Satellite solar power stations

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A review is given of the present state of work on the development of satellite solar power stations (SSPS) that will be placed in geosynchronous orbits and will convert solar into electric energy and then transfer it in the form of a microwave beam to the earth's surface. The idea of the SSPS was first put forward in 1968 and has since been the subject of considerable development work by a number of companies and government agencies in the USA. SSPS may be regarded as a promising variant of a power system that is capable, at least in principle, of solving the basic problem in power engineering since it is capable of drawing upon an inexhaustible source of energy (the sun). It is also capable of eliminating the problem of ecological contamination, of high efficiency of the energy transfer system (up to 80%), and of flexibility in the redistribution of the available energy among remote consumers. The review analyzes the individual aspects of the problem of developing the SSPS.

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CONTENTS

"By extraterrestrial production, I understand a whole complex of procedures. Scientists and engineers are working on such questions in many countries. The development of power stations in space is one of such questions."

V. P. Glushko[1]

"...It is worth noting that, before electrical engineering was pressed into service by power engineering, it was almost exclusively occupied with electrical communication problems (telegraphy, signalling, and so on). It is very probable that history will repeat itself: at present, electronics is used mainly in radio-communication, but its future lies in solving major problems in power engineering."

P. L. Kapitza[2]

INTRODUCTION

In its broad sense, power engineering has always been the base for growth in the material well being of human society. The characteristic feature of the last century was the increase in available power, based largely on the utilization of natural fuel reserves such as coal, oil, and gas.

The reserves of such fuels are finite and of great potential value as raw materials for future technological processes. The development and utilization of new sources of energy is thus quite clearly a topical problem.[3–5]

Large-scale development of power engineering involves, in a very fundamental way, the question of possible environmental pollution, including thermal contamination on a global scale.[5] One has to face the possibility that, in the future, the solution of this "attendant" problem will force mankind to undertake projects on a gigantic scale.[6]

The utilization of solar energy, which is inexhaustible and fundamentally "clean," has recently attracted increasing attention.[5–17] Developed capitalist countries such as the USA, the Federal Republic of Germany, and Japan have elevated this problem to the status of governmental programs. There is no doubt that solar energy could be used to produce electric power and to supply independent consumers with water and heat, and that this field is clearly of great potential importance.[3,4,18–20]

The difficulties involved in solar energy utilization on a large scale are connected above all with the vari-

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ability and the low mean density of the solar radiation flux on the earth's surface (of the order of 100 W/m^2).[4]

The present state of space technology and its rapid rate of development enable us, even today, to analyze the possibility of industrial utilization of space,[1,16,21-28] including the placing of solar collectors directly in space where the solar radiation flux is stable and has a much higher density (~1.4 kW/m^2).

Although the technological and economic parameters of satellite solar power stations (SSPS)[1)] can at present be predicted only with a measure of uncertainty, there is no doubt that further work on this range of problems is desirable and will be useful.

BASIC SSPS SYSTEMS

The first proposal for the large-scale utilization of solar radiation in space, including its conversion into electric power, was put forward and developed as far back as 1928–1929 by V. P. Glushko, who examined the possibility of using this energy in the engines of his solar rockets.[26]

The principle of the SSPS was formulated by Glaser in 1968.[27] It was subsequently developed further and extended.[2)]

The essence of this is as follows. Large solar cell panels generating dc power are placed in a geosynchronous orbit (~35 800 km). This power is used to supply a system of powerful microwave generators, mounted on a high-efficiency transmitting antenna, which transmits this energy to the earth in the form of a directed beam of electromagnetic waves (Fig. 1). The receiving system on the earth's surface transforms this energy into dc or low-frequency ac power, and transmits it to consumers. An SSPS in a geosynchronous orbit in the equatorial plane of the earth will be stationary relative to the earth's surface and, because of the 23.5° inclination of the equatorial plane to the plane of the ecliptic, the SSPS will be illuminated by solar radiation for over 99% of the year. The earth's shadow will upset the operation of the SSPS only for a short period of time during the 24 days before and after the spring and fall equinoxes, with maximal duration of about 1.2 h. These periods can be accurately predicted. Moreover, they occur close to midnight at the receiving end, so that the demand for power is then usually low.

TABLE I.

	Earth's surface	Geosynchronous orbit	Earth/orbit ratio
Intensity of solar radiation, kW/m^2	1.1	1.4	4/5
Mean time during which solar radiation can be used, h	8	24	1/3
Percentage of cloudless sky	50	100	1/2
Cosine of the angle of incidence	0.5(1)	1	1/2(1)
	Resulting value 1/15(1/7.5)		

The intensity of solar radiation at the geosynchronous orbit is practically constant and amounts to 1.395 kW/m^2 ±2%,[39] which is greater by a factor of 7.5–15 as compared with the earth's surface (Table I).

Thus, the efficiency of the expensive batteries of solar cells in a geosynchronous orbit is greater by roughly an order of magnitude. When such batteries are used on the earth's surface, they require additional buffer storage systems, which increases the cost and reduces the reliability of the power system as a whole.

A satellite solar power station operating under zero-gravity conditions in a deep vacuum may take the form

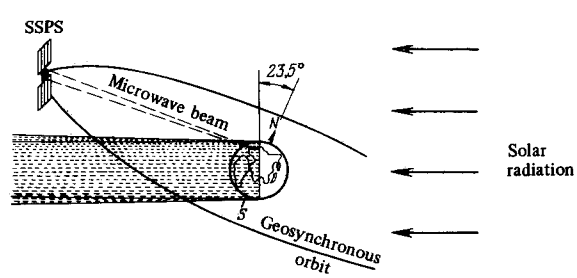

FIG. 1. SSPS in a geosynchronous orbit.

1) Also known as powersats.

2) A special issue of the Journal of Microwave Power devoted to SSPS problems was published in 1970. The principle was patented by Glaser in 1971.[29] A year later, a common research group was formed by Arthur D. Little, Inc., Grumman Aerospace Corporation, Raytheon Corporation, and Textron, Inc.

In 1973, the United States Congress appropriated about 3 billion dollars and instructed the National Aeronautics and Space Administration (NASA) to undertake development work on solar energy utilization, emphasizing the importance of satellite solar power stations.[30] Since then, all this work has been coordinated by the NASA Lewis Research Center.

The Boeing Aerospace Corporation published its own SSPS project in 1974-1975.[31-33]

A five-year program of experimental terrestrial work was begun in the middle of 1975 by the Jet Propulsion Laboratory and the Lewis Research Center.[34]

At the beginning of 1976, William B. Lenoir, an American astronaut-scientist at the NASA Johnson Space Center, who heads the SSPS work at NASA, proposed to the Senate Aerospace Technology and National Needs Subcommittee a program consisting of a number of stages and providing for the experimental development of energy transport from space to earth in the middle or at the end of the nineteen-eighties,[35] and commercial SSPS by 1995–2000.[24,25]

It was agreed in 1976 that the Energy Research and Development Agency (ERDA) would supervise all work under this specific energy program. Meanwhile, NASA will continue mainstream work of direct relevance to SSPS.[36,37]

In Europe, SSPS projects have been analyzed by the Dornier Company and by AEG-Telefunken.[38,90]

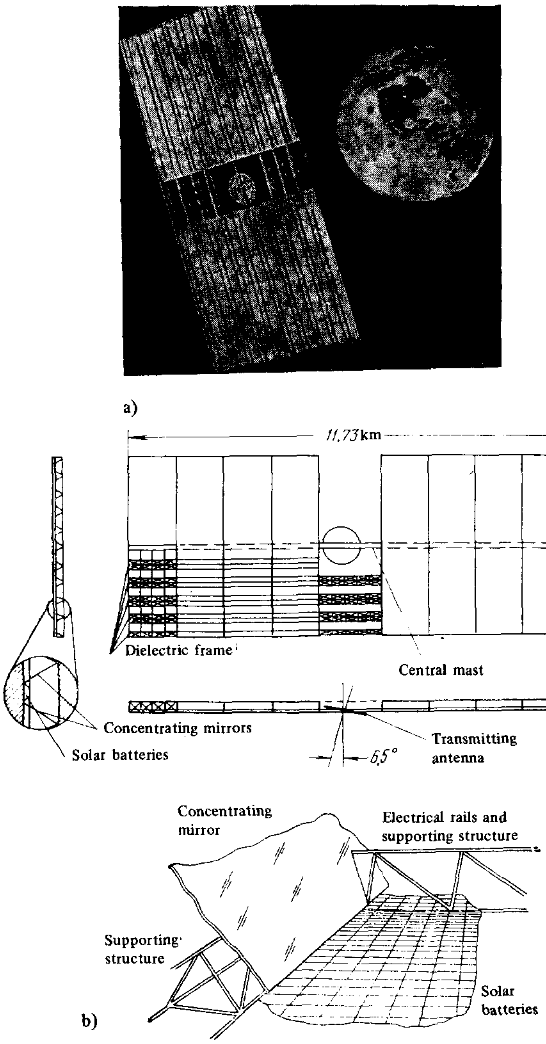

FIG. 2. a—Overall appearance of the SSPS with photoelectric conversion of solar energy (Arthur D. Little, Inc., Grumman Aerospace Corporation); b—SSPS with photoelectric conversion of solar energy (Arthur D. Little, Inc., Grumman Aerospace Corporation).

of a relatively large engineering structure. However, it requires the minimum amount of material because, apart from zero gravity, the system is not subject to factors such as wind, moisture and dust which, under terrestrial conditions, would appreciably complicate the design and increase the cost of the solar power systems.

Additional power sources (for example, ion engines producing a resultant force of about 45 N) are necessary to maintain the SSPS at a given point on the geosynchronous orbit, owing to disturbing factors such as solar radiation pressure, "recoil" due to the emission of the microwaves, magnetic forces, and fluctuations in the earth's gravitational field.

Economically feasible SSPS power levels lie between 2 and 20 million kilowatts.[24,40]

The base variant of the SSPS design (Arthur D. Little, Inc. and Grumman Aerospace Corporation) used in economic and technological analyses is shown in Fig. 2.

Two panels of solar batteries with an overall area of about 45 km^2 are mounted on a supporting dielectric frame and produce 4 million kilowatts of electric power each (40 kV, 100 000 A). When the resultant efficiency is taken into account, this should provide terrestrial consumers with 5 million kilowatts of electric power.

Reflecting mirrors ensure an approximate doubling of the solar flux concentration and are made from a special thin film which reflects only the part of the spectrum that is the most useful for the photoelectric batteries. This reduces the heating of the solar cells and increases their efficiency.

The transmitting antenna has a diameter of 1 km and is in the form of an active phased array. It sends out a high-power coherent beam of electromagnetic waves ($f = 2450$–3000 MHz, $\lambda \approx 10$–12 cm) to the receiving antenna system on the earth's surface, which has a diameter of about 7 km.

The SSPS variant based on the utilization of solar batteries presupposes that substantial technological improvements will be made in these batteries. Above all, they will have to be cheaper and lighter.

The Boeing Aerospace Corporation[31–33] has independently developed a different variant of the SSPS using existing engineering possibilities. This system incorporates solar concentrators working in conjunction with turbogenerators based on the closed Brayton cycle. The system consists of a number of independent modules (Fig. 3) and is designed to generate 13.5 million kilo-

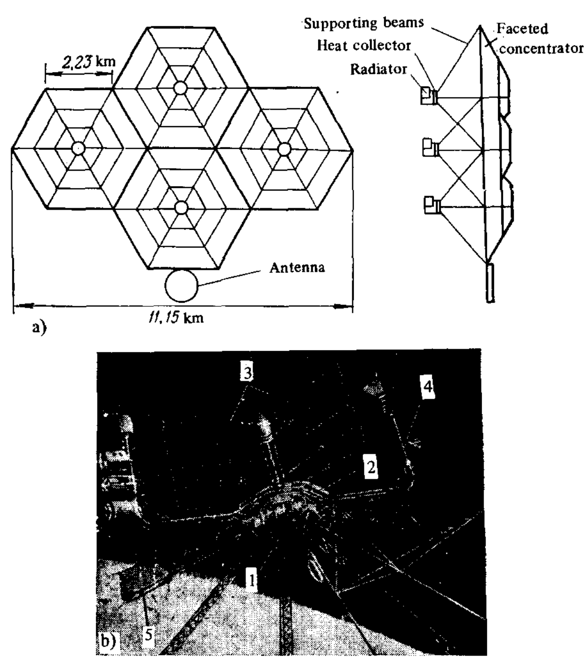

FIG. 3. a—SSPS using a thermal turbine to transform solar into electric power (Boeing Aerospace Corporation); b—SSPS with a thermal turbine being assembled in a low-lying orbit. 1—Heat collector, 2—compartment containing the turbogenerators; 3—radiator panels, 4—mooring line and space shuttle delivering the SSPS components, 5—assembly of one of the supporting beams of the concentrator (Boeing Aerospace Corporation).

watts of electric power which should realistically provide terrestrial consumers with 10 million kilowatts.

Six such stations will satisfy the electric power requirements of Japan and thirty to forty stations would satisfy the needs of the USA.[33]

The SSPS can also act as a centralized source of power for space laboratories and industrial complexes of the future.

The weight of the first SSPS is estimated at 10–12 000 tons, and that of the second at 60–70 000 tons.

Both variants of the SSPS are designed for a 30-year period of operation and are capable of generating electric power at a cost of 2.5 cents per kilowatt-hour.

The time scale is such that the experiments in space will be performed in 1985, the SSPS prototype is planned for 1992, and commercial examples should become available in 1997.[24]

PROBLEMS IN THE CONVERSION OF SOLAR INTO ELECTRIC POWER

There are different known ways of converting solar energy into electric power (photoelectric, thermoelectric, thermionic emission, thermal turbine, and so on).

Only one of these methods, i.e., the photoelectric method, is capable of direct conversion of energy. All the others necessarily involve an intermediate stage of conversion into heat.

1. Photoelectric batteries are based on the absorption of the photons of light in the *p–n* junctions of semiconducting structures which are usually based on silicon (one of the most abundant elements in nature).

The discrete nature of transitions in semiconductors, and the relatively broad spectrum of solar radiation producing the transitions, mean that some of the photons, i.e., those with energies less than the transition energy, do not participate in forming electron-hole pairs. On the other hand, photons of higher energy expend it uselessly in heating the semiconductor.[3)] Even this very simple mechanism essentially restricts the efficiency which, when certain additional factors are taken into account, has a theoretical limit of the order of 22–26% in the case of silicon photocells.[7,41]

In practice, the efficiency of silicon photoconverters usually lies in the range 10–16%.

Photocells are usually based on single-crystal silicon plates with areas of a few cm^2 and are joined into batteries with the necessary switching arrangements to produce the required output voltage and current.[41]

The American Vanguard 1 and the Soviet Sputnik 3

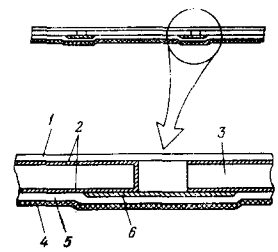

FIG. 4. Schematic diagram of a thin-film solar battery.[54] 1—Protecting plate, 25 μ; 2—metal, 6 μ; 3—solar battery; 4—plastic base, 13 μ; 5—protecting plate, 13 μ; 6—internal metal contact, 25 μ.

(March and May 1958, respectively) were the first space vehicles equipped with solar batteries. The power output of the photoconverters on Vanguard 1 was only 0.1 W, and this may be contrasted with modern space stations which have at their disposal 20–25 kW.[15]

Solar batteries have been among the most expensive sources of power: more than one hundred thousand dollars per kilowatt. This high cost was partly due to the limited range of application of the solar batteries which have been used mainly in space technology where their cost is a minute fraction of the cost of a particle space project as a whole.

The extensive solar energy utilization program for domestic and industrial purposes,[7,18,20,42,43] which has recently been introduced, has radically altered the situation in the sense that the cost of electric power has essentially completely determined the cost effectiveness of solar batteries.

The program for the development of photoelectric sources of energy, which is being implemented by the Energy Research and Development Agency (ERDA) in the United States, provides for a reduction in the cost of these sources down to 250–500 dollars per kilowatt as early as 1985.[42,43]

For large-scale space applications, an equally important problem is the weight of the solar batteries per unit power output. Technological developments involving thin-film batteries based on silicon, gallium arsenide, and cadmium sulfide[19,41–44] are very promising in this context because they will reduce by factors of ten both the weight and cost price of photoconverting devices.

For the SSPS, Glaser plans to use solar batteries with a specific weight of about 0.9 kg/kW, a thickness of 50 μ, and an efficiency of 18% in the case of the thin-film design based on gallium arsenide (Fig. 4).

Solar photoconverters operating in the vicinity of the earth are subject to ageing due to meteor erosion, cosmic radiation, and the effect of protons and electrons in the earth's radiation belts.[19,41]

Existing communication satellites (e.g., Intelsat IV) are designed to function over a ten-year period, so that the proposed plan for the SSPS provides for a thirty-year working life.[40] The reduction in the power level generated by the solar batteries (about 6% over 5 years) can be compensated by the addition of a small number of new panels.

Further improvements in the design of the SSPS, including its weight, can be achieved by increasing the

[3)] In principle, it is possible to devise photoelectric generators with multistage structure so that the light flux successively penetrates *p–n* junctions of semiconductors with different gap widths.

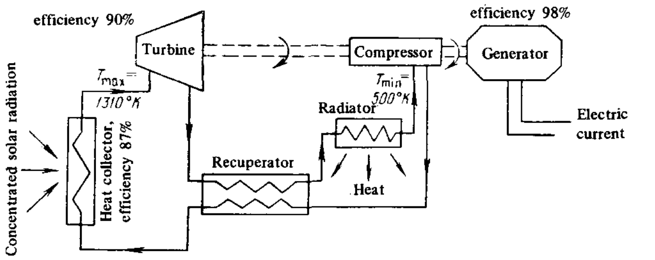

FIG. 5. Schematic diagram of the turbothermal machine based on the closed Braiton cycle.

TABLE II.

	Efficiency
Generator	0.98
Heat engine	0.37
Heat collector	0.87
Concentrator	0.69
Facets	0.84
Resultant value	0.183

concentration of solar radiation intercepted by the photoconverting devices. Concentrators designed for operation in space can take the form of light, geometrically precise, and mechanically robust systems.[45,46] On the other hand, a new type of photoconducting device has been developed under the direction of N. S. Lidorenko in the form of parallel- or series-connected photobattery matrices with working surfaces perpendicular to the plane of the junctions. These are capable of operating under illumination by highly concentrated light beams.[47–50]

The recently developed gallium arsenide photoelectric converters[51–53] produce up to 10 W of electric power per 1 cm^2 of the surface with an efficiency of 21–32%, and can operate at a steady temperature of 300 °C. It is hoped that the efficiency of these cells can be raised to 35–40%.[53]

2. The turbothermal method of solar energy conversion is more complicated than the photoelectric method, but it has been extensively studied, and a very much greater amount of technical experience has now been accumulated because it has been extensively employed in conventional power engineering.

It is well known that the efficiency of heat engines does not exceed the efficiency of the Carnot cycle, i.e., $(T_1 - T_2)/T_1$, where T_1 and T_2 are, respectively, the temperatures of the source and sink in units of the Kelvin scale. The upper temperature limit depends on the strength of the materials used in the heat collector and the turbine, whereas the lower limit is connected with the technological possibilities of the sink. Practical values of the efficiency usually lie in the range 55–70% of the Carnot-cycle efficiency, and amount to not more than 40–45%.

In the turbothermal variant of the SSPS (Fig. 3), the solar energy concentrators form an important element. They intercept the incident radiation over a large area and then concentrate it on the heat collector of the heat engine. The perfect concentrator in the form of a paraboloid of revolution with the necessary surface precision and gigantic size would be too massive since its effective weight per unit area would be 1.5–3 kg/m^2. An acceptable practical solution can be achieved by using the principle of the faceted paraboloid. The individual facets are in the form of aluminum-coated thin film and are simple in shape so that the weight can be reduced down to 0.15–0.25 kg/m.[2,32] The reflecting aluminum coating can be periodically restored by an automatic process involving vacuum deposition of aluminum directly in the course of operation of the system.

Woodcock and Gregory[31–33] have used a set of turbogenerators operating on the closed Brayton cycle (Fig. 5). The working material is a mixture of two inert gases, namely, argon and xenon. A prototype generator of this kind with a power output of 2–15 kW, designed for operation in space in combination with a nuclear reactor, has been built and tested.[55]

Each individual generator in the SSPS system is designed to produce 500 MW and its specific weight is about 2 kg/kW. This is less than the corresponding value for existing solar batteries (≥ 4 kg/kW) but is greater than the figure planned for the solar batteries in the future (0.8–1 kg/kW).

The resultant efficiency is made up of the efficiencies of the individual subsystems[32] (Table II).

The efficiency of conversion of solar into electric power generated in this way thus turns out to be roughly the same as in the case of the photoelectric systems.

The presence of rotating units and components and the relative importance of the weakest link in the chain, namely, the turbine blades, introduce a degree of unreliability in the case of the turbothermal variant.

A much more promising solution may be provided by the use of MHD generators which are capable of direct conversion of thermal into electric power with an efficiency of 55–60%.[3,56] The development of closed-cycle MHD systems designed for operation in space will reveal additional possibilities for the improvement of space power systems.

ENERGY TRANSPORT BY CONCENTRATED BEAMS OF ELECTROMAGNETIC WAVES

The idea of "transmission of energy without the use of conducting lines" is usually associated with the name of the celebrated electrical engineer, Nikola Tesla. It was put forward at the beginning of this century and was more than fifty years in advance of the necessary developments in technology.

The development of radar during World War II stimulated intensive scientific and development work in the field of microwave engineering. All this activity resulted in improved methods of generation, reception, and coherent emission of directed beams in the centimeter band. Tetel'baum[57] appears to have been the first to point out and quantitatively estimate the possi-

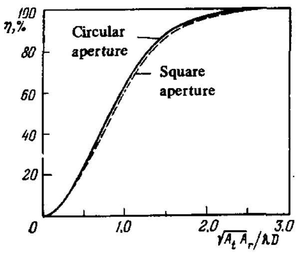

FIG. 6. Efficiency of the energy transmission channel as a function of the parameter τ.

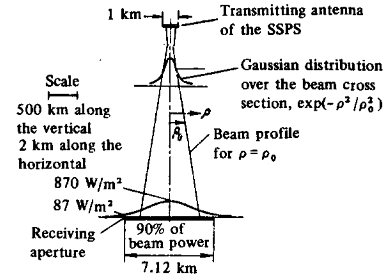

FIG. 8. Profile of the microwave beam carrying energy from the synchronous orbit to the earth's surface.

bility of energy transport by means of this new technology.

Kapitza[2] investigated and emphasized the new possibilities connected with the transmission of power along waveguides in microwave form under terrestrial conditions. The most striking aspects of this method are the high power level, low losses, absence of insulation, masts, and supports, and the possibility of placing the waveguides on the ground so that neither forestry nor agriculture need be disturbed. Although the cost effectiveness of this new method was found to be acceptable under certain particular conditions,[58] it was relatively difficult to place it in competition with the established and extensive electrical engineering industry which, on the whole, was coping well with the current power problems.

In space, where tradiational methods of electric power transmission are either inconvenient or totally unacceptable, the use of a powerful coherent beam of electromagnetic waves may provide the solution to the problem of operational transport of energy both between space stations and between stations and the earth.[2]

The first experiments on the transport of energy by a microwave beam were carried out at the Spencer Laboratory (Raytheon Corporation) in 1963.[59a,60] During the last 7–8 years, the problem has been researched mainly in relation to the SSPS.[61–70]

1. At wavelengths of 10–12 cm, the electromagnetic beam passes through the entire ionosphere and the atmosphere practically without distortion of the phase front and with very small losses.[61,62] The latter amount to 3–7% only in the case of relatively strong precipitation (100–150 mm/h). The losses grow rapidly as the wavelength is reduced and this is undesirable because such losses must be compensated by increasing the size of the antennas.

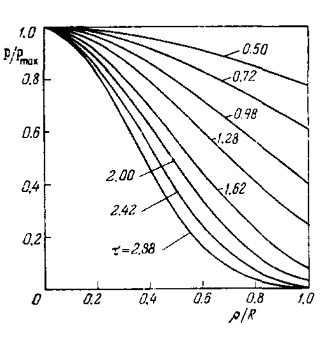

FIG. 7. Radial power density distribution for the optimized beam (R is the radius of the aperture of the receiving or transmitting antenna).

The efficiency of the energy transmission channel is governed by the value of the parameter $\tau=\sqrt{A_r A_t}/(\lambda D)$ (Fig. 6), where A_r, A_t are the aperture areas of the receiving and transmitting antennas, D is the distance between them, and λ is the wavelength.[61] The curves plotted in Fig. 6 correspond to optimized distributions of amplitudes and phases corresponding to the maximum efficiency. The optimized wave beam has a spherical phase front both at the transmitting and receiving ends with radius equal to the distance D. The corresponding power density distributions are shown in Fig. 7.[4)]

The proposed size of transmitting and receiving antennas and the corresponding radiation power levels are shown in Fig. 8 for the case of the 5 GW SSPS. The maximum intensity at the center of the beam is of the order of 870 W/m^2, which is less than the normal insolation on a cloudless day. The density falls to 87 W/m^2 at the edges of the receiving aperture. This is less than the biological threshold adopted in the USA (100 W/m^2) but is much higher than the corresponding USSR standard (0.1 W/m^2).

2. The efficiency of microwave devices, their life, and their reliability assume considerable importance in connection with the attainment of high microwave power levels under the conditions prevailing in space. Brown[65,69] considers that amplitrons (Fig. 9), i.e., a variety of crossed-field microwave amplifiers, are the most suitable class of devices. Existing amplitrons have efficiencies up to 85% or even up to 90% under laboratory conditions. The latter can be taken as the base figure because, when special amplitrons designed for operation in space are developed, one can concentrate one's attention on parameters that are decisive under these conditions (at the expense, for example, of the working bandwidth, and so on). Moreover, the amplitron efficiency increases with increasing ratio of the cyclotron-to-working frequency, and the present level of development of the highly effective samarium-cobalt magnets will ensure a frequency ratio of the order of 10.

The excellent vacuum in space and the secondary-emission platinum-coated cathode assist in overcoming the second difficulty and ensure that such devices have

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4) The field structure corresponds to the lowest mode of oscillation in open resonators with confocal spherical mirrors. The question of optimum energy transmission between two apertures has been investigated by Goubau,[59a] Vaǐnshteǐn,[59b] and several other authors.

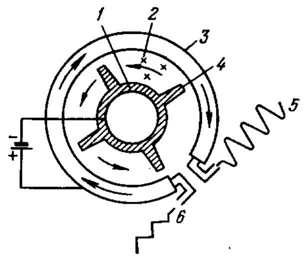

FIG. 9. Illustration of the amplitron principle: rotating space-charge "spokes" induce currents in the microwave circuit and ensure efficient amplification of the input signal: 1—secondary-emission cathode of pure metal; 2—magnetic field parallel to the axis; 3—microwave circuit (slowing down system); 4—rotating "spokes" of the space charge; 5—amplified signal out; 6—microwave signal in. Efficiency = (output microwave power—input microwave power)/(power drawn from the dc source).

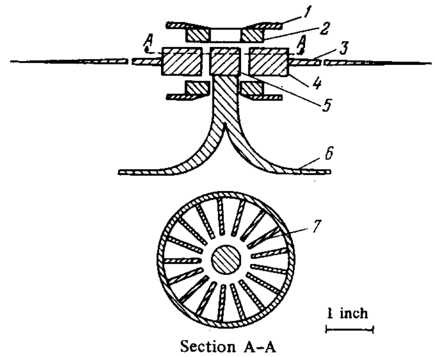

FIG. 11. Heat releasing radiators: 1—iron polepiece; 2—SmCo magnet; 3—cooling fin (anode); 4—anode; 5—cathode; 6—cooling fin (cathode); 7—amplitron segments.

practically unlimited life and can be very compact (Fig. 10). Since the amplitron leads need not be hermetically sealed in space, the amplitron itself can operate at a temperature of up to 300 °C without deterioration in its life or reliability. This means that the cooling of the device becomes a relatively simple problem. This can be achieved by means of the efficient pyrolytic graphite radiating fins which have an emittance of 0.92 when the radiation is emitted into space (~0 °K) at 300 °C (Fig. 11). Absorption of solar radiation reduces the efficiency of the radiating fins but not to any great extent because the density of the scattered radiation is 10.6 kW/m^2, whereas the density of the absorbed radiation does not exceed 1.4 kW/m^2. The final specific weight of amplitrons can be less than 0.13–0.3 kg/kW at a cost of not more than 25 $/kW.

3. For such large transmitting apertures (~1 km) and under the stringent conditions imposed on the phase coherence of the beam, the reradiating active phased array is the most convenient form of transmitter which does not require particular mechanical surface precision and can ensure the necessary field amplitude and phase distribution over the cross section of the aperture.

The antenna consists of 5×5 m sections, each of which is in the form of slotted waveguides with inserted amplitron amplifiers (Fig. 12). Under these conditions, 80% of the power carried by the wave propagating in the waveguide is lost through radiation via the slot and the remaining 20% is used to excite the amplitron in the next stage, and so on.[69]

The transmitting antenna is stabilized relative to the point of reception by means of a pilot signal radiated from the center of the receiving system and containing additional frequency modulation on a subharmonic of the working frequency of the SSPS.[61] This is used in an automatic system for the correction of the phase front of the microwave beam.[69] Existing electronics ensures a root mean square error in the targeting of the microwave beam of about 10 m,[70] which is negligible in comparison with the aperture of the receiving system (7–10 km). In the absence of the pilot signal (for example, in an emergency), the radiation becomes scattered and is lost mainly in space.

4. Whereas the techniques involved in the generation and emission of microwave beams have had direct applications in radar and communication systems, so that considerable experience has been accumulated in this area, the reverse problem, i.e., the conversion of the microwave radiation into dc power, has been studied exceedingly little. The techniques of radiowave reception have so far been developed mainly in relation to the extraction of information from the received signal and this has been done by improving receiving systems, by reducing their intrinsic noise, by protecting them from external interference, and so on.

Most of the high-power electron devices working in the microwave band (magnetrons, klystrons, traveling-wave tubes, and so on) are, at least in principle, ca-

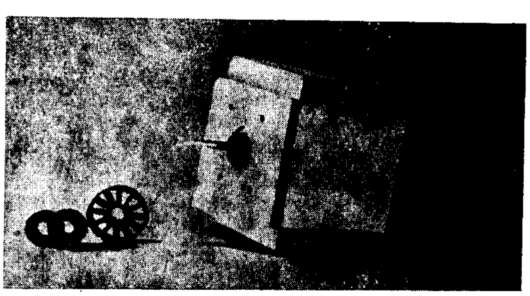

FIG. 10. General view of the amplitron for surface applications (right) and its components used under space conditions (left).

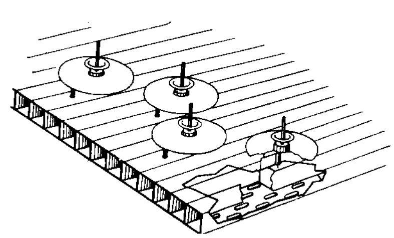

FIG. 12. Antenna array with block built-in amplitron amplifiers.

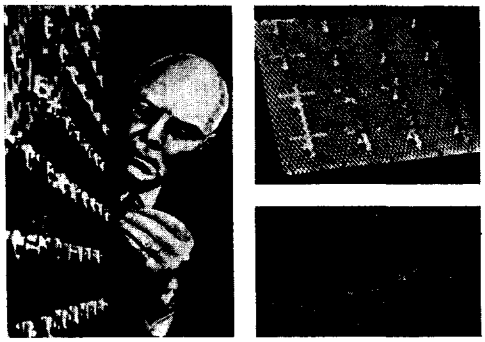

FIG. 13. Laboratory versions of antennas.

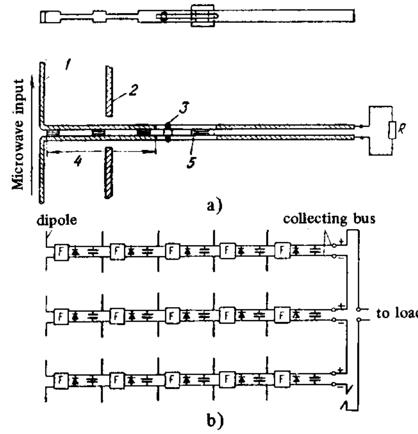

FIG. 14. a) Experimental half-wave dipole with two-section low-frequency filter and half-wave rectifier (Schottky barrier diode): 1—half-wave dipole antenna; 2—reflecting plate; 3—mobile diode with Schottky barrier; 4—low-frequency filter; 5—mobile plunger with spring-loaded rods and blocking capacitor. a) Method of connecting the individual dipoles in the rectenna (F—filter preventing reradiation of harmonics).

pable of operating in the reverse mode in which the electrodynamic system of the device receives an extraneous microwave signal and useful dc or low-frequency ac power is released in the load of the collector circuit.

In view of this, the receiving system can be imagined as the converse of the transmitting system. Instead of amplitrons, one can use, for example, the corresponding magnetrons which convert the microwave power into dc power. Since each section now operates independently, the receiving system as a whole need not be very directional, the conditions imposed on the mechanical precision of the overall surface become less stringent, and so on.

It turns out, however, that there are several difficulties in the efficient utilization of classical microwave devices but these can, to some extent, be overcome by abandoning traditional principles and designs, and by using for rectification the simpler and more natural idea involving the conversion of the energy of the electron beams is reversible magnetic fields.[59a,71,72]

The other way is to use semiconducting elements in the antenna array. An antenna consisting of a set of half-wave dipoles with aligned semiconducting diodes, designed for the simultaneous reception and rectification of microwave radiation, is commonly called a rectenna (from the words rectifier and antenna) (Fig. 13).

Each of the half-wave dipoles has an aligned high-efficiency Schottky barrier diode and a number of filters preventing power losses due to reradiation on the second harmonic of the working frequency.[68] The individual dipoles are combined in a low-frequency circuit, so that the necessary voltage and current levels can be achieved (Fig. 14).

TABLE III. Present and planned values of the microwave channel efficiency.

(Frequency 3000 MHz, $\lambda = 10$ cm)	Achieved efficiency, %	Expected efficiency using existing technology, %	Expected efficiency after additional development, %
Efficiency of microwave power generation	76.7	85	90
Efficiency of energy transport from the output of the generator to the aperture of the receiving system	94	96	96
Reception and rectification (efficiency of rectenna)	80	85	90
Total efficiency (ratio of dc power at the output of the rectenna to the dc power feeding the microwave generator):			
a) calculated	57.7	69	78.0
b) measured	54		
Laboratory experiments at power levels in the range 300–900 W			

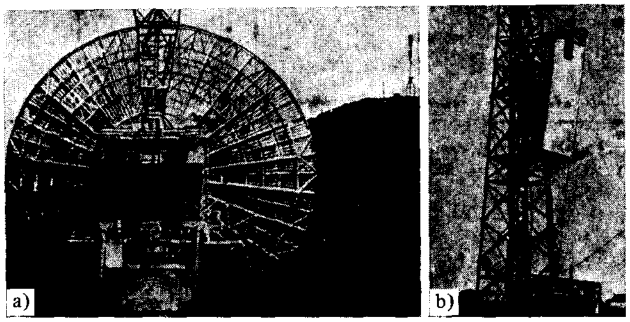

FIG. 15. a) Illuminating antenna with parabolic mirror; b) receiving rectenna.

The results of laboratory tests on rectennas, performed in recent years, have demonstrated a steady improvement[63–69, 73, 74] and have shown that up to 80% of the microwave beam energy can be usefully converted (Table III).

In the middle of 1975, the Jet Propulsion Laboratory, working in collaboration with the Lewis Research Center (NASA), succeeded in transporting 30 kW of microwave power over a distance of 1 mile (1.6 km).[34, 73] A parabolic transmitter designed for long-range communications in space (Fig. 15a) was employed. The receiving array (3.6×7.5 m, Fig. 15b) contained about 5000 dipoles and received only a proportion of the microwave beam power, amounting to 36.8 kW. The dc power was up to 30.4 kW, which corresponded to a rectenna efficiency of 82.5% for an experimental accuracy of 2.5%. The program for further work provides for the use of a transmitter in the form of an active phased array, in order to improve the efficiency, and for the investigation of the power transmission system as a whole.[34]

Completion of the development work on the transport of energy between space and the earth is planned for 1985–1990 and will involve the space shuttle.[35]

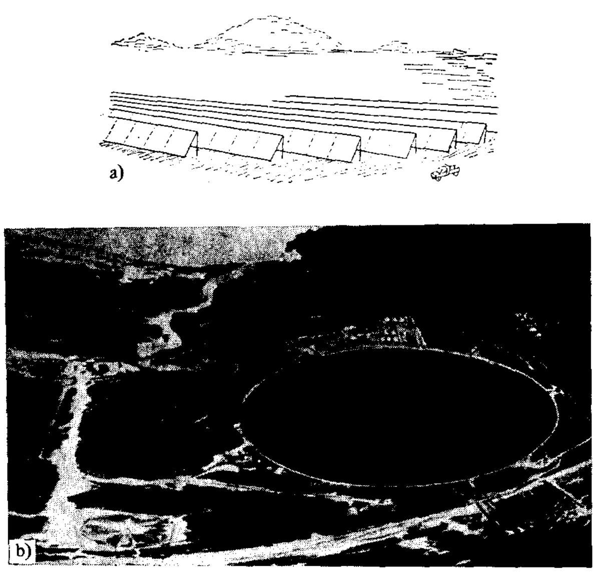

FIG. 16. a) Sketch of the rectenna design for the latitude of 40°; b) aerial view of the complex on Cape Kennedy.

TABLE IV.

Wavelength	10 cm
Rectenna diameter	7.4 km
Area	$43 \cdot 10^6$ m^2
Mean power density	
at 10 million kW	232 W/m^2
at 5 million kW	116 W/m^2
Total number of rectenna elements	$1.23 \cdot 10^{10}$
Density of elements (dipoles) in the rectenna	284 m^{-2}
Maximum power per element	
at 10 million kW	3.0 W
at 5 million kW	1.5 W
Capital outlay per kilowatt of generated dc power	
at 10 million kW	50 $/kW
at 5 million kW	100 $/kW

The rectennas have the following advantages[68]:

1) The receiving surface need not be highly directional and need not be accurately pointed in the direction of the transmitter.

2) The mechanical tolerances on the design of the receiving aperture are much greater.

3) There are no problems with matching the distribution of the incident radiation to the polar diagram of the usual receiving aperture.

4) The nonuniform intensity and phase distribution over the receiving aperture, which results from the combination of the very large receiving aperture and atmospheric nonuniformities over the cross section of the incident beam, present no problems.

5) The amount of microwave power received by local segments of the receiving aperture are well matched to the power possibilities of the solid-state microwave rectifiers.

6) The heat released due to inefficient rectification processes can easily be removed from local segments of the receiving aperture.

The overall appearance of the rectenna system designed for operation at a lattitude of 40° is illustrated in Fig. 16a. The rectenna occupies an elliptical area and consists of steps so that the working surface is always perpendicular to the incident beam. The front surface is a fine metal grid carrying a large number of elementary dipoles. This ensures maximum simplicity at minimum cost.

An aerial view of a complex implementing the annual launching of an SSPS, and the appearance of the first rectenna on Cape Kennedy,[32] are shown in Fig. 16. The electric power generated by the rectenna (10 million kilowatts) is used partly in the manufacture of fuel (liquid hydrogen and liquid oxygen) and is partly transmitted to consumers on US mainland.

Some of the technical characteristics of the rectennas are summarized in Table IV.[69]

The operational characteristics of rectennas, con-

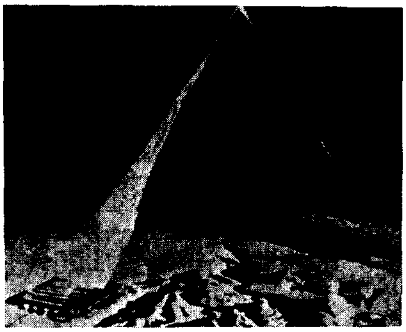

FIG. 17. Energy transport from the power complex to consumers via a passive reflector in a geosynchronous orbit.

nected with the possibility of producing high voltages, which are desirable for the subsequent transport of energy to the consumers, and their efficiency under different meteorologic conditions (increased temperature, humidity, snow cover, icing, and so on), will require additional studies.

The aperture of the receiving system can be assembled on a composite basis. Some of it will operate with semiconductor diodes and will supply power to nearby consumers, and the remainder contains high-voltage electrovacuum converters[71,72] and will provide electric power for remote consumers.

5. It will be advantageous in future to concentrate power-generating complexes (nuclear, solar, and so on) in remote unpopulated areas.[4] This will give rise to the problem of transmitting large amounts of energy over land and water to consumers. A radical solution of this problem has been suggested by Ehricke,[73,75–77] who envisioned reflecting satellites in space. A power-generating complex of this kind will include a microwave transmitting center. The electromagnetic beam will be reflected from a passive mirror in space and will reach the rectenna located in the immediate neighborhood of the consumer (Fig. 17). If the reflecting mirror has a diameter of about 1.25 km for transmitting and receiving apertures of the order of 8 km, a total weight of 250–350 tons can be achieved by using a light metal grid. This will require a minimum of additional devices ensuring the orientation of the mirror and its positioning on the geosynchronous orbit.[5)]

6. A high-power microwave beam incident on the earth's surface will give rise to a number of important problems that must be carefully investigated.

The conventional view is that the medico-biological effect of microwaves is mainly thermal. At the edges of the rectenna, the incident radiation is less than 100 W/m^2, i.e., it is below the permissible level adopted in the USA for prolonged irradiation. The region under the rectenna is completely safe because of the strong absorption and the screening action of the rectenna. It can therefore be used for various purposes, including power-consuming industrial complexes, for example, aluminum-producing industries and systems for the production of liquid hydrogen through the electrolysis of water.

Aeroplanes and helicopters intercepting the incident radiation will reflect practically all of it. Animals and birds will experience thermal effects that are unusual for them, and will probably leave the area.[77]

The powerful microwave beam will unavoidably give rise to electromagnetic interference due to lateral emission associated with fluctuations on the phase front of the incident beam. Preliminary estimates indicate that the frequency band in which this interference will be important is of the order of 100 MHz.[69]

The microwave power absorbed in the atmosphere does not exceed 20–40 W/m^2, which is well below the level of natural processes associated with the absorption of solar radiation and the radiation reemitted by the earth.

Although preliminary results look quite promising, there is a range of environmental problems that will require detailed and comprehensive investigation in the future.

7. The transport of energy in space is free from atmospheric restrictions and is feasible at shorter wavelengths. The minimum wavelength is governed largely by the availability of microwave technology capable of achieving acceptable efficiency in the energy transmission channel as a whole. It would appear that, so far, one can consider only the short-wave part of the centimeter band or, at best, the long-wave part of the millimeter band.

At $\lambda = 1$ cm, a transmitting aperture of 1 km, and a receiving aperture of 20 m (individual space module), the beam energy-transport efficiency of 90% corresponds to a distance of 1000 km.

The suitability of rectennas for high-density short-wave microwave beams will require further investigation. It may well turn out that passive concentrators working in conjunction with high-power electron energy converters will turn out to be useful in this area.

Laser energy transport systems are potentially promising but are not as yet capable of ensuring acceptable efficiency. The main problem here is the mismatch between the spectral region in which high-power lasers with relatively high efficiencies have been developed and the spectral region where the reverse conversion of optical energy into useful power can be achieved.[78]

ECONOMIC ESTIMATES

The particular feature of the SSPS is the presence of a large number of identical elements, components, and details such as the concentrator, film solar batteries, supporting elements, amplitrons, waveguides, dipoles, rectenna diodes, and so on. All this means that, in

[5)]We are forced to ignore almost entirely the various types of space solar reflector[16,22,45,46] and the SSPS variant in which it is positioned in a geostationary orbit but the microwave beam is transported to the earth through an intermediate passive geosynchronous reflector.[22]

TABLE V.

Photoelectric SSPS, $/kW		Turbothermal variant of SSPS,[32] $/kW	
Solar batteries and concentrators	300–700	Turbothermal machines	210
		Generators	70
Transmitting micro-wave system	80–150	Heat collectors	70
		Radiators	160
Surface rectenna	50–120	Concentrators	170
Additional equipment	30–50	Additional equipment	30
Transport and assembly	150–500	Surface rectenna	120
		Transport and assembly	390
Total	610–1520	Total	1300

principle, it will be possible to use such a high degree of automation in fabricating the various components that their cost will be essentially governed by the cost of the raw materials. The amount of raw materials per unit generated power turns out to be unusually low (2–2.5 kg/kW)[6)] as compared with existing terrestrial power systems.

There have been many predictions of the capital investment necessary per unit power generated by the SSPS,[21,28,31,32,37,40,54,66,70,73,77,79,85,91] but it must be noted that these estimates cover a relatively broad range from 500 to 4000–4500 $/kW. This is partly connected with the different stages of the technological-economic analysis of the idea itself as well as the fact that there is genuine difficulty in producing an economic forecast covering twenty years ahead. Table V summarizes what, in our view, are average predictions available at present.

A degree of caution must be exercised when these data are compared with the corresponding parameter values for power-generating systems operating on the earth's surface because the engineering data in the table must be translated into commercial terms which allow for the cost of research and development work. On the other hand, SSPS is capable of transporting energy directly to the regions in which the consumers are localized, whereas conventional power-generating systems involve additional costs in constructing transmission lines, mining, enrichment of materials, transport of fuel, and so on. Finally, there is an important social aspect of estimates of the cost of electric power generation, which takes into account factors such as the effect on the environment, safety, demographic effects, and so on.

The second-generation space-transport systems capable of repeated use will be particularly suitable for delivering half-finished objects, units, and components to the SSPS in orbit. The proposed space shuttle[80] will ensure that the specific cost of delivering useful payload to a low orbit will be of the order of 360 $/kg, but this figure may well be reduced in the future by an order of magnitude or more.[24b,32,81,82,83] Particular problems associated with the transport and assembly of the SSPS in space have been reviewed in the literature.[32,79,84]

Energy transport via a reflecting satellite on a geosynchronous orbit (Fig. 17) will involve minimum losses and can be paid for by increasing the cost of electric power by roughly 3 cent/kWh at power transmission levels of 7–10 GW.[75,77] The overall cost of a power complex of this kind, including the generation of electric power (10 GW), its transformation into microwaves, transport via the reflecting satellite, and converting systems on the earth, is estimated at 5.03 billion dollars.[73]

POSSIBILITIES FOR THE FUTURE

"As yet, this is a thankless, risky and exceedingly difficult task. ... and yet the prospects are truly splendid." K. É. Tsiolkovskiĭ

It is probably still difficult to imagine with adequate clarity the power engineering of the future. Nevertheless, there is no doubt that traditional sources of energy, which for centuries have been based on fossil fuels, will have to be replaced by the new power sources which will include solar, nuclear, geothermal, and so on, contributions. Its main features will be higher power levels, mobility, and minimal environmental effects.

Further developments in mankind's exploitation of the space surrounding the earth will unavoidably lead to an increasing emphasis on space power engineering.

So far, the developments in this area have been confined to low-power independent sources supplying individual space vehicles of various kinds. However, the situation may change radically during the next decade.

Extra-terrestrial industrial manufacturing which initially will have to be confined to the development of new technologies under the conditions of weightlessness (or variable "gravitation"), high vacuum, and low temperatures will eventually develop along the lines of producing high-quality products which, as a rule, require high-energy consumption. It is equally clear that there can only be an expansion in space power engineering in the future (through the advent of lunar industries, and so on).

The second important aspect is the utilization of power generated in space by industrial and domestic consumers

[6)]The amount of noble metals, such as platinum, necessary for the secondary-emission cathodes in the amplitrons is not more than 2% of the annual consumption in the USA.

on earth.

The "purity" of the received energy, including the minimal thermal losses in the atmosphere, the fact that remote locations on the earth's surface can be supplied with this energy, and the possibility of operational switching of consumers are among the main attractive advantages of this method.

The common interest in protecting the environment of the earth as a whole and the prospect of large-scale (intergovernmental or intercontinental) cooperation in the distribution of power may well serve as a good base for a joint international effort in research, development, and construction work.

Results obtained from the preliminary development of the two main SSPS projects form the first important step in estimating technological and economic parameters and the time scale involved in bringing the project to practical fruition.

There is no doubt that many additional possibilities and new radical approaches will be discovered. It may well turn out, for example, that it will be cheaper by factors of two or three to fabricate and assemble to SSPS on inhabited industrial complexes in space, using materials supplied from the surface of the moon[87–89] because much less energy is necessary to overcome the weak gravitational field of the moon, which has no atmosphere.

Nuclear and, later, thermonuclear space power stations are also promising alongside the SSPS. The nuclear stations will be able to produce as much plutonium as they will consume, so that there will be no need for the dangerous transport from the earth's surface. Space is particularly favorable for thermonuclear reactors because of the high vacuum in an unlimited volume and the ease with which superconducting magnets can be produced. The annual delivery of fuel will not exceed 5 tons/GW of generated power which presents no particular transport difficulties even for a hundred or more such stations.[32] In both cases, space insulation will reduce or totally eliminate problems encountered in terrestrial utilization of nuclear and thermonuclear power stations such as thermal contamination of the atmosphere, the danger of explosion, the removal and transport of radioactive waste, and so on.

The great promise presented to us by space power engineering will become a reality provided sufficiently flexible and efficient energy transport systems capable of operating under the new specific conditions become available.

The successful solution of this problem will be a prerequisite for the centralization of power generating systems designed for space applications and for the attainable level of "pure" energy from space which mankind can expect for the development of civilization in the future.

The solution of this fundamental problem will have to be achieved on a composite basis, including engineering-physics, technological-economic, medicobiological, and social aspects.

[1] A. P. Romanov, Raketam pokoryaetsya prostranstvo (Rockets Conquer Space), Politizdat, M., 1976.
[2] P. L. Kapitza, Élektronika bol'shikh moshchosteĭ (High-Power Electronics), Izd. AN SSSR, M., 1962.
[3] P. L. Kapitza, Kommunist No. 1, 43 (1975).
[4] P. L. Kapitza, Usp. Fiz. Nauk 118, 307 (1976) [Sov. Phys. Usp. 19, 169 (1976)].
[5] N. N. Semenov, Nauka i Zhizn' No. 10, 16; No. 11, 25 (1972).
[6] E. Stuhlinger, J. Microwave Power 5, 207 (1970).
[7] A. J. Rozenblatt, Elektronika No. 7, 26 (1974).
[8] F. Daniels, Direct Use of the Sun's Energy, Ballantine Books, 1975.
[9] B. J. Brinkworth, Solar Energy for Man, Halsted Press, New York, 1973 (Russ. transl., Mir, Moscow, 1976).
[10] A. V. Sheklein, Tr. Energ. Inst. im. G. M. Krzhizhanovskogo No. 24, 6 (1974).
[11] A. V. Sheklein, Geliotekhnika No. 4, 81 (1976).
[12] I. I. Sobel'man, Usp. Fiz. Nauk 120, 85 (1976) [Sov. Phys. Usp. 19, 758 (1976)].
[13] Kak dobyt'solnechnoe toplivo [How to Obtain Solar Fuel (Stern Magazine)] transl. in: Za rubezhom No. 15, 20 (1975).
[14] Ukroshchenie solnechnogo lucha (Taming the Solar Beam), *ibid*. No. 25, 20 (1976).
[15] W. R. Cherry, Astronaut and Aeronaut, No. 8, 30 (1972).
[16] A. Vladimov, Nauka i Zhizn', No. 7, 78 (1976).
[17] Special Report on Solar Energy, Astronaut and Aeronaut No. 11 (1975).
[18] P. A. Nedotko and E. A. Lebedeva, Energokhozyaistvo za Rubezhom No. 1, 38 (1975).
[19] N. S. Lidorenko, Geliotekhnika No. 6, 3 (1969).
[20] N. S. Lidorenko *et al.*, Kommunist No. 2, 62 (1976).
[21] G. R. Woodcock, Raumfahrtforschung No. 3, 135 (1973).
[22] K. A. Ehricke, Schweissen und Schneiden 27, 479 (1975).
[23] R. Salkeld, Astronaut and Aeronaut No. 9, 30 (1975).
[24] a) P. E. Glaser, in: Twenty-Sixth Intern. Congress of IAF, Lisbon, 1975; b) J. Grey, Astronaut and Aeronaut No. 10, 29 (1976).
[25] G. F. von Tiesenhausen, in: Twenty-Seventh Intern. Congress of IAF, Los Angeles, October, 1976.
[26] V. P. Glushko, Raketnye dvigateli GDL-OKB (Rocket Engines GDL-OKB), APN, Moscow, 1975.
[27] P. E. Glaser, Science 162 (No. 3856), 857 (1968); see also Geliotekhnika No. 1, 37 (1971).
[28] Special Issue on Satellite Solar Power Station and Microwave Transmission to Earth, J. Microwave Power 5 (4) (1970).
[29] P. E. Glaser, Patent of USAm No. 3.781.647; 26.07.1971.
[30] Congress Asks NASA Work on Solar Energy, Electron, Design 21, No. 16, 48 (1973).
[31] J. T. Patha and G. R. Woodcock, J. Spacecraft and Rockets 11, 409 (1974).
[32] G. R. Woodcock and D. L. Gregory, AIAA Paper No. 640 (1975).
[33] Boeing Engineers Envision 10 000 Megawatt Power Station in Space, Aerospace Daily, July 15, 78 (1975).
[34] R. T. Davis, Microwaves No. 10, 9 (1975).
[35] C. Covault, Aviation Week and Space Technology, Feb. 9, 54 (1976).
[36] Senate Unit Hits Energy Fund Oversight, *ibid.*, April 26, 20 (1976).
[37] Satellite Power Station: Unplugged, Astronaut and Aeronaut No. 3, 10 (1976).
[38] N. Treinies, Umschau der Wissenschaft und Technik 75, 661 (1975).
[39] K. M. Hubbert, Scientific American 224(3), 60 (1971).
[40] P. E. Glaser, AIAA Paper No. 637 (1975).
[41] A. M. Vasil'ev and A. P. Landsman, Poluprovodnikovye fotopreobrazovateli (Semiconductor Photoconverters), Sovetskoe Radio, M., 1971.
[42] "Solar cell research program in Congress," Elektronika No. 17, 16 (1975).

[43]"Solar batteries: projects and conflicts," *ibid.* No. 20, 15.
[44]M. B. Kagan, N. S. Koroleva, and T. A. Nuller, Geliotekhnika No. 2, 28 (1970).
[45]A. V. Luk'yanov, Kosm. Issled. **7**, 952 (1969).
[46]A. V. Luk'yanov, Plenochnye otrazhateli v Kosmose (Film Reflectors in Space), Moscow State University, 1977.
[47]A. P. Landsman and D. S. Strebkov, Geliotekhnika No. 2, 15 (1970).
[48]A. P. Landsman and D. S. Strebkov, Radiotekh. Elektron. **15**, 2625 (1970).
[49]A. P. Landsman and D. S. Strebkov, Geliotekhnika No. 3, 3 (1970).
[50]A. M. Vasil'ev, V. M. Evdokimov, A. P. Landsman, and A. F. Milovanov, Geliotekhnika No. 2, 18 (1975).
[51]"High-efficiency solar batteries," Elektronika No. 11, 4 (1975).
[52]Varian Develops New Type Solar Cell, Interavia Air Lett. No. 8288, 6 (July 4, 1975).
[53]"GaAs cell produced 10 W from sunlight," Electronic Design, July 19, 22 (1975).
[54]P. E. Glaser, Astronaut and Aeronaut No. 8, 60 (1973).
[55]T. J. Miller, in: Intersociety Energy Conversion Engineering Conference Proceedings, 1971, p. 403.
[56]Magnito-gidrodinamicheskiĭ metod polucheniya élektroenergiĭ (Magnetohydrodynamic Method of Producing Electric Power), ed. by V. A. Kirillin and A. E. Sheĭndlin, Énergiya, M., 1972.
[57]S. I. Tetel'baum, Élektrichestvo No. 5, 43 (1945).
[58]D. A. Dunn and W. Loewenstern, in: Microwave Power Engineering, ed. by E. C. Okress, Vol. 1 Academic Press, 1968 (Russ. transl., Mir, M., 1971).
[59]a) Collection cited in[58]; b) L. A. Vaĭnshteĭn, Otkrytye rezonatory i otkrytye volnovody (Open Resonators and Open Waveguides), Sovetskoe Radio, M., 1966.
[60]W. C. Brown, IEEE Intern. Conv. Rec. **12** (pt. 2), 8 (1964).
[61]G. Goubau, J. Microwave Power **5**, 223 (1970).
[62]V. J. Falcone, J. Microwave Power **5**, 269 (1970).
[63]W. C. Brown, J. Microwave Power **5**, 279 (1970).
[64]W. J. Robinson, J. Microwave Power **5**, 233 (1970).
[65]W. C. Brown, J. Microwave Power **7**, 223 (1972).
[66]W. C. Brown, IEEE Spectrum No. 3, 38 (1973).
[67]W. C. Brown, IEEE Trans. Microwave Theory Tech. MTT-21, 753 (1973).
[68]W. C. Brown, Proc. IEEE **62**, 11 (1974).
[69]W. C. Brown, AIAA Paper No. 642 (1975).
[70]E. Andrew and R. Schuh, cited in[24].
[71]D. C. Watson, R. W. Grow, and C. C. Johnson, J. Microwave Power **5**, 72 (1970).
[72]V. A. Bardenkov, V. A. Vanke, I. S. Gorshkov, and V. M. Lopukhin, Radiotekh. Elektron. **21**, 821 (1976).
[73]W. von Braun, Popular Science **13(9)**, 65 (1975).
[74]Energy via Radio, *ibid.* (7), 8.
[75]K. A. Ehricke, Rockwell Intern. Report E-74-3-1, March, 1974.
[76]C. Covault, Aviation Week and Space Technol., Jan. 8, 47 (1973).
[77]J. R. Williams, Astronaut and Aeronaut No. 11, 46 (1975).
[78]K. W. Billman, Astronaut and Aeronaut No. 7/8, 56 (1975).
[79]R. Kline and C. A. Nathan, AIAA Paper No. 641 (1975).
[80]V. Shatalov, Nauka i Zhizn' No. 11, 25 (1974).
[81]R. Salkeld, Astronaut and Aeronaut No. 3, 52 (1974).
[82]B. Z. Henry and J. P. Decker, Astronaut and Aeronaut No. 9, 18 (1976).
[83]"Outlook" panel sees cost gains in shuttle upgrade heavy launcher," Aerospace Daily **77**(40), 320 (1976).
[84]T. A. Hagler, Astronaut and Aeronaut No. 5, 56 (1976).
[85]R. P. Hudock, Astronaut and Aeronaut No. **9**, **11** (1976).
[86]K. É. Tsiolkovskiĭ, Izbrannye trudy (Collected Papers) ed. by A. A. Blagonravov, Izd. AN SSSR, M., 1962, p. 368.
[87]G. K. O'Neill, Science **190** (No. 4218), 943 (1975).
[88]T. A. Heppenheimer and M. Hopkins, Astronaut and Aeronaut No. 3, 58 (1976).
[89]G. K. O'Neill, Astronaut and Aeronaut No. 10, 20.
[90]B. Gohrbandt and E. F. Schmidt, in: Twenty-Seventh Intern. Congress of IAF, Los Angeles, October, 1976.
[91]P. E. Glaser, Spaceflight **18**(6), 198 (1976).

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