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Space Solar Power Satellite Technology Development at the Glenn Research Center—An Overview

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Space Solar Power Satellite Technology Development at the Glenn Research Center—An Overview

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Abstract—NASA Glenn Research Center (GRC), is participating in the Space Solar Power Exploratory Research and Technology program (SERT) for the development of a solar power satellite concept [Fig 1]. The aim of the program is to provide electrical power to Earth by converting the Sun's energy and beaming it to the surface.

This paper will give an overall view of the technologies being pursued at GRC including thin-film photovoltaics, solar dynamic power systems, space environmental effects, power management and distribution, and electric propulsion. The developmental path not only provides solutions to gigawatt sized space power systems for the future, but provides synergistic opportunities for contemporary space power architectures. More details of Space Solar Power can be found by reading the references sited in this paper and by connecting to the web site http://moonbase.msfc.nasa.gov/ and accessing the "Space Solar Power" section "Public Access" area.

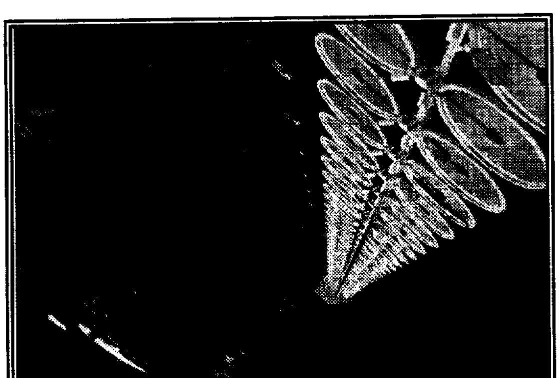

Fig 1.—Concept of a SSP satellite—
Pat Rawlings, SAIC.

1. Introduction

The global demand for energy is increasing due to population growth at the same time that growing energy use is driven by the equally strong economic growth in many developing nations. Electricity continues to be the most rapidly growing form of energy consumption as reported in the U.S. Dept. of Energy report "International Energy Outlook" projections through 2020 [Fig.2]. http://www.eia.doe.gov/oiaf/ieo98/elec.html

In the IEO98 reference case, the worldwide demand for electrical power will rise from 12 billion kilowatt-hours in 1995 to almost 22 billion kilowatt-hours in 2020. To supply this need, 403 gigawatts of new generating capacity will be required by 2020 to meet growing demand and to replace retiring units.

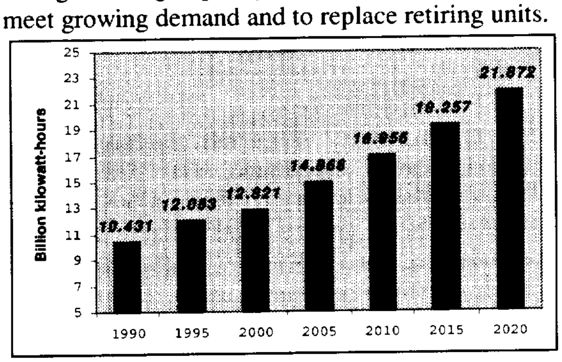

Fig 2.—Worldwide Demand for Electrical Energy.

2. Space Solar Power - an "old" idea

Producing electricity from sunlight in space is not new. It has already been done by hundreds of operating satellites. The major difference would be that SSP would capture much more energy and beam it down to earth for our use.

Capturing the sun's rays in space has distinct advantages since there is no loss of microwave energy passing through the Earth's atmosphere and there is no contribution to the global warming problem by the addition of CO_2 during the production stage. In addition, the orbit of rotation can be selected such that sunlight is received by the satellite ~96% of the time.

Credit must be given to Dr. Peter Glaser, formerly of NASA, who first described the concept in 1968. This idea would place square miles of solar collectors in high GeoSynchronous Orbit (GSO is an orbit 36,000 km above the equator), collect the sun's power, convert it to microwave energy and beam it to large receiving antennas (rectennas) on earth for distribution on the national electric power grid. Since then, a number of studies have been conducted to investigate the feasibility of SSP as a commercial enterprise.

Background

DOE and NASA examined the Solar Power Satellite (SPS) concept extensively in the 1970s. During 1995-1997, NASA conducted a "Fresh Look" study of space solar power (SSP) concepts and technologies [Ref 1]. Following review by the NASA Administrator, and with the Congress, a follow-on activity was initiated. NASA Marshall Space Flight Center led an inter-Center and external team in the "1998 Space Solar Power Concept Definition Study (CDS)", which identified commercially viable SSP concepts which are credible, with technical and programmatic risks identified. In FY 1999, NASA conducted the Space Solar Power Exploratory Research and Technology (SERT) Program.

3. Concept Description

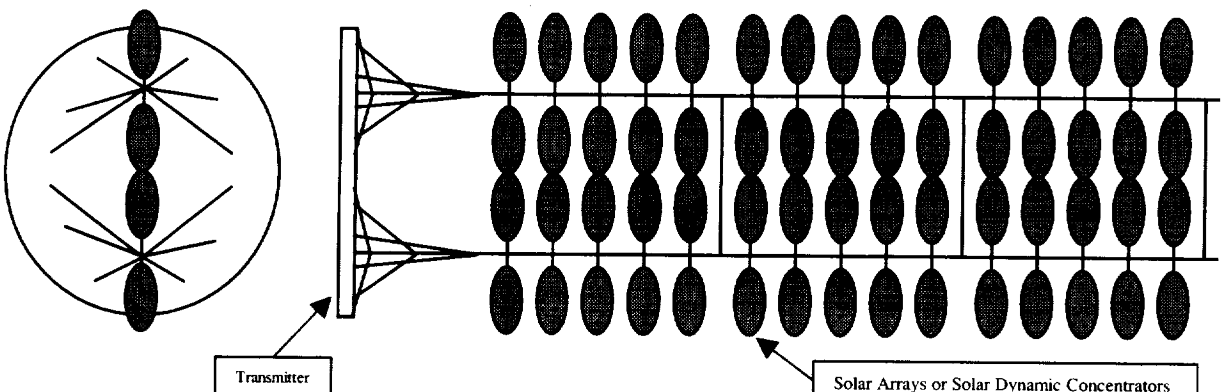

Fig 3.—"Sun-Tower" Design.

Of the many spacecraft platform configurations being considered, the "Sun Tower" concept [Fig 3] is typical. It is a constellation of medium-scale, gravity gradient-stabilized, RF-transmitting space solar power systems [Fig 4]. Each satellite resembles a large, Earth-pointing sunflower in which the face of the flower is the transmitter array, and the 'leaves' on the stalk are solar collectors. The concept is assumed to transmit at 5.8 GHz from an initial operational orbit of 36000 km, geosynchronous, at a transmitted power level of about 1.2 GW RF. Total beam-steering capability is 60 degrees (+/-30 degrees). A single transmitting 'element' is therefore projected to be a hexagonal surface approximately 5 cm in diameter. These elements are pre-integrated into 'sub assemblies' for final assembly on orbit. For 1.2 GW transmitted RF power, the transmitter array is an "element and subassembly-tiled plane" which is essentially an oval, approximately 500 x 1000 meters. Sunlight-to-electrical power conversion must be modular and deployable in "units" with a net 1 MW electrical output (approximately). Technology options include an inflatable photovoltaic gossamer structure with concentrator lenses or solar dynamic engines to convert solar flux into electricity. Selection of the power operating system is subject to on-going trade studies. These collection systems are presumed to be always sun facing (with the system in a sun-synchronous orbit) and to be attached regularly in pairs along the length of a structural/power-transmitting tether to the backplane of the transmitter array. Heat rejection for power conversion and conditioning systems is assumed to be modular and integrated with the power conversion systems.

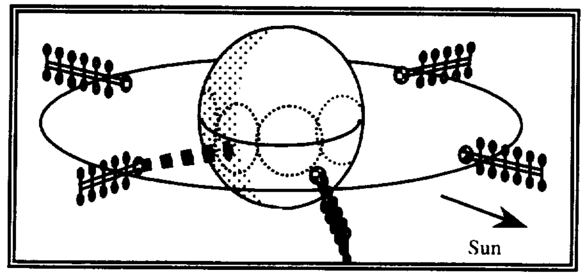

Fig 4.—Sun Tower Orbit.

4. SERT Program

The SERT program was initiated by John Mankins of NASA HQ [Ref 2] and lead by Joe Howell of MSFC in March 1999 for the purpose of the following:

- Perform design studies of selected flight demonstration concepts;
- Evaluate studies of the general feasibility, design, and requirements.
- Create conceptual designs of subsystems that make use of advanced SSP technologies to benefit future space or terrestrial applications.
- Formulate a preliminary plan of action for the United States (working with international partners) to undertake an aggressive technology initiative.
- Construct technology development and demonstration roadmaps for critical SSP elements.

Implementation of the SERT program involved the integration and use of uniquely developed expertise at the various NASA centers throughout the country.

GRC -Solar Power Generation, Power Management & Distribution Electric Propulsion, and System Modeling,

MSFC - Program lead, ETO Transportation, In-Space Transportation, Tether Systems, Environmental Studies and Space Transportation Applications of SSP Technologies

ARC - Robotic and Autonomous Systems, Environmental Studies, Life Sciences Research

GSFC - Advanced space platform systems

JPL - Environmental Studies, Space Science Applications of SSP Technologies

JSC - Robotics (assembly, maintenance, etc.), Exploration Applications of SSP Technologies

LaRC - Structural Concepts, Materials, Space Environments

KSC - ETO Transport Launch Operations

For purposes of coordinating activities among the various teams, "Model System Categories" (MSCs) were defined. These range from relatively small-scale demonstrations to very large-scale operational SPS systems. In broad terms, each MSC represents a notional projection of what may be achievable in a particular future timeframe in terms of scale, technology, missions, etc. Four are described here.

- MSC 1 year 2005, approx. power level 100 kW, Free-flyer, demo-scale commercial space option
- MSC 2 year 2010, 100 kWPlanetary Surface System; demo-scale; space exploration option
- MSC 3 year 2015, ~10 MW Free-flyer; WPT, SPG and PMAD, Transportation; Large demo; HEDS ("solar clipper") option
- MSC 4 year 2020, 1 GW Free-flyer; Full-scale solar power satellite commercial space option

The program activities were focused through a set of tasks consisting of R&D investments, guided by systems studies with the maximum degree of leveraging of existing resources inside and outside NASA. There were three complementary elements:

- Systems Studies and Analysis
- SSP research & Technology
- SSP Technology Demonstrations

The GRC in Cleveland Ohio supported each of these areas.

5. Solar Power Generation

Thin-film Solar Cells

Solar cells of the current generation are heavy, expensive and hard to deploy considering the enormous numbers needed for SSP. Thin film cells represent one viable option for the future [Fig 5]. They hold promise for low mass, low cost, and high production capability by depositing special materials in very thin (microns) layers on rolled substrates similar to newspaper printing. In addition, they are flexible, which lends themselves for deposition on lightweight deployable / inflatable structures needed for packaging of extremely large arrays in launch vehicles. Unfortunately, the materials considered for these structures (i.e. kapton), do not have the high temperature properties needed to allow cell growth deposition.

Accordingly, Al Hepp of GRC has pursued development of a low temperature growth process for thin film solar cells [Refs 3 and 4].

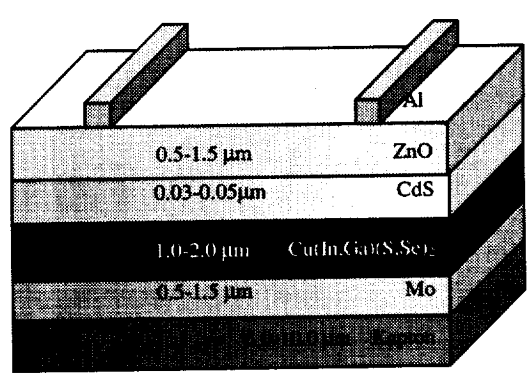

Figure 5.—Material Layers of Thin-Film PV Solar Cell.

Milestones/Products

7/99 Optimized single-source precursor for CuInS2.
8/99 Achieved low-temperature deposition of ZnO, CdS, Cu(In,Ga)(S,Se)2.
9/99 Synthesized thin-film heterojunction solar cells on a flexible substrate.
11/99 Installed and tested precursor analysis. and characterization tool.
1/00 Produced 5% efficient prototype small-area cells.
6/00 Produced 10% efficient prototype on kapton

Very High Efficiency Photovoltaics

In addition to the above activities, which may be characterized as development efforts, there are two long-range research investigations into higher efficiency solar cells being undertaken. The first involves utilization of specific ranges of sunlight focused through a prism onto cells tailored to the wavelengths and thusly is termed "Rainbow". The other takes advantage of an ensemble of quantum dots in a size range that will capture most of the radiation from the terrestrial and space solar energy spectrum. Such a collection of different size quantum dots can be regarded as an array of semiconductors that are individually size tuned for optimal absorption at their bandgaps throughout the solar energy emission spectrum. If successful, theoretical efficiencies of 50 - 70% are possible.

High Voltage Issues for SSP -- Arc-mitigation techniques for photovoltaic arrays

The current state-of-the-art voltage level for photovoltaic arrays is 160v used on the International Space Station. It is estimated that the arrays for a SSP platform would have to operate at 1000v or higher. At these higher levels it is known that self-destructive arcing occurs [Fig 6]. Design and manufacturing techniques to prevent such damage are in the process of development by Dale Ferguson of GRC [Refs 5 and 6]. In order to utilize existing facilities and equipment, initial development is being performed at the 300-volt level.

Fig. 6.—Example of Self Destructive Arcing.

Laboratory testing and computer and analytical modeling have been used to evaluate several arc-mitigation techniques. Samples incorporating the most promising techniques have been acquired and tested to achieve a "rad" hard high voltage array (>300v) which will not arc in GEO environments.

Milestones and Products

- 9/99 Spectra obtained of a specific material—anodized aluminum arc (arc initiation studies)
- 11/99 Sample designs (with mitigation techniques to reach 300 V) completed
- 4/00 A "High Voltage Solar Array and Arc Mitigation Guidelines" report completed.
- 6/00 Understanding of arc initiation by micrometeoroids and debris is in process through high-impact tests.

Solar Dynamics

Solar Dynamic (SD) power systems concentrate sunlight into a receiver where the energy is transferred to a heat engine for conversion to electrical power. Brayton heat engines utilize a turbine, compressor, and rotary alternator to produce power using an inert gas working fluid. Lee Mason of GRC [Ref 7] has devised a system for use on a SSP shown in the schematic diagram of Figure 7.

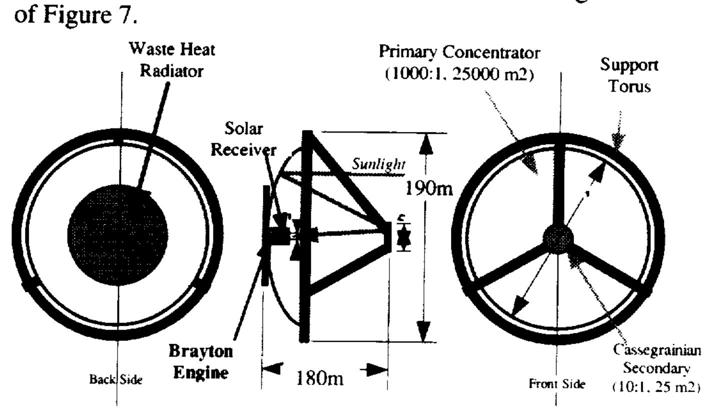

Fig. 7.—Solar Dynamic System.

A system study was performed comparing the cost, mass, and technical risk of various Solar Power Generation (SPG) options for a solar dynamic system. For a 10MW SD system, the results show that at high power levels this technology is competitive with projected photovoltaic systems.

Testing was performed by Wayne Wong of GRC [Refs. 8 and 9] to determine the characterization of high temperature secondary concentrator refractive materials in a typical SD environment. Existing analytical and design tools were utilized to design a prototypical refractive secondary concentrator with a concentration ratio of 10:1. This, combined with a primary concentrator of 1000:1 will result in a very high 10,000:1 ratio which permits a reasonable pointing accuracy requirement of 0.1°. The performance of the sapphire concentrator was evaluated via an on-sun calorimeter test. The tests were conducted in the NASA GRC Solar-thermal/Vacuum Facility

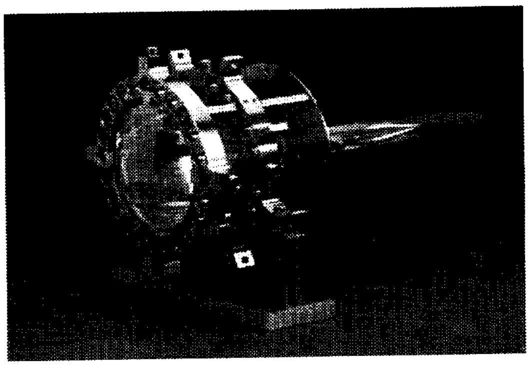

Fig. 8.—Secondary Concentrator.

6. Power Management & Distribution

Power Management and Distribution (PMAD) is a very broad topic covering the entire power system between the source or power generator and the load, which in this case is the transmitter. A number of trade studies are being conducted by Jim Dolce of GRC, to determine what technologies make the most sense for a system of this size and scope. However, as one can easily surmise, all of the switches, conductors and converters are immense compared to any spacecraft known to date. Many questions are being investigated such as AC vs DC power distribution, grounding schemes, standard current conductors vs high and/or low temperature super-conductors, system voltage level vs environmental arcing mitigation strategies (also discussed under section 4), types of power converters and system protection devices, and high temperature radiation resistant circuit elements. Results of the system studies will remain underway for the duration of the program and will be published by the Systems Analysis and Technology Working Group (SATWG) at the culmination of the FY 98-99 SERT program. Meanwhile, certain technologies have been selected for immediate pursuit taking advantage, wherever possible, of the element of leverage into other government technology investigations:

Superconductors

Dr. Jim Powell, Plus Ultra Technologies, Inc., is continuing to study the implementation of super-conductors on the SSP. His initial studies show that transmission voltages could be reduced to levels easily mitigating arcing effects (<300 Volts). Complications provided by superconductors include the need for cryogenic cooling systems including armor to protect against micrometeoroid impact and penetration; and specialized connectors at segment, switch and power converter interfaces. An interesting artifact presented by Dr. Powell is the tremendous magnetic repulsion force (on the order of 3.5 MT/meter radially at 1 Megamp) which could be used for deployment and to present an extremely rigid structure, a scheme of interest to the Structures Team.

Silicon Carbide Power Electronics

Silicon Carbide technologies leading to power devices are currently being pursued via in-house research under Phil Neudeck [Ref 10] and a contract with Dr.Krishna Shenai, the University of Illinois at Chicago. This activity leverages heavily against work already being funded by DARPA to develop defect free and thick SiC epitaxial substrates. Although substrates can now be manufactured with acceptably small numbers of micropipe defects, the next goal is to reduce other defects that can harm the performance of power devices. An objective of this project is to demonstrate the high temperature operation of high-voltage SiC diodes, MOSFETs, and JFETs in a DC-DC power converter and develop models for predicting the influence of defects on device performance.

Milestones/Products

- 8/99 Demonstrate a 2 kilowatt SiC thyristor operating at 300C; Breadboard 300 volt switch
- 10/99 Breadboard 600 volt switch
- 12/99 Complete dynamic characterization of SiC thyristors
- 3/00 Complete converter topology vs device study with a breadboard converter prototype; Test 600 volt, 100 amp solid body fuse

The technology investment plan uses a time phased methodology to develop hardware and systems starting at 600 volts, followed by 10,000 volts, and ending with 100,000 volts to spread development and testing infrastructure costs over the life of the program rather than incur them at the start. In addition, the 600-volt technology has an immediate application for the Advanced Space Transportation Program (ASTP).

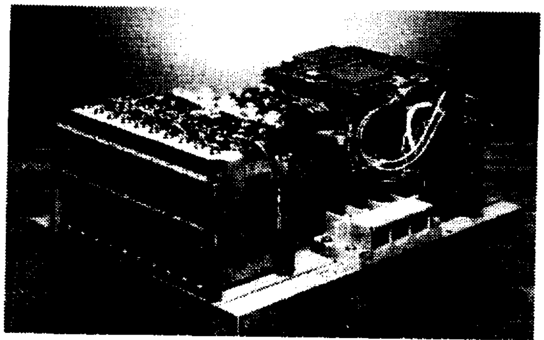

Fig 9.—600 volt switch.

7. Electric Propulsion

Electric propulsion is an enabling technology for SSP LEO to GEO orbit transfer and station keeping. Studies conducted by Steve Olsen of GRC [Refs 11 and 12], show that advanced electric propulsion can provide a factor of 5 increase in payload for Earth to orbit transfer when compared to storable biprop and cryogenic biprop thrusters; payload mass that normally would be manifested for propellant. Com-parisons made to gridded ion thrusters, magnetoplasmadynamic and pulsed inductive thrusters [Fig 10] show that Hall thruster technology provides overall greater benefits. Those benefits include quicker trip times, good power density, a good contemporary technology base and good flight history that translates into acceptance by the commercial industry.

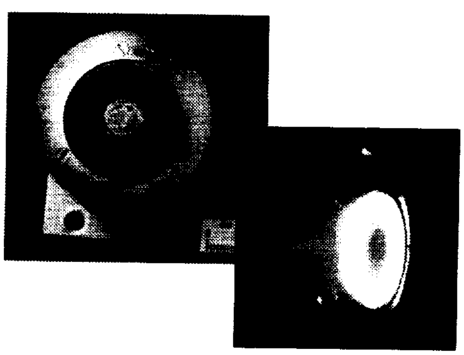

Fig 10.—2-Stage Hall Thruster.

Advances such as direct power drive from the solar arrays and single and/or two-stage operation will allow payloads of 13 to 15 metric tons per 20 metric tons to LEO from launch as opposed to only 2 metric tons using chemical propulsion. Trip times from LEO to GEO are also reasonable at 120 to 230 days depending on performance setpoint [Fig 11]. The proposed Hall thruster system consists of four 50 kW krypton Hall thrusters directly driven from a 200 kW solar array. The propulsion system will be included on each SSP segment. Performance required from the Hall thruster units is 2000 to 3500 sec ISP and overall system efficiency of 52% to 57%. Due to the amount of fuel mass required to place the entire system into geostationary orbit, propellants besides xenon (normally used), such as krypton and noble gas mixtures are proposed. Additional work on alternative fuels will eventually need to be conducted

Milestones/Products

- 3/00 Test state-of-art high power Hall thruster
- 8/00 Evaluate 1st generation domestic 50kW breadboard engine in GRC high power Hall thruster test bed along with high current cathode development

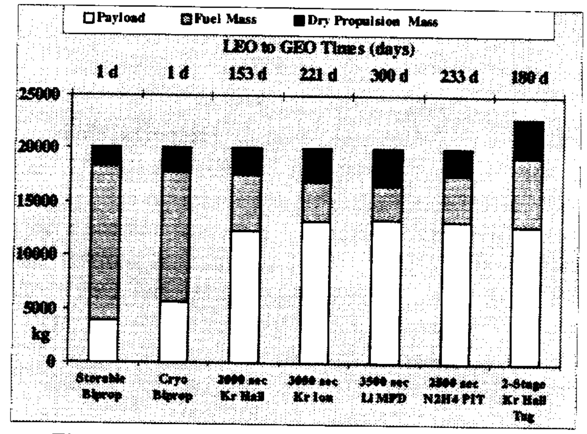

Fig 11.—Masses and trip times for on-board propulsion options.

8. Conclusion

The increasing global energy demand is likely to continue for many decades. New power plants of all sizes will be built. However, the environmental impact of those plants and their impact on world energy supplies and geopolitical relationships can be problematic. Renewable energy is a compelling approach—both philosophically and in engineering terms. However, many renewable energy sources are limited in their ability to affordably provide the base load power required for global industrial development and prosperity, because of inherent land and water requirements.

Based on the recently completed Concept Definition Study, space solar power concepts may be ready to reenter the discussion. Certainly, solar power satellites should no longer be envisioned as requiring unimaginably large initial investments in fixed infrastructure before the emplacement of productive power plants can begin. Moreover, space solar power systems appear to possess many significant environmental advantages when compared to alternative approaches. The economic viability of such systems depends, of course, on many factors and the successful development of various new technologies—not least of which is the availability of exceptionally low cost access to space. However, the same can be said of many other advanced power technologies options. Space solar power may well emerge as a serious candidate among the options for meeting the energy demands of the 21st century

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