ENGINEERING RESEARCH FOR SOLAR POWER SATELLITE SPS 2000

Recherches d'Ingenierie pour Satellite Solaire de Puissance SPS 2000

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Abstract

SPS 2000 is a strawman model of Solar Power Satellite (SPS) which the SPS Working Group at the Institute of Space and Astronautical Science (ISAS) has been working on as a research project since late 1980's. The configuration has been modified more or less with the progress of the study. The latest SPS 2000 is a 10 Mwatt class model with a shape of trigonal prism of 300 m scale each side on an equatorial orbit of 1,100km height. In the initial study phase, the fundamental concept was developed by analysis, computer simulation and group discussion. In the latter phase, some of the key technologies involved in the design have been further studied experimentally. The laboratory work includes experiments on survivability in space environment, a system level test using an electrical functional model, and an automatic construction simulation of the truss beam. This paper presents the major results of the engineering studies which represent a steady progress in the conceptual study of SPS 2000.

1. Introduction

Power from space has recently been recognized as one of the potential options for the energy system in the 21st century to cope with the global environmental problem. Especially early in 1990's, the SPS has been widely referred to not only in the field of space engineering, but also in economy and sociology. It also appeared in the political discussion associated with the issues of CO_2 emission. For example, SPS was regarded as a potential future energy technology in the New Earth 21 Action Program [1] proposed by the Japanese government in 1991. In the same year, the symposium SPS 91 was held in Paris and more than 200 researchers were involved in active discussions on "power from space". Public concern for the SPS concept has grown worldwide after the decade stagnation since the SPS Concept Development and Evaluation Program (CDEP) of the USA in late 1970's.

In the movement, the SPS 2000 task team was organized in 1991 to promote a conceptual design of practical and low cost SPS. The study of the SPS strawman model which was much smaller than the US reference model had been started earlier by the members of the SPS Working Group at ISAS. The task team was organized by the researchers from wider disciplines to forward the conceptual design more systematically and profoundly. For a practical study, a 10 Mwatt class SPS on the equatorial low earth orbit is considered. Commercially-available technologies in the time frame around 2000 are premised. The cost target is set to be competitive with existing utility electricity. In 1993, the SPS 2000 task team published a report on the preliminary design of SPS 2000. After the preliminary report, the team members have continued the research activities in planning of precursor experiments, experimental studies on key technologies, field surveys for the ground segments, and cost analysis for economical evaluation. In the research activities for SPS 2000, great importance has been placed on trial productions, experiments, and field works. The practical approach has been one of the conspicuous aspects of the SPS 2000 research.

Engineering research has been conducted for several key technologies for SPS 2000. For the power generation, candidate solar cells, new type of flexible amorphous silicon, were tested to evaluate the radiation resistance for life estimation in space. Impact of debris or meteoroids to the large

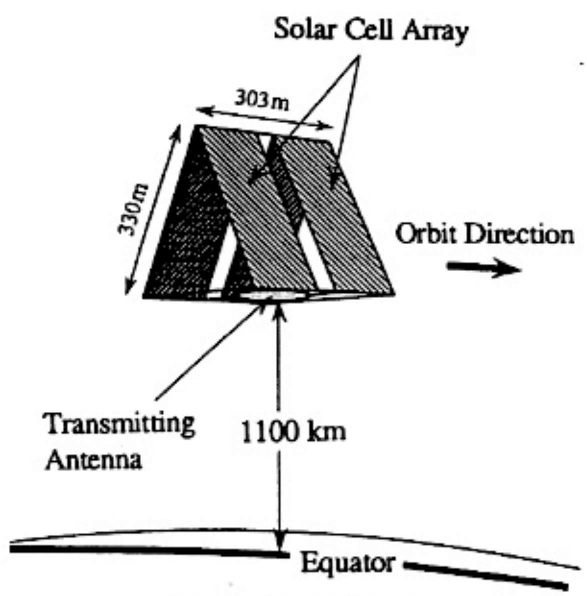

Fig.1 General view of SPS 2000.

solar cell arrays is practically inevitable. Hyper-velocity impact experiment to the thin-type solar cell was conducted to estimate the size of impact damage, which is required to design the array layout. SPS 2000 is designed to use a high voltage for the power generation and transmission. Interaction of the high voltage with the ionospheric plasma was studied in a laboratory experiment to evaluate the surface degradation and contamination. The microwave power transmission by phased-array antennas for SPS 2000 has been studied mainly by the researchers of Hokkaido University [2] . At ISAS, an electrical functional model consisting of solar cell arrays and microwave transmitters has been developed to study the electrical interface on the system level. Several types of receiving antenna element were produced and tested in combination with the electrical functional model. For the construction of SPS 2000, a mechanical system to build the truss beam automatically was developed to study the feasibility of unmanned construction scenario. The results of these engineering researches have been reflected in the design and evaluation of SPS 2000.

2. SPS 2000 System

Figure.1 shows the general view of SPS 2000. It has the shape of a triangular prism with a length of 300 m each side. The prism axis is in the north-south direction, perpendicular to the flight direction. The solar arrays are attached at the two upper planes of the prism, while the transmitting antenna is installed at the bottom plane, facing the ground all the time. The power level of microwave transmission is 10 MW and the operating orbit is at an altitude of 1,100km above the equator, which is a compromise of transportation cost and environmental concerns. To simplify the overall system, the model SPS has no energy storage, and the attitude is stabilized merely by gravity-gradient force. Since the total weight of SPS 2000 is estimated to be about 240 ton, it is impossible to lift the whole system once by the existing or near future launch vehicle. It is to be modularized into about 20 flight units for space transportation. The construction module is lifted to the operational orbit and is automatically assembled there. The operational capability as an SPS is tested during the phased construction. For transportation to the equatorial orbit, Ariane 5 launch vehicle is considered to be most practical among the existing vehicles.

The main structure of SPS 2000 is made of double-bay single-raced beam, which is assembled of 3 meter-long aluminum pipes of 12 mm diameter with quick connection mechanisms. The task analysis for construction method has shown that unmanned assembly is feasible under gravity-gradient force. The solar array consists of 180 rolls of 3 m x 300 m strips of solar panel. For transportation from ground and deployment in space, amorphous silicon (a-Si) solar cell, a thin film type, is selected as a potential candidate. The conversion efficiency of the cell is assumed to be 15% as is predicted in the near future. Flat cables made of 1 mm thick copper plate are used for the electrical power collection. For the microwave power transmission, 2.45 GHz is selected as the most practical frequency for near-future application because of technical maturity. The spacetenna 132 m by 132 m square consists of 2,000 subarrays, each including 1,300 antenna elements. The phased array system is capable of directing the microwave beam ± 30 degrees in north-south and ± 17 degrees in east-west to the normal. The size of rectenna is typically 1 km circular and a power of 300 kW will be available on average at each rectenna site. Two types of rectenna have been investigated ; a simple mesh type called "magic carpet" and a hogline rectenna with circular micro-strip antennas [3] . Both are almost transparent for the sunlight to reduce the environmental impact. The power supply to the existing commercial utilities is studied from engineering and economical stand points. Totally 19 rectenna sites along the equator are selected as the candidates, and field survey has been conducted for several candidates by the members of SPS 2000 task team [4] . More detailed description on the concept of SPS 2000 is given by Nagatomo et al. [5] and is also available at the web site : http : //spss.isas.ac.jp.

Table 1 Characteristics of a-Si solar cell used for environmental tests.

Type	Amorphous Silicon
Dimension	113×120×0.25mm
Area	135.6cm^2
Weight	4.5 gram
Protective Cover	PET(0.05mm thick)
Temperature Coefficient	Voc -0.4 ~ -0.2
	Isc +0.1 ~ +0.2
	Pmax -0.2 ~ -0.03

3. Engineering Research

3.1 a-Si Solar Cell Degradation Test

For SPS 2000, deployable a-Si solar cells have been selected as the design element. The a-Si solar cell came forward in 1976 as a potentially low cost solar cell. This type of solar cell is extremely thin so that it has a higher specific power per unit weight (~ kw/kg) than the other types. The conversion efficiency of the a-Si solar cells is approximately 10 % at present which is lower than that of the crystalline cells, but is expected to be considerably improved in the near future. Since the a-Si solar cell are relatively newborn, its resistance in space environment has not been well verified. We have tested the radiation resistance of the a-Si solar cell using newly-developed commercial cells available in Japan. The characteristic features of the a-Si solar cell module we tested are listed in Table 1.

The irradiation experiments were conducted by electron and proton beam accelerators of Japan Atomic Energy Research Institute (JAERI) . The energetic electrons of 0.15-3 MeV were irradiated up to a fluence of 5 x 10^{15}electrons/cm^2 in the atmosphere. For proton irradiation, the effect of energy at 3-10 MeV was studied up to 2.5×10^{14} protons/cm^2 in vacuum. The performance of the solar cells before and after irradiation was measured by a pulse solar simulator of ISAS. In several experiments, crystalline Si solar cell was also irradiated as a reference. Figure 2 shows the degradation curve with respect to the fluence in case of electron irradiation [6] . The test cells were degraded considerably at the fluence of 5×10^{15} electrons/cm^2, but maintained typically more than 90% of the initial performance with the fluence less than 10^{15} electrons/cm^2 which corresponds to the total fluence for the orbit of SPS 2000 during 15 years. Both the electron and proton irradiation experiments indicated that the a-Si cells have a higher radiation resistance than the conventional crystalline cells. One of the reasons for the higher resistance could come from extremely thin structure of the cell layer typically less than 1 μ m.

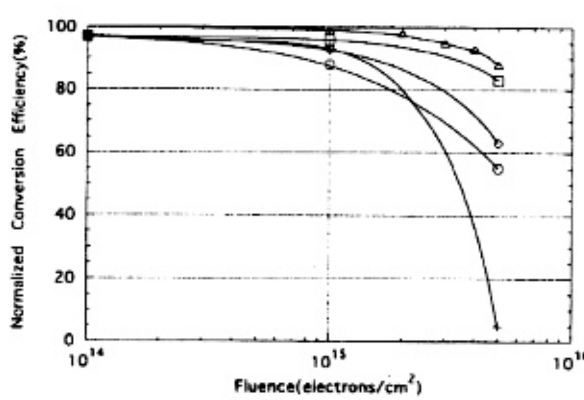

Fig.2 Effect of 1 MeV electron irradiation on the relative conversion efficiency for a-Si solar cell. Totally five cells were tested.

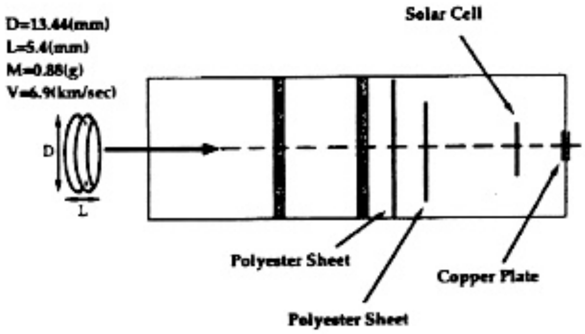

Fig.3 Setup for hyper-velocity impact experiment to a-Si solar cell module.

In the irradiation experiment, the recovery of the cell performance with time was also studied. Although the cells were stored in room temperature after irradiation, annealing effect was clearly observed. One possible mechanism to explain the annealing effect at room temperature is the recombination of hydrogen atoms in the cell. Although further study is required for a quantitative assessment, the annealing effect could reduce the degradation rate of a-Si solar cell in space environment.

3.2 Hyper-velocity Impact Experiment

The impact damage by space debris or meteoroids has been studied by colliding a high speed projectile to the a-Si solar cell module and equivalent thin films. The impact experiment was conducted by a rail-gun at ISAS, which can accelerate a projectile made of polycarbonate of 1 gram at a speed of 5-7km/sec. The setup for the impact experiment to the a-Si solar cell module is shown in Fig.3. The first two metal plates with a hole at the center are used to stop the plasma ejected from the gun. The two sheets of polyester with a hole at the center are set in front of the solar cell module to detect the plasma propagating through the metal plates. Behind the solar cell module, a copper plate target is installed to catch the projectile after the impact.

Before the experiment using the a-Si cell module, impact experiment to a polyester film sheet of 0.2 mm thickness was conducted twice. The impact produced a hole of 4-9 cm diameter on the sheet, which was much larger than the projectile of 1cm size. The craters generated on the aluminum plate behind the sheet indicated that the projectile was destroyed into 4-6 pieces by the impact. This suggests a strong interaction between the sheet and projectile took place more than expectation.

Figure 4 shows the damage of the a-Si cell module after the impact [7]. A through hole was produced with the same size of the projectile. In addition to the hole, there was a damage of 6 cm diameter around the hole, where the layers of both PET and amorphous silicon tore off. No such damage was observed in the rear side of the solar cell module. The projectile was destroyed into more than 9 pieces after the impact and were collected by the copper plate. The impact experiments have shown that the damage on the thin film is typically 10 times larger than the size of the projectile with 1 gram weight, 1 cm size and 5-7 km/sec velocity. According to the result, the layout of the array unit is designed to confine the effect of the damage. By applying the experimental result to the SPS 2000 power generator on the 1,100 km equatorial orbit, approximately 1% of the initial power is estimated to be lost by the debris/meteoroid impact during 10 years.

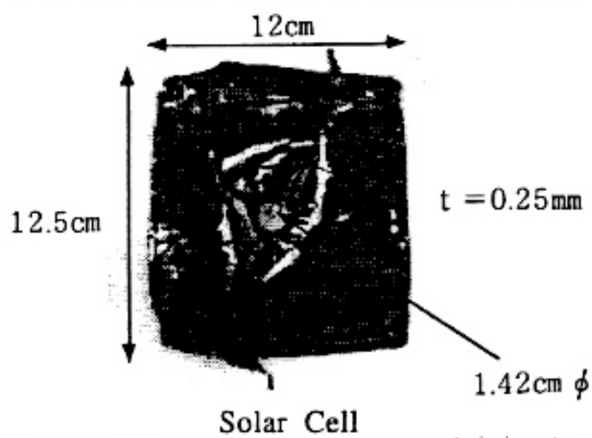

Fig.4 Damage of a-Si solar cell module by hyper-velocity impact.

3.3 High Voltage Interaction Experiment

SPS 2000 will use a high voltage in the power system to reduce the power loss in the cables and loads. 1,000 V is generated by connecting the solar cell modules in series. Exposure of the high voltage to space plasma environment causes not only power loss, but also ion bombardment to the negatively-biased conductor which results in material degradation and contamination. The ion sputtering effect results in a loss of surface material. The ejected secondary ions return to the surface by the electrostatic force and could lead surface contamination and insulation failure. Insulation of the conductive surface to avoid the plasma interaction is not a realistic solution because insulation cannot be guaranteed over a long term in the space environment. Furthermore, insulation failure by the impact of small debris or meteoroids is an inevitable risk with a certain probability.

To evaluate the material degradation and contamination caused by the high voltage, we have made a laboratory experiment in which an energetic oxygen ion beam up to 1.5 keV was irradiated on an aluminum thin film. The experimental setup is shown in Fig.5. The ion gun is contained in a vacuum chamber and the target is set in another higher-vacuum chamber. The beam flux is 7.1×10^{13} ions/cm^2 · sec, which is almost 5,000 times larger than the ion flow to spacecraft orbiting at an altitude of 1,000km. A half-transparent sample of aluminized polyimide was used as the target to measure the sputtering rate by an optical method. The secondary ions were detected by the mass spectrometer.

With the experimental results on the sputtering rate and ion production rate, we can estimate the material degradation and contamination quantitatively. In the calculation, we used a model of the space charge limit current for a conductive sphere in plasma. Figure 6 shows the mass loss rate for a 1 m diameter sphere negatively biased at 1,000 V for altitudes from 400 km to 1,000 km [8]. At an altitude of 1,000 km as an example, the mass loss rate, contamination rate and power loss are estimated typically as 0.6 μ m/year, 160 Å /year and 0.3 Watt, respectively. These numbers are used as design guidelines for the interconnecting cell cables, flat power cables, and insulators of the SPS 2000 power system.

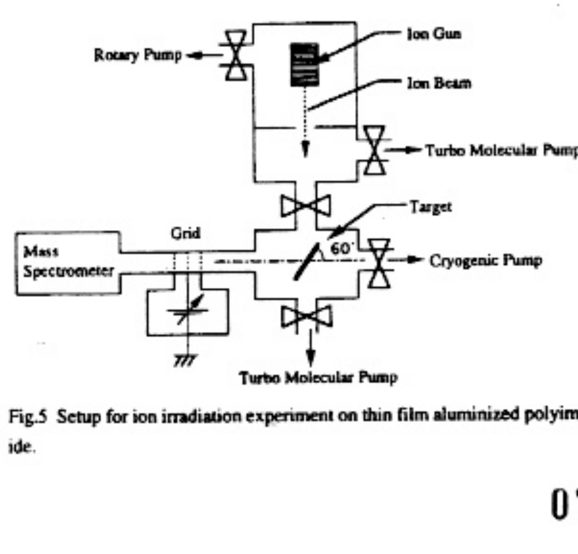

Fig.5 Setup for ion irradiation experiment on thin film aluminized polyimide.

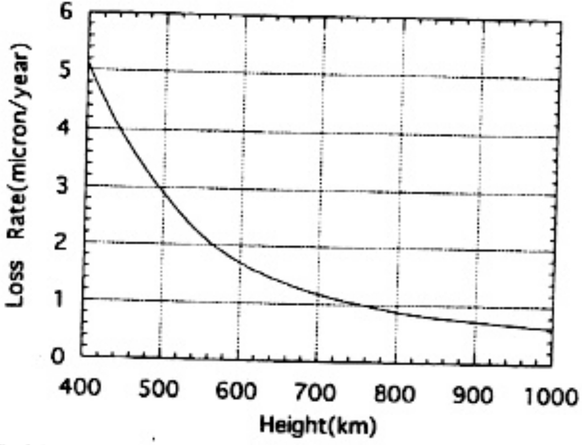

Fig.6 Loss rate per year for an aluminum sphere of 1 m diameter biased at -1,000 V.

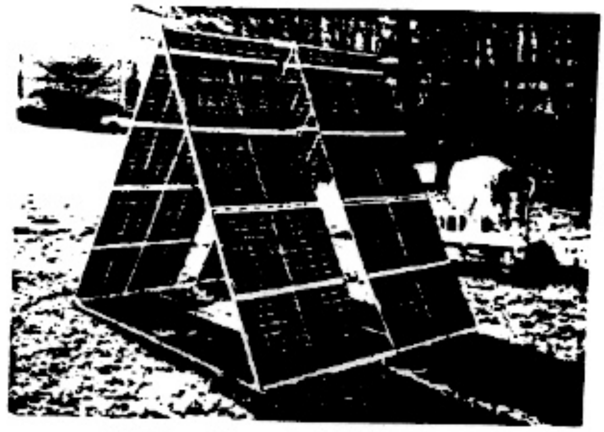
Fig.8 View of the new electrical function model.

3.4 SPS 2000 Functional Model

An electrical functional model has been developed to study system-level problems of SPS 2000, associated with system integration, operation, safety, and subsystem interface. The functional model includes a power generator consisting of solar cell panels and a microwave transmitting system which are integrated on a triangular prism frame structure. Halogen lamps are used as the primary power source. The model is operated in combination with a microwave receiving system as the ground segment. The block diagram of the model is shown in Fig.7.

Two functional models have been developed since 1994 [9]. The first one, a 1/300 scale model, was a 1 watt transmitting power system without phase control. The second one, a 1/200 scale model, was a 4 watt power system with a capability of phase control for the beam steering $\pm$ 30 degrees. Two types of antenna, a circular microstrip type and a dipole type, have been developed for the rectenna. The separation between the functional model and rectenna was 1-2 meters. The received power was rectified and supplied to dummy loads consisting of LEDs and miniature motors.

In the test using the functional model and ground segment, the performance of each subsystem of SPS 2000 has been evaluated from a stand point of system integration and operation. The functional model was exhibited at the ISAS annual open house and the Wireless Power Transmission Workshop at Reunion Island of France in 1994 and 1995. A more powerful functional model is now under development supported by an MOE Grant-in-Aid for Scientific Research. It is a 1/150 scale model with a capability of power generation more than 300 watt in the sunlight. It will be capable of transmitting a microwave power of several tens of watts. The picture of the new model is shown in Fig.8. The system will include a new concept of a compact integration for a microwave amplifier and a transmitting antenna.

3.5 Automatic Building System

One of the most challenging technologies for SPS 2000 is automatic construction of the large structure in space. There have been several options to build the truss beam consisting of meters-long pipes. One idea is to use a moving robot on the truss with arms to connect the pipes. This scenario has been extensively investigated by analysis, and quick connection mechanism has been devised for this scenario.

Another idea is to have an automatic building system from which the truss beam is extended [10]. In order to study the feasibility, an automatic building system of SPS 2000 truss beam has been developed for ground testing. The system layout is illustrated in Fig.9. The system automatically assembles the folded triangle elements of 1m length aluminum

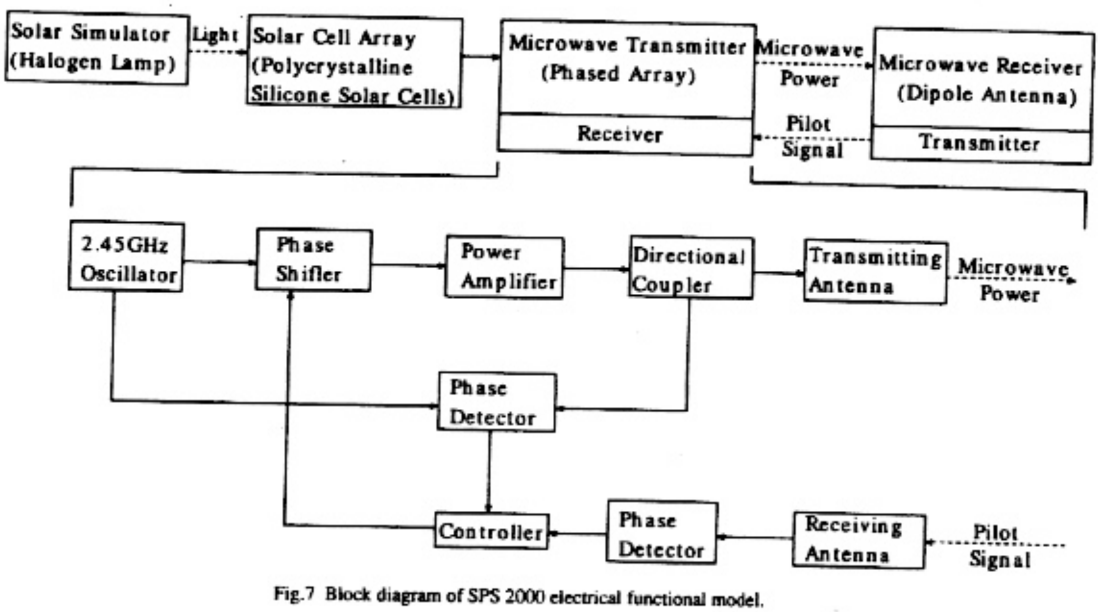

Fig.7 Block diagram of SPS 2000 electrical functional model.

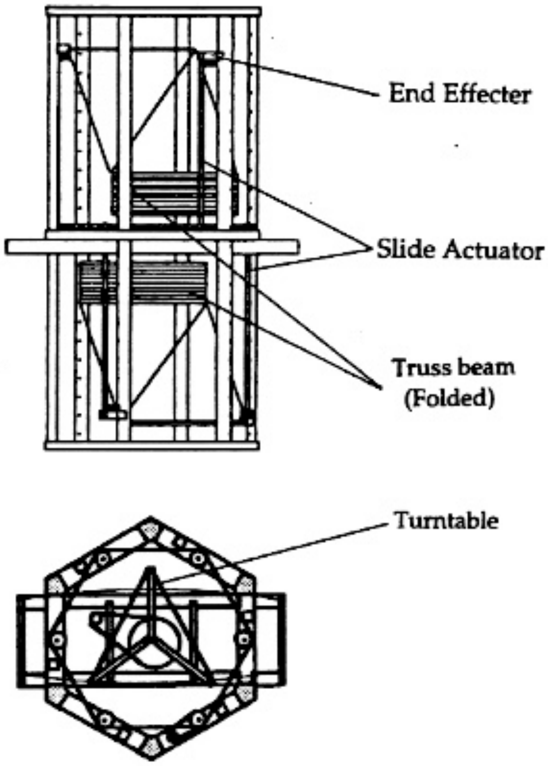

Fig.9 System layout of automatic builder for SPS 2000 truss beam.

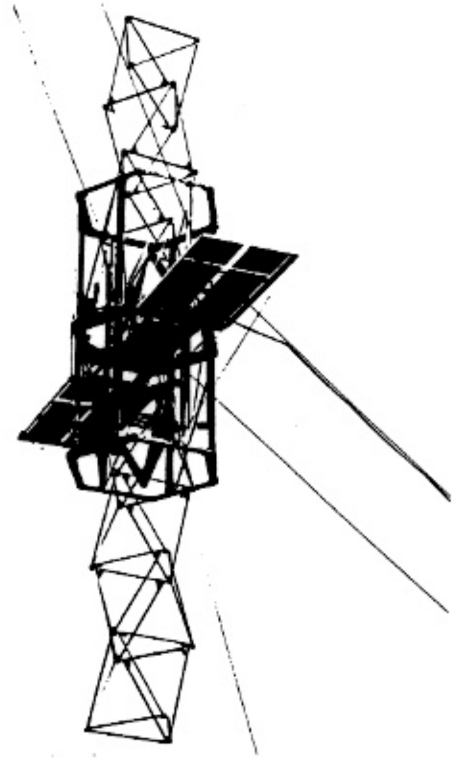

Fig.10 Demonstration of automatic building of SPS 2000 truss beam.

pipes (1/3 scale of SPS 2000 truss element) into a truss beam structure. The builder alternatively repeats two functions ; movement and connection of the truss element. The truss is extended by 10 m vertically parallel to the gravity field upward and downward synchronously to cancel the gravitational force. The building system is electrically powered by solar cell arrays directly connected to the driving mechanism without voltage regulation. Even in a low light condition, the construction continues with a low speed.

The development of the system has not been completed yet, but basic function has been demonstrated. The preliminary test has shown that the frictional force in the driving mechanism is larger than the gravity force, and the effect of gravity cancellation is not practically seen. The gears responsible for the excessive friction have been identified and will be improved in the next phase development. Figure10 shows the picture of the demonstration test at the ISAS annual open house in 1996.

4. Conclusion

The results of the engineering research associated with the SPS 2000 conceptual design have been described. The experiments on the environmental effects, the high energy radiation and space debris/meteoroid, have shown that the capability of power generation is estimated to keep more than 90 % of the initial level during 10 years. For the high voltage system of SPS 2000, typical data have been obtained for the mass loss, contamination, and power loss at the surface. The development and operation of the SPS 2000 functional model have provided design guidelines for the cabling network and the electrical interface between the power generator and microwave transmitter. The trial manufacture and experiment of the automatic truss builder have demonstrated the feasibility of automatic construction in space and cancellation of the gravity effect for ground testing. The results obtained in the series of engineering research are reflected in the conceptual design of SPS 2000 to create a highly realistic SPS model.

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