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# Solar power systems (SPS) — investigations at the Institute of Space and Astronautical Science of Japan

M Nagatomo, S Sasaki, Y Naruo, V A Vanke

## Contents



## 1. Introduction

It is evident that the problems of clean power generation are some of the top-priority global problems arising for mankind. It is also evident that a modern solution to these problems should be looked for in various directions and should be based on physical ideas and principles.

The generation of solar power has attracted expert attention for a long time because of its ecological cleanness and because of the inexhaustible (renewable) nature of the Sun's energy. However, the large scale use of solar energy on the ground is difficult because of its fluctuating nature (e.g. daily variations of intensity, influence of weather conditions) and its low mean density at the Earth's surface.

In this review we would like to give a conceptual and brief characterisation of work in the field of space solar power generation from the time when these ideas were discussed in Ref. [1] and also to emphasise the original contribution of the Institute of Space and Astronautical Science of Japan to the development of this fundamental topic. First, we would like to review the main concepts of the Space Solar Power Station (SPS†) (Fig. 1) proposed by Peter Glaser in 1968 [2].

**M Nagatomo, S Sasaki, Y Naruo** SPS Working Group, Space Power System Section, Research Division for Space Applications, The Institute of Space and Astronautical Science, 3–1–1 Yoshinodai, Sagamihara 229, Japan
Tel. (81) 427 51 39 80; Fax (81) 427 59 42 39
E-mail: e34939@tansei.cc.u-tokyo.ac.jp
E-mail: sasaki@isasmac1.newslan.isas.ac.jp
**A Vanke** M V Lomonosov State University, Physics Department, Leninskiiy Gory, 119899, Moscow
Tel. (095) 939 40 88; Fax (095) 292 65 11
E-mail: vanke@mesps.phys.msu.su

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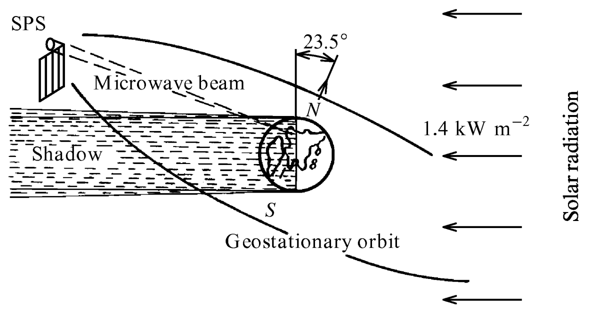



**Figure 1.** The SPS in geostationary orbit.

Large solar-cell panels of the SPS are placed in geostationary orbit (GEO), i.e. in the circular orbit in the equatorial plane at a distance of 36000 km from the Earth's surface. The angular velocity of a satellite is equal to the rotational velocity of the Earth. Thus, the satellite will be motionless relative to the Earth's surface. The flux of solar radiation is sufficiently strong at the geostationary orbit (1.4 kW m$^{-2}$), and the satellite is almost continuously illuminated by solar radiation because of the natural inclination of the equatorial plane (Fig. 2). Exceptions occur for the short time periods near the days of the Spring and Autumn equinoxes, when the satellite enters the Earth's shadow. The sum of these dark periods is not more than 1% of the full duration of a year and can be precisely predicted. The energy generated by the solar-cell panels is transformed into microwave energy and then transmitted to the Earth's surface at a frequency of 2.45 GHz by means of a well-focused electromagnetic beam which has very low atmospheric loss (less than 1%) even in the case of rather intense precipitation (more than 150 mm h$^{-1}$). Microwave energy is transformed by a special receiving system on the Earth's surface into dc or low-frequency ac power which is then distributed to consumers.

†The abbreviation SPS (Solar Power Satellite or Solar Power System) is often used.

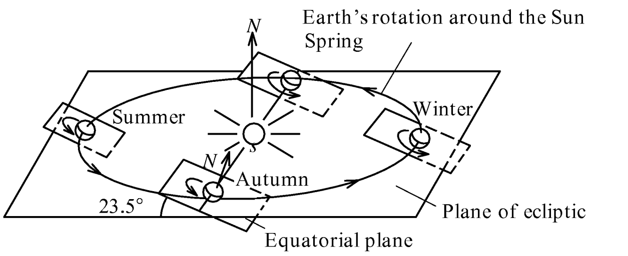



**Figure 2.** The location of the Earth's equatorial plane (SPS orbital plane) relative to the Sun and ecliptic plane during the different seasons of the year.

## 2. The US DOE/NASA research programme†

A special research programme aimed at the definition of SPS prospects, was realised in the USA between 1977 and 1980 [3 – 13]. Within the framework of this programme, the possibility of the construction of 60 SPSs, each with 5 GW of power, was analysed. The rate of implementation was to be two SPS per year from the year 2000. The programme was managed by the US Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA).

The previous stages of the investigation [1, 2] gave an opportunity to determine some basic SPS concepts (i.e. the Reference System‡, (Fig. 3). It should be noted that it was not claimed that this Reference System was a unique concept or had a strict optimum of technical solutions. However, it had to allow a full and all-round system analysis owing to the relative simplicity of its construction.

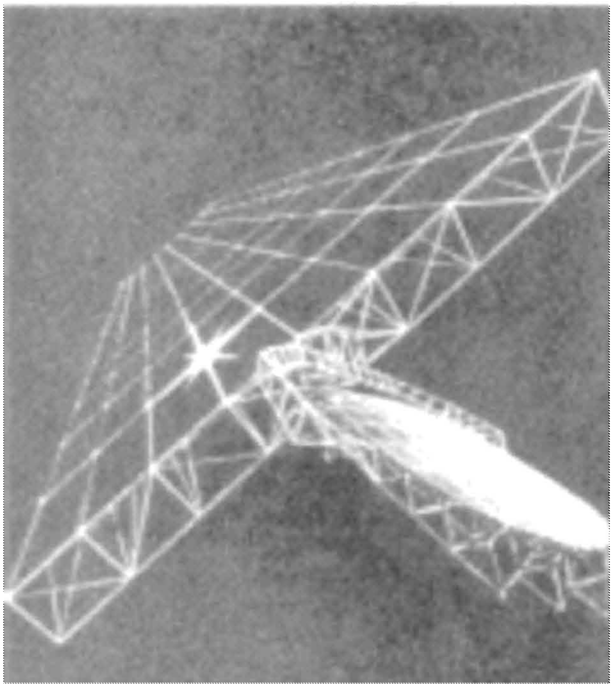


**Figure 3.** Basic concept for the SPS of the DOE/NASA research programme.

Two Reference Systems were analysed: one with Si solar-cell panels and one with GaAlAs solar-cell panels. The latter used simple flat concentrators with double concentration of the solar flux. The efficiency of the solar cells was chosen to be about 12%, and the efficiency of microwave energy transmission was about 56%.

Solar-cell panels are always perpendicular to the flux of solar radiation. The microwave antenna is a reradiating adaptive phase array fitted with a rotary joint in a Cardanic suspension, so that it is continuously directed to the ground-based receiving station. Precise orientation of the beam is realised by means of a pilot-signal which is radiated from the centre of the ground-based receiving system and is analysed by a set of special transducers distributed over the surface of the transmitting antenna. Klystrons are used as microwave generators in the transmitting antenna array. The ground-based receiving system (rectenna§) utilises dipoles placed over the reflecting plane and loaded independently onto semiconducting Schottky barrier diodes [1, 4].

At first, SPS transportation to low earth orbit (LEO) is achieved by means of special rocket transport with a single delivery capability of about 400 – 500 t. The materials and supplies stored in LEO are then tugged from LEO to GEO by use of electric propulsion ion engines. At GEO, special automatic devices manufacture the main SPS units and carry out the SPS assembly with a minimum of manual assistance provided by astronauts.

Seven US Federal Government Agencies, four US DOE laboratories, fifteen Universities, thirty-five private companies, and the US National Academy of Science were involved in this project [10].

The basic parameters for the DOE/NASA SPS research programme, are presented in Table 1.

Despite the impressive size of many figures given in Table 1, most of the space organisations and firms involved in the research programme have confirmed the reality of the creation of this principally new energy system within

**Table 1.** Characteristics of the SPS in the DOE/NASA programme.

| | |
|---|---|
| Total number of SPSs | 60 |
| Power of a single SPS/GW | 5 |
| Size of solar-cell panel/km$^2$ | 5 × 10 |
| Diameter of transmitting antenna/km | 1 |
| Mass of single SPS/kt | 30 – 50 |
| Size of ground-based receiving system at 35° degrees latitude/km | 10 × 13 |
| Density of power radiation at the centre of transmitting antenna/kW m$^{-2}$ | 30 |
| Density of microwave power at the centre of the ground-based receiving system/W m$^{-2}$ | 230 |
| Capital investment for 20 year development period, including the first SPS launch/$ billion | 110 – 120[1] |
| Cost of each subsequent SPS/$ billion | 11 – 12 |
| SPS operation time/years | 30 |
| Period of SPS economic return/years | 6 |

[1]Or $25 billion if the cost of the development and construction of special launch systems is excluded.

†This section is written with the aim of keeping in succession with a previous publication [1] devoted to SPS problems.
‡The term 'Reference System of DOE/NASA SPS Concept Development and Evaluation Program' was used originally.

§The word 'rectenna' is formed from the words 'rectify' and 'antenna' [1, 6, 7, 30].

20 years from the beginning of the work, provided there is sufficient financial support.

Also, it is important that the system was examined completely and new fundamental knowledge would not be required for its realisation. In its turn, new science and technological achievements would only improve the technical and economic properties of the SPS.

The Office of Technology Assessment (OTA) of the US Congress [11] and a specially formed National Research Council† of the US National Academy of Science were engaged in the evaluation of the results of this project. The first report (OTA) suggested several levels of financial support for the continuation of the project. The second one underlined the SPS perspectives as an energy system of the future, but considered the economic estimates of the DOE and NASA as about 2–2.5 times undervalued, and thus did not recommend financial support of these investigations for the near decades. It was suggested that most of the technical and technological SPS problems could be solved as a result of the fulfilment of other space programmes [12].

It is important to emphasise that an undervaluing of economic estimates by a factor of about 2.5 lies most probably within the limits of error, especially when the difficulties involved in providing an economic forecast for a period of 20 years in such an intensely developing field as space science and technology is taken into account. Besides, in their estimations, the experts ignored the results of the investigations of Rockwell Int., one of the major aerospace companies, which suggested another concept of SPS construction over the same time period that would allow a 50% reduction in the capital investments required for SPS manufacture [13].

Although this document [12] was exposed to sharp and many-sided criticisms, it is important because, although the report was outwardly positive, it led to the reduction and then to the full cessation of governmental financial support of SPS research in the USA. In its turn, it negatively influenced the level of support for research work in other countries.

We will return to the discussion of the problems of SPS economic forecasts but now we should underline only the rising interest in this clean energy system that has arisen in more than 20 countries during the last 5–8 years [14, 15]. The International Astronautical Federation Power Committee, founded in 1983, carries out international coordination in the field of SPS.

## 3. Early stages of Japanese research in the field of SPS

The appearance of the SPS concept in 1968 coincided with the establishment of basic administrative structures in the field of space science and technology in Japan. The Space Activities Commission (SAC), under the direction of the Prime Minister, was established in 1968, and the National Space Development Agency (NASDA), a nongovernmental organisation under the control of the Science and Technology Agency (STA), was formed in 1969. NASDA has its own staff and space centres near Tanegashima and Tsukuba.

†The staff of the Council are listed in Ref. [10].

In 1968, the University of Tokyo was preparing for the launch of Japan's first satellite, which was successfully realised two years later. On account of this activity, the scientists were too busy to notice the appearance of the SPS concept. A little later, a proposal for the development of SPS technology was made by MITI (Ministry of International Trade and Industry of Japan), which is also responsible for national policy in the field of energy generation.

In 1981, the Institute of Space and Astronautical Science of Japan (ISAS) left the University of Tokyo and gained an independent position within the framework of the Ministry of Education, Science and Culture of Japan (MOE), which is responsible for fundamental research and is carrying it out on the basis of the Universities and its own scientific research institutes. Simultaneously with the reorganisation of the ISAS‡, the Space Power Systems Section was founded and the Annual ISAS Space Energy Symposium began its work [16, 17].

The development of the DOE/NASA SPS Reference System attracted scientific and public interest in Japan. The 'Energy from Space' concept was essentially more attractive in various ways for Japan than the flight of Americans to the Moon was.

At the Second ISAS Space Energy Symposium (1982), the viewpoint of Japan with respect to the results of the DOE/NASA work in the field of SPS was presented, emphasising the following in particular:

—An SPS will be a solution for the problem of continuously increasing energy consumption and limited natural resources in Japan. However, various problems need to be solved before an SPS could be installed into Japan's energy system.

—An SPS is considered to be an expensive power system because of the high cost of space transportation. But this opinion will not correspond to reality because technology will be able to overcome this problem. However, the cost of the ground area required for the receiving antenna will be the critical factor that will determine the cost of SPS energy.

Because of this latter reason, investigations started with the problems of the construction of ground-based receiving stations oriented towards the DOE/NASA SPS Reference System. It was proposed to locate the rectenna systems beyond the mainland—within 200 miles of Japan's littoral economical zone. It was necessary to design a construction that was resistant to earthquakes, storms, and wind loads. A successful solution was a floating construction [18] which could be manufactured and assembled on special ships.

In parallel, S Adachi's group studied the formation and optimisation of the SPS electromagnetic beam for both energy transmission efficiency and suppression of side-lobe radiation [19]. Another group, headed by K Itoh, studied the circular microstrip antenna§ application to receiving systems in order to suppress the higher harmonic reradiation that could seriously degrade the operation of communication and navigation systems [20].

‡The budget of the ISAS was about US $200 million in 1992, the budget of NASDA was about US $1 billion.

§Circular microstrip antennas have higher resonance harmonics which are not integer multiples of the dominant resonance frequency. This fact is used for the suppression of higher harmonic radiation arising due to the nonlinearity of Schottky barrier diodes during conversion of microwave power (rectenna) (Fig. 12b and Fig. 13).

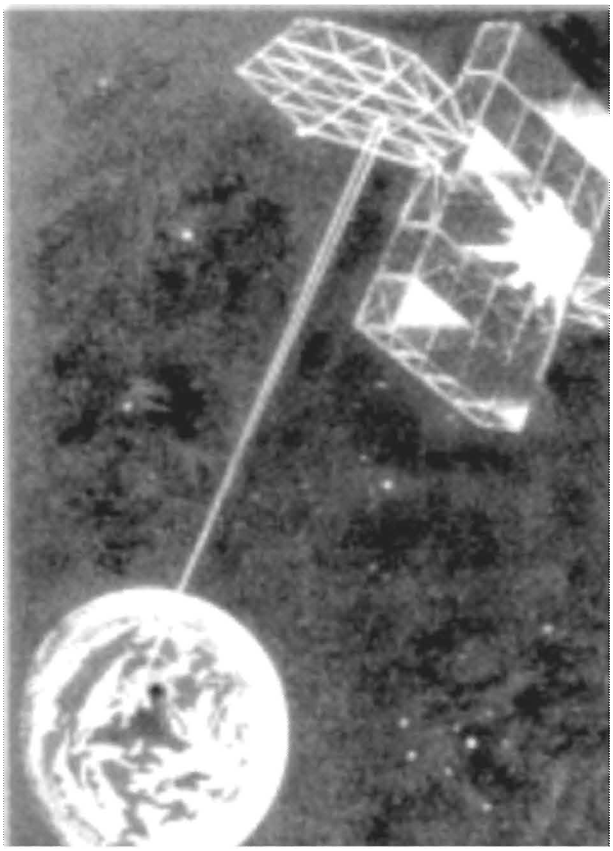


**Figure 4.** Concept of SPS prototype utilising solar-cell panels with a total power level of 10 MW (ISAS ).

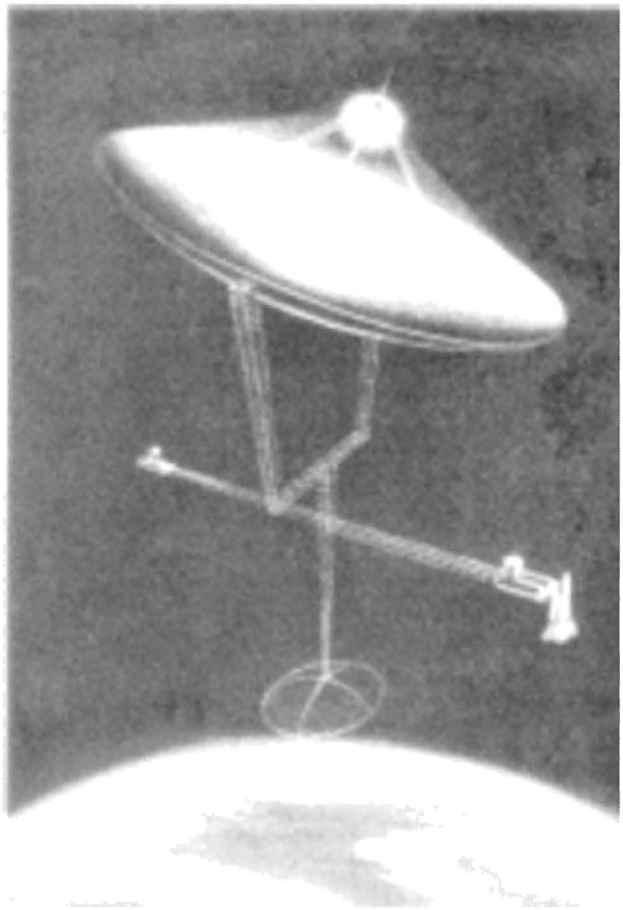


**Figure 5.** Concept of an SPS prototype with a power level of 70 MW, based on the use of a solar-energy concentrator, transformation of solar energy into heat energy, and fitted with further energy storage (ISAS).

It was decided that the proper variant of SPS prototype was to have a low power level and be of light construction in order to allow its realisation in the near future, for example in the year 2000 (SPS 2000). In addition, this prototype was not to be realised as a space device based, as usual, on expensive technologies but probably as a space seg-ment of a ground-based energy system. The objective of the designers was to produce an SPS prototype that was simple and could deliver electric energy at a convenient cost.

Only two SPS prototypes have had technical presentation in Japan. The first one, an SPS with a power level of 10 MW (Fig. 4), was studied by the Space Technology Committee of Japan Machinery Federation as a basic alternative design for demonstration of the prospects of the space programme [21, 22]. The second one, an SPS with power storage and periodic energy transmission to the Earth (Fig. 5), was studied by ISAS and the Toshiba company. The first prototype used photovoltaic cells for energy transformation and it was,in fact, a small copy of the DOE/NASA Reference System. The second one contained a solar energy concentrator, heat energy storage, a thermodynamic method of transformation, and was designed for a 70 MW power level [23].

## 4. The SPS 2000 project of ISAS

The ISAS SPS Working Group is divided into thirteen investigation subunits specialised in different fields. Nine of these subunits investigate the various kinds of SPS subsystems. The other four subunits study the influence of the SPS on the environment. The principal topics of these subunits could be formulated, in brief, as:

*Study of subsystems and technologies.*

— Microwave power radiation
— Reception and back-conversion of microwave beam power
— Large-scale construction in space
— Powerful laser technology
— Solar-cell panels
— Powerful thermodynamic generators
— Engines
— Space robots

*Study of influence on the environment.*

— Spacecraft environment
— Space electromagnetic environment
— Communication systems
— Biology and ecology

An analysis of the SPS models, presented in Fig. 4 and Fig. 5, has shown that they are too large and will need special transportation systems and the use of an extremely high level of large-scale space construction technology.

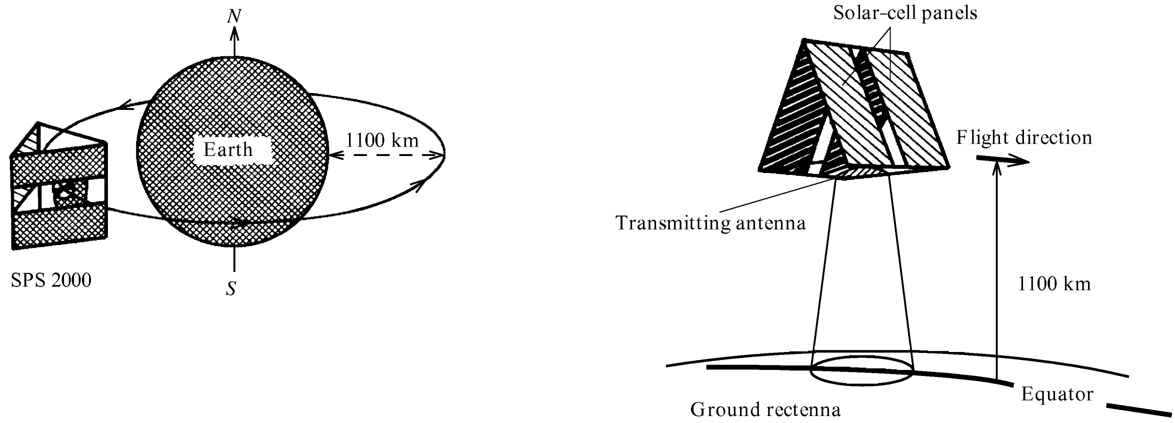
To simplify the system, it was decided that the SPS prototype would not contain energy storage and that the gravitational principle should be used for stabilisation. Besides, it was shown that the rotating joint located between solar-cell panels and the microwave antenna, turned out to be a rather complicated unit, and it was not necessary, in principle, to use it in the light SPS model if its operation is based on the use of solar-cell panels.

Because even a small SPS would require multiple flights of launch vehicles, it is desirable that every unit which is being formed after every launch could obtain the main functions of the SPS. This would provide an opportunity to study the system immediately. The accumulation of such units during subsequent launches would allow system assembly to the necessary level. This problem is very important, although very general, and its solution is far from simple.

The concept of the SPS prototype has gradually developed and now is known as SPS 2000. The project is now being developed further (Figs 6 and 7) but preliminary results are already available, [24, 25]. The structure of SPS 2000 is in the form of a triangular prism. Two plane surfaces contain solar-cell panels. The microwave transmitting antenna is fixed to the lower plane of the main body, which is oriented towards the Earth's surface [25 – 28].

SPS 2000 will have a circular orbit in the Earth's equatorial plane at an altitude of 1100 km from the surface and its axis will be oriented perpendicular to its motion. The satellite passes over the same points on the Earth's surface every rotation because its orbit is situated in the equatorial

a

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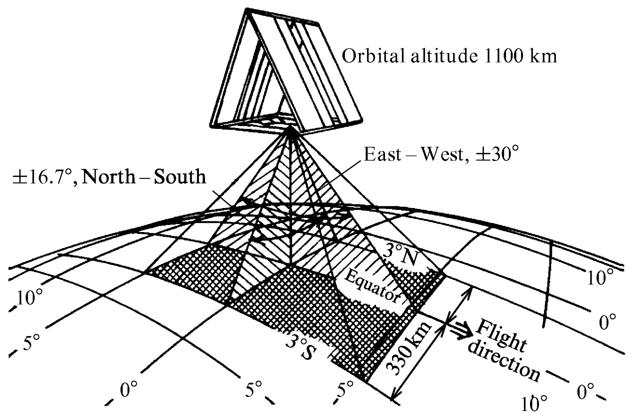



**Figure 6.** (a) General scheme of the SPS 2000. (b) Scanning region of the microwave beam.

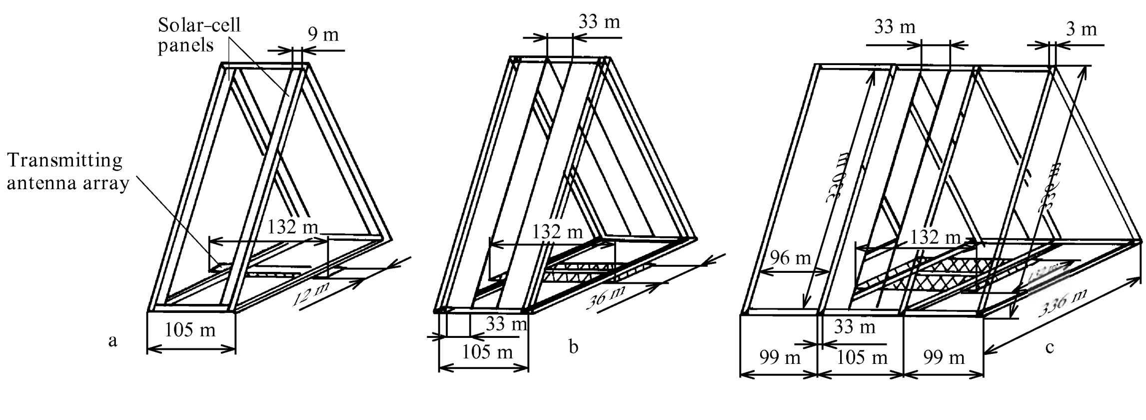



**Figure 7.** General scheme of SPS 2000 assembly. After two primary launches, the unit created (a) possesses all the functions of the SPS 2000 with a power level of 0.7 MW. After five launches (b) the power level is increased to 2.56 MW. Sixteen launches are enough for the creation of the full-scale SPS with a power level of 10 MW (c).

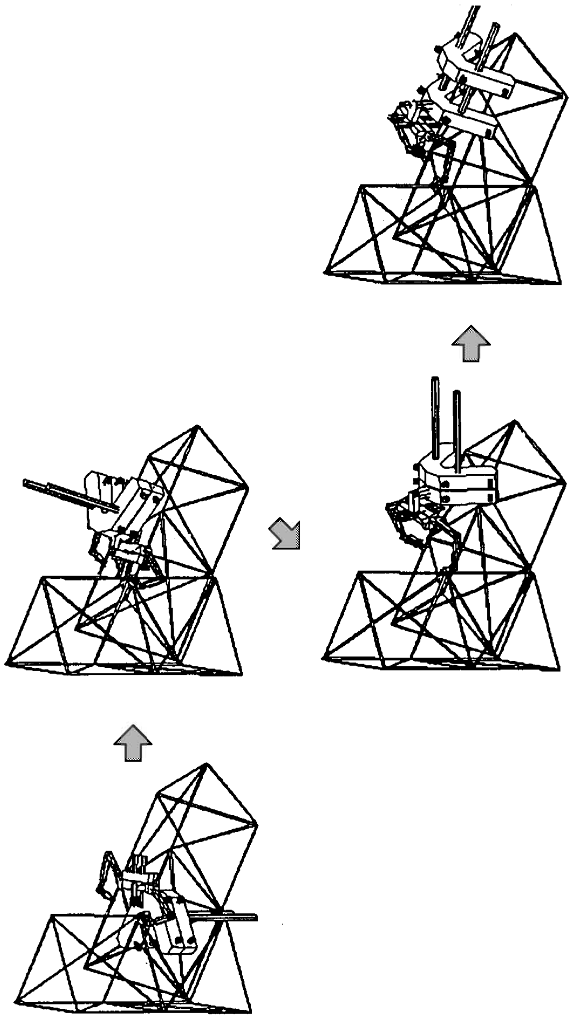


Figure 8. Variant of a robot carrying out the assembly of a support truss in the construction of the SPS 2000.

plane and provides suitable conditions for the use of one or several rectennas (ground-based receiving systems). The orbital altitude has been chosen as a compromise to the set of various requirements (transportation cost, time of transmission to ground rectenna, aerodynamic deceleration, degradation of solar-cell panels, etc.).

The present construction of the transmitting antenna allows the microwave beam to be scanned within an angular interval of between $-30°$ and $+30°$ in the East–West direction and between $-16.7°$ and $+16.7°$ in the North–South direction (Fig. 6b) in order to illuminate the receiving system.

The in-orbit assembly of the SPS units by robots is one of the most complicated problems. Fig. 8 demonstrates one of the robot models assembling the SPS 2000 support construction.

The maximum power density at the transmitting antenna is not very high in this case (500–600 W $m^{-2}$) and therefore SPS 2000 will be able to utilise semiconductor technology on a full scale. The radiating elements of the antenna array have a simple design — a rectangular resonator with a slot is connected to a microwave power amplifier that is based on FETs (efficiency 65%, output power $\sim$4 W, voltage 15 V).

The rectenna system is based on the use of circular microstrip receiving antennae loaded onto Schottky-barrier diodes. The microwave power density is lower than the US continuous microwave exposure standard level (10 mW $cm^{-2}$), even at the centre of the rectenna system, and the strictest level in the world (the Russian standard of $10^{-2}$ mW $cm^{-2}$) is fulfilled a small distance from the edge of the rectenna. Thus, the SPS 2000 is an ecologically clean system. The main parameters for the SPS 2000 [25–27] are given in Table 2.

The SPS 2000 will be an intermittent system: the time of operation with the rectenna (i.e. the SPS flight time across the angular interval of $-30°$ and $+30°$ relative to the

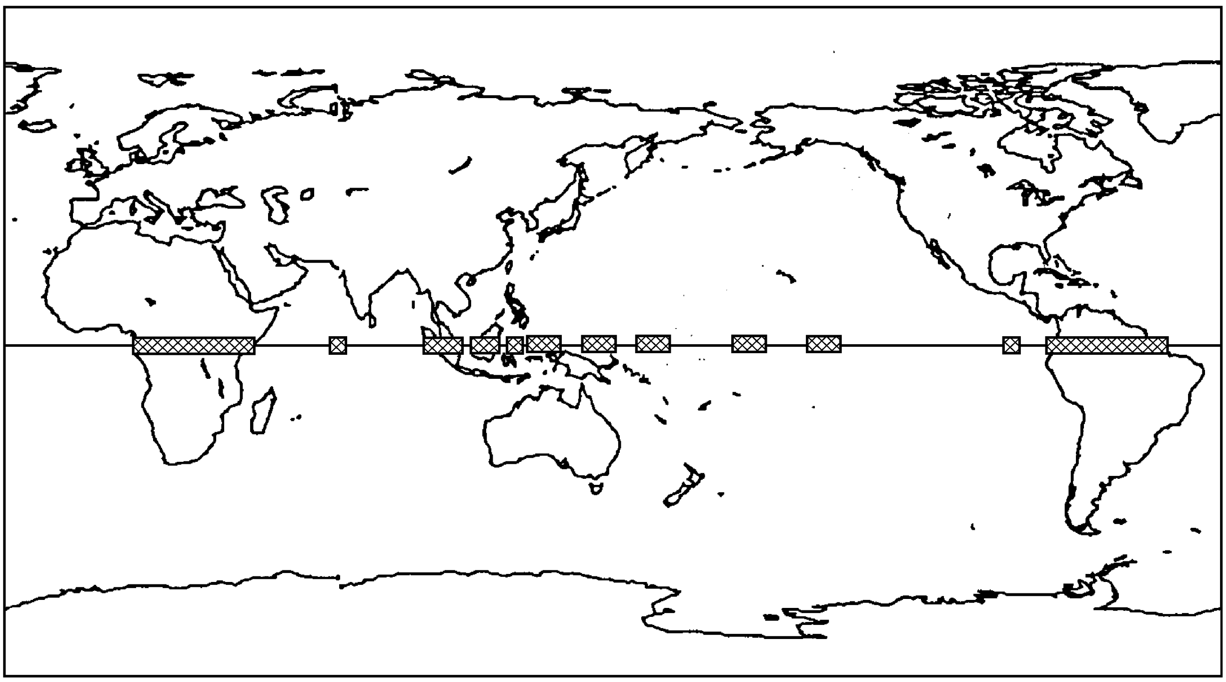


Figure 9. Areas convenient for the location of SPS rectennas.

**Table 2.** Main parameters of the SPS 2000.

| | |
|---|---|
| Planned year of creation | 2000 |
| Operational lifetime/years | 10 |
| Radiated power/MW | 10 |
| Type of solar cells | a-Si |
| Efficiency of solar cells/% | 15 |
| Specific power of the solar cells/kW $kg^{-1}$ | 0.95 |
| Size of transmitting antenna/$m^2$ | 132 × 132 |
| Diameter of rectenna/km | 1 |
| Operational frequency/GHz | 2.45 |
| Method of assembly | robots |
| Total mass/t | 223.6 |
| including: solar-cell panels | 37.5 |
| transmitting antenna | 134.4 |
| Candidate launch-vehicles | Ariane-5, Proton |
| Number of necessary launches for completion of SPS 2000 | 16 |

normal) is about 200 s, i.e. a little more than 3 min. The operation takes place during the daytime only, when the solar-cell panels are illuminated and working.

The main purposes of the SPS 2000 project are:
— to check out the main principles and ideas as a basis for a full-scale SPS programme;
— to demonstrate the viability of such energy systems ;
— to gain necessary technological experience for the creation of commercial systems.

Nevertheless, further evolution could also be quantitative — a set of SPS 2000 type satellites located in the same orbit would essentially increase the efficiency of rectenna systems, which could then be placed along the equator (Fig. 9) and thus deliver energy to the developing countries [28].

The launch of an independent space module — Space Flyer Unit, (SFU) planned conjointly by ISAS, MITI, and STA in 1995, will allow the fulfilment of a set of experiments directly connected with SPS 2000 (space plasma testing, deployment of two-dimensional constructions in space, high-voltage solar-cell panels, etc.).

The Microwave Garden experiment being carried out on the campus of ISAS at the present time, is also directly connected with the SPS 2000 project. Two adjacent 15 $m^2$ sites contain similar biological objects. One of them is radiated by microwave power with a density of 10 mW $cm^{-2}$, another is used for the control. To date, no noticeable effect connected with microwave radiation of that power density level has been detected.

## 5. The MINIX and ISY-METS experiments

"*... 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.*"

September, 1962.
P L Kapitza, Nobel Prize Winner [29].

Microwave energy transmission is one of the more significant features of SPS units. Its ground-based development has been carried out very successfully for a long time [1, 30, 31].

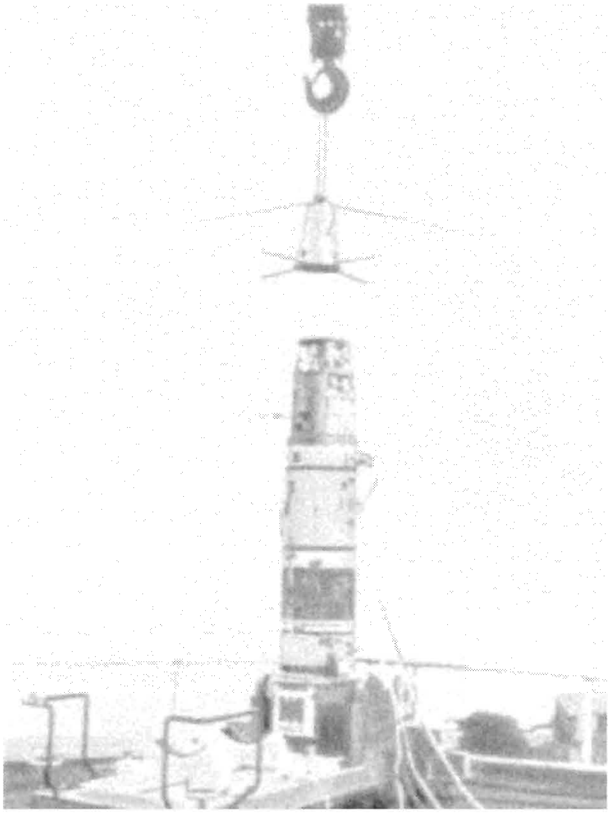


**Figure 10.** Pre-launch tests of the S-520-6 sounding rocket. This photograph shows the simulation of the separation of the daughter section, which contains microwave, HF and VLF receiving equipment.

However, the SPS microwave beam will pass through the ionospheric plasma. The intensity of the microwave beam is about 11 – 12 times greater than the intensity of electromagnetic beams used in ordinary space communication channels. Nonlinear interactions have been

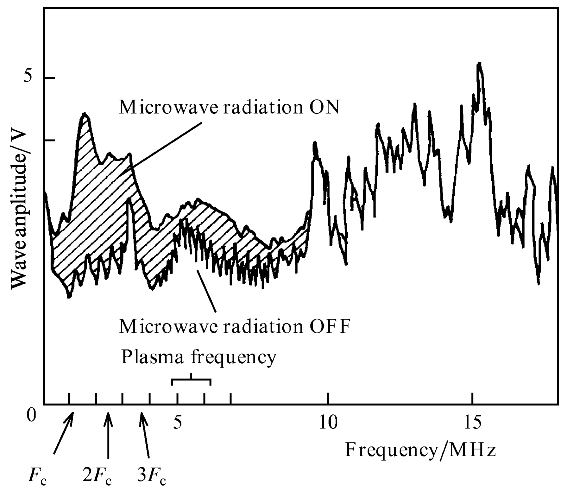



**Figure 11.** Dynamic spectra of plasma waves observed in the MINIX experiment. ($F_c$ is the local magnitude of the electron cyclotron frequency).

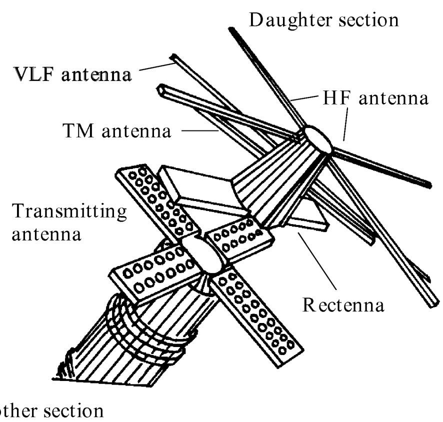
theoretically predicted for a powerful SPS beam passing through ionospheric plasma [32 – 34].

The first experiment, named MINIX (Microwave ionosphere nonlinear interaction experiment) was proposed by N Kaya and H Matsumoto and was realised in 1983. A single-stage sounding rocket with a separable daughter section was used for the experiment (Fig. 10). The rocket, with 150 kg of payload, achieved an altitude of 250 km. Two magnetron generators with truncated waveguide antennae orientated along and across the direction of rocket motion, were installed on the mother rocket and radiated microwave power of 800 W continuously at a frequency of 2.45 GHz. The separable daughter section contained measuring equipment for several bands of wavelength.

The experiment consisted of three stages. The first stage was conducted at the altitude of 85 – 110 km and was designed to investigate ionospheric heating. The separable daughter section was connected with the mother section during this stage. The second stage of the experiment was similar to the first one except for the pulsed character of microwave generation: 5 s operation, 5 s pause. The third stage began with the full separation of the daughter (instrumental) section. The highest altitude was achieved during this stage. The experimental system passed through the field of maximum electron density, where various wave excitations were expected.

The results of the experiment could be summarised as the following:
— the heating effect was not detected;
— noticeable wave excitation was observed at 1.5 times the local electron cyclotron frequency (Fig. 11);
— the rectenna system located radiated microwaves, but scattered waves were not registered [16, 35 – 38].

The second experiment on microwave transmission in space, named ISY-METS (International Space Year Microwave Energy Transmission in Space), was conducted in February 1993 [39]. The experiment was suggested by the ISAS SPS Working Group in 1991 and its general purpose was similar to that of the previous experiment. However, the ISY-METS experiment was performed with essentially enhanced technology. An active phase array was used for energy transmission in space for the first time and consisted of four rectangular antenna paddles deployed in a cross shape (Fig. 12a). Each paddle contained 16 circular microstrip radiating elements (Fig. 12b) fed by microwave amplifiers made with FETs of high efficiency and with an output power of 13 W. The phase and amplitude distribution on the transmitting antenna array was controlled by a computer. The microwave receiving system



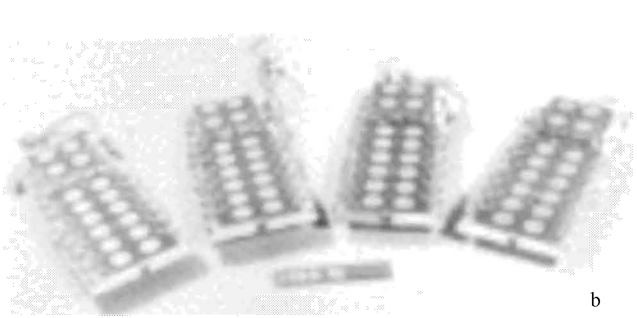




**Figure 12.** (a) General scheme of the configuration of the ISY-METS payload section. (b) Paddles of the transmitting microwave phase-array antenna constructed from circular microstrip antennae.

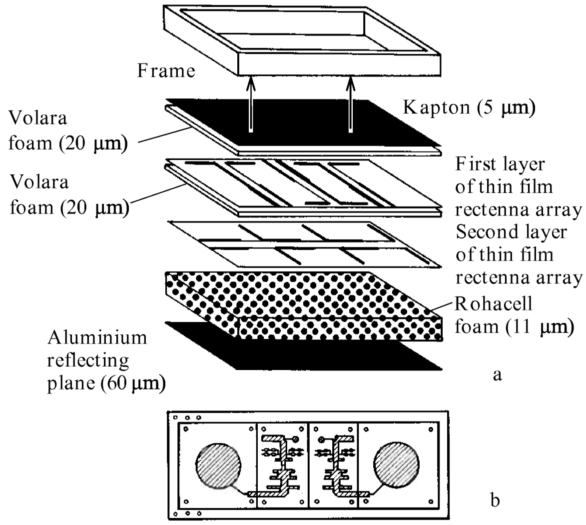



**Figure 13.** Two variants of rectenna used for the ISY-METS experiment. (a) Structure of the rectenna developed by ISU/Texas A&M University. (b) Structure of the rectenna developed by CRL. (Thickness shown in parentheses.)

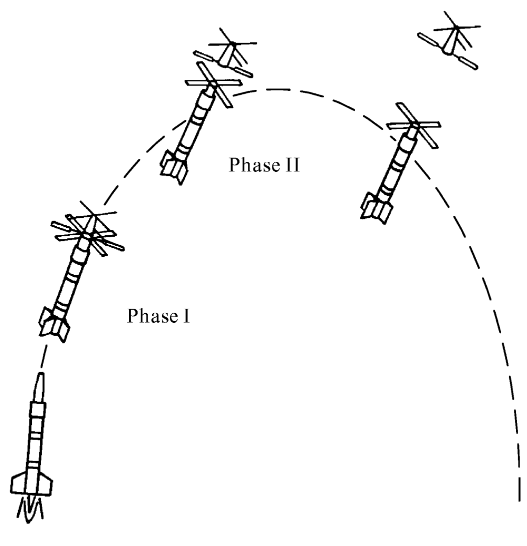



**Figure 14.** Scheme of the ISY-METS experiment.

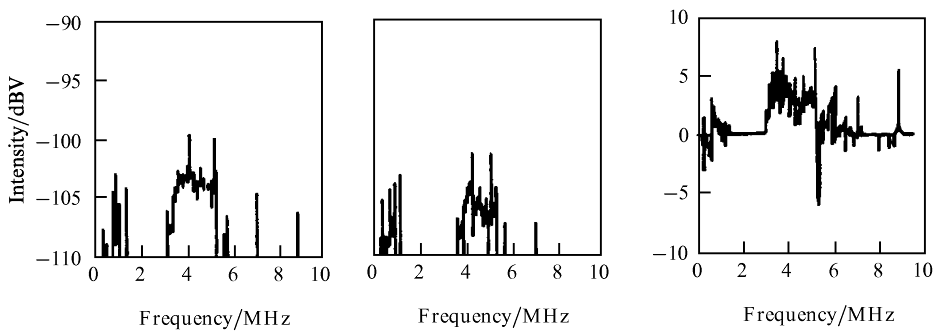



**Figure 15.** Dynamic spectra of the plasma waves observed in the ISY-METS experiment.

consisted of two parts. One part contained a disc microstrip construction and was designed by the Communication Research Laboratory (CRL). The other part was developed by Texas A&M University and was composed of mutually perpendicular linear dipoles and constructed from microstrips (Fig. 13). In addition, the daughter section contained several types of antennae for plasma wave observation in the HF and VLF ranges.

The experiment consisted of two phases (Fig. 14). All the antennae for plasma-wave observation and the microwave antenna were deployed 55 s after the launch. The microwave-transmitting antenna paddles were deployed 2 s later. The daughter section was not separated from the mother one during the first phase of experiment. The nonlinear plasma wave excitation and ionosphere instabilities were examined at this stage.

The direction of the microwave antenna array radiation could be varied during the experiment. Four main directions of radiation were used in order to increase the number of experimental conditions:

— along the rocket axis;
— 30° to the rocket axis;
— along the direction of the local geomagnetic field;
— perpendicular to the local geomagnetic field.

Microwave radiation of approximately 800 W was switched on 65 s after the launch and was periodic: 7 s radiation, 3 s pause.

An example of the dynamic spectra of the plasma waves is shown in Fig. 15. The left panel in the figure indicates the spectrum in the presence of microwave radiation, the centre one shows the spectrum of the natural ionosphere. The right panel shows the difference spectrum, which clearly illustrates the plasma wave excitation around the local electron plasma frequency under the action of powerful microwave radiation. The cyclotron wave spectrum observed in the earlier MINIX experiment (Fig. 11), was not registered here. The transmitting antenna in the MINIX experiment was a truncated waveguide antenna with a local microwave power density of 15 W $cm^{-2}$ in its aperture; during the ISY-METS experiments the maximum power density was 150 times lower (0.1 W $cm^{-2}$) and probably was not sufficient to excite a noticeable level of cyclotron oscilla- tions.

Separation of the daughter section for the realisation of the second phase of the experiment started 222 s after the launch. The measured value of relative speed between the daughter and the mother sections was equal to 8.6 cm $s^{-1}$. Microwave energy transmission functioned perfectly in space conditions and was in agreement with the ground test parameters. No noticeable influence of the plasma wave on the efficiency of power transmission was detected.

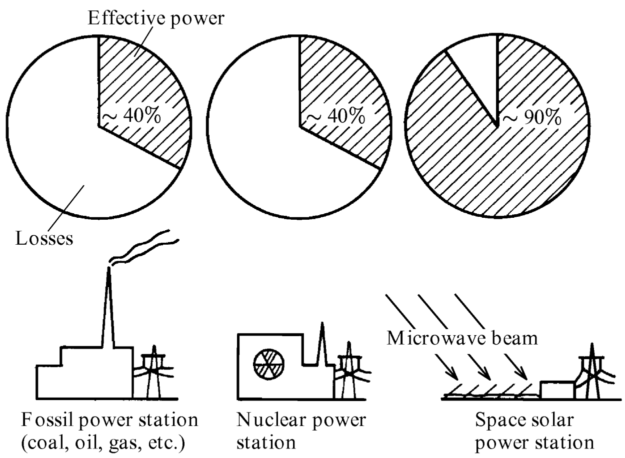



**Figure 16.** Heat losses for different types of power stations.

Some of the ISY-METS experimental results are still being processed and will be published later.

## 6. Discussion

First, we would like to formulate the main advantages of SPS as an energy system of the future:

1. The SPS uses the inexhaustible (renewable) energy of the Sun, i.e. the natural thermonuclear reactor to which all life on our planet owes its existence.
2. Natural Earth resources which are exhaustible and valued for future technological processes, are not being expended (coal, oil, gas, etc.).
3. There are no waste products polluting the atmosphere.
4. The SPS provides minimum heat loss (Fig. 16), this is very vital — thermal pollution is one of the greatest global problems arising for mankind.
5. There are no problems connected with the burial of radioactive waste and/or out-of-date radioactive equipment.
6. There are no problems connected with carbon dioxide.
7. There is a level of safety for the population of the Earth.
8. The rectenna system, being 80% – 90% transparent to solar radiation, could be raised above the Earth's surface to allow efficient use of the system area for industrial or agricultural purposes.

9. The microwave SPS beam could be easily transferred from one receiving system to another, thus providing operational energy switching to remote consumers.

A natural question appears — why is such an energy system, that seems to be so promising, making such slow progress? The answer to this question can hardly be simple or complete. Nevertheless, one can emphasise two main problems here: public opinion and the financial risk.

Today, every schoolchild has heard about efforts in the field of thermonuclear synthesis but by no means does every specialist who deals with physics, engineering, power generation, or even space exploration† have a complete enough comprehension of the SPS. Very often one can hear the opinion that it is impossible to create an antenna of such a size in space or, if it is possible, then the microwave beam will burn all alive on the Earth, etc.

It could be that the SPS is a newcomer to the energy sphere, where a quite specific balance of interests and influences is already formed and where the appearance of new ideas are rarely conceived or promoted because of current interests.

The usual method of estimating the economic profitability of a power system is rather specific. The capital cost per kilowatt hour produced by the SPS is calculated according to the expenses of the system development and, after that, the defined cost is compared to the cost of existing energy systems — fossil-fuel stations, hydroelectric stations, nuclear stations, etc.(see Ref. [12] for example). One can consider this problem from a different point of view. Each full-scale SPS created implies the replacement of one extant energy system which is expending natural resources and/or polluting the human environment. And who can give a precise answer today to the question of how many cents per kilowatt hour should be added to the economic estimates of existing energy systems that are destroying the Earth's ecology or that have a high risk of explosion; and how many cents per kilowatt hour should be subtracted from the cost of SPS energy because of the absence of these problems?

It is very possible that, in the future, mankind will have to carry out projects of such a scale, which seem absolutely impossible today, to solve the growing global problems.

One should also take into account that realisation of great space programmes such as the creation of SPS, when the work is being fulfilled with the leading-edge of technology and is supported by the most modern scientific achievements, technologies, and methods, will already provide economic return at the development stage, because intermediate results from similar fields of science and technology are being used.

Let us remember the 'Apollo' project (human's first flight to the Moon; USA; about $25 billion). This flight was an extremely prestigious space programme and it was not intended to provide any special economic return. However, this project has compensated itself many times (by a factor of between 7 and 12 according to different estimates) exactly as a result of the application of modern technologies, achieved during fulfilment of the programme, to the different spheres of human activities.

†In Japan the concept of the SPS is better known. A survey of more than 100 specialists in the field of space investigation gave SPS the highest priority. Statistics for the forecast of the year in which the SPS will be accomplished are as follows: earliest, 2008; latest, 2026; average, 2015.

International collaboration is a vital factor in reducing commercial risk. In addition, the developing countries, as potential large-scale consumers of this energy, could participate in the work aimed toward the creation of an SPS.

The SPS 2000 project is the simplest way to demonstrate to mankind what 'Energy from Space' means and also to accumulate the necessary organisational and technological experience required for the creation of a full-scale system, thereby minimising the commercial risk. The SPS Working Group of the Institute of Space and Astronautical Science of Japan is actively working on the SPS 2000 project and is open to international cooperation in the field of large-scale SPS.

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