provide mainly peaking power, whereas the SSPS will provide base load power. Economic analyses to date have not included the cost of social and environmental impacts. These costs would adversely affect the economics of most large-scale terrestrial generation systems and thus would further enhance the overall economic attractiveness of the SSPS.

SSPS Development Program

The SSPS development program can be divded into three phases. During the first phase, the development of technology to meet performance and cost goals will proceed and the technology will be verified to provide data on the performance of components and subcomponents under expected operating conditions. The technology verification activities can be done on Earth, being supplemented only by those space experiments needed to provide data on specific system and components functions, potential interactions of the microwave beam with the ionosphere, and microwave frequency and beam power densities as they relate to biological-effects criteria.

The critical technology developments will be concerned with improvements in solar energy conversion methods; techniques for manufacturing and assembling components in orbit; system stability and control, and stationkeeping (including ion engine development); microwave generation and transmission, including the development of dc-to-rf converters and filters, the development of waveguide materials, phase-front control, control of the transmitting antenna attitude, and control or suppression of radio frequency interference; mechanical systems, including rotary joints, slip rings, motor drives, and switch gears; and approaches to operate for extended period in the synchronous orbit environment.

During the first phase, assessment of environmental and socio-economic issues should proceed in parallel. Analyses of these issues will provide feedback into the design and development process and help assure that the technology can be designed to minimize any adverse impacts.

At the end of the first phase, the subsystems and system functions would be verified in an orbiting test facility, which may take the form of a space station. In parallel with the definition of the SSPS technology, the development, production, and operation of the space transportation system for materials, equipment, and personnel from launch through deployment for the specified mission orbit would proceed.

The development of the space transporation systems would include the development of the second-generation space shuttle, transfer vehicles between low-Earth orbit and synchronous orbit, orbital propellant storage, and maneuvering vehicles to transport equipment, materials and propellants to the vicinity of the assembly site. The development of the space transportation system would coincide with the assembly of a large prototype SSPS which should be operated long enough to provide data and experience to guide the design of the full-scale operational unit.

After the successful completion of the second phase of the SSPS development program, the emphasis would shift to mass producing SSPS, to provide at least 100 units by the year 2025. This development program is geared to achieve commercialization of the SSPS by the year 2000 so that this option for the large-scale use of solar energy can play an increasingly important rôle in the generation of power on a world-wide scale in the 21st century and serve as the focus for the industrialization of space.

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