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Before the

Subcommittee on Space and Aeronautics
Committee on Science
U.S. House of Representatives

September 7, 2000

Mr. Chairman and Members of the Subcommittee,

I am pleased to have the opportunity to speak with you today concerning the topic of space solar power. During the past 5 years, NASA has examined the viability of large-scale space solar power (SSP) systems through a series of studies and preliminary technology research activities.

Very briefly, our results and findings to date can be summarized as follows:

- Large-scale SSP is a very complex integrated system of systems that requires numerous significant advances in current technology and capabilities
- A technology roadmap has been developed that lays out potential paths for achieving all needed advances – albeit over several decades
- Ongoing and recent technology advances have narrowed many of the technology gaps, but major technical, regulatory and conceptual hurdles continue to exist
- This NASA-funded SSP activity has made significant contributions to narrowing the technology gap (e.g. a three-fold reduction in mass at the solar array level over current state-of-the-art)
- An incremental and evolutionary approach to developing needed technologies and systems has been defined, with significant and broadly applicable advances with each increment
- The technologies and systems needed for SPS have highly leveraged applicability to needs in space science, robotic and human exploration, and the development of space
- The decades-long time frame for SPS technology development is consistent with the time frame during which new space transportation systems, commercial space markets, etc. could advance
- Power relay concepts appear technical viable using space solar power technologies, but may depend upon higher frequency power beaming

- The question of ultimate large-scale solar power satellite economic viability remains open.

Now I would like to get into some detail on each of these points and provide you with more information on NASA's ongoing research and development efforts. First, I would like to summarize the historical context of these efforts

Background

The idea of using sunlight to power spacecraft – particularly using photovoltaic (PV) arrays – dates to before the earliest days of the "space age" more than forty years ago. However, the concept of a large "solar power satellite" (SPS) that would be placed in geostationary Earth orbit (GEO) to collect sunlight, use it to generate an electromagnetic beam and transmit energy to the Earth was invented by a Czech-American, Dr. Peter Glaser of Arthur D. Little, in 1968. NASA and industry studied this concept into the early 1970s. During the same period, a number of exploration applications of large space power systems were identified – most notably the idea of using large space power to electrically propel vehicles from Earth to Mars. Due to the limitations of PV array technology at the time, however, these exploration studies tended to anticipate the use of space nuclear power systems rather than space solar power systems.

During 1976-1980, a major study of the SPS concept—spurred in part by the energy crisis of the times—was conducted by the then-newly-created U.S. Department of Energy (DOE), with the support of NASA. This effort, funded at a level of more than $50M in FY 2000 dollars, resulted in a wide range of useful research reports on many topics – but is best remembered for the "1979 SPS Reference System". The central feature of this concept was the creation of a large-scale power infrastructure in space, consisting of about 60 SPS, each delivering 5 gigawatts (GW) of base load power to the U.S. national grid (for a total delivered power of about 300 GW). However, connections to interim applications of space solar power were tenuous and the space infrastructure requirements were projected to be significant. The "cost-to-first-power" of the 1979 Reference System was expected to be more than $275 billion (in FY 2000 dollars). As a result of the huge price tag, lack of evolutionary approach, and the subsiding energy crisis in 1980-1981, all significant U.S. SPS efforts were terminated. In a 1980 NRC report on SSP, it recommended that the concept be re-assessed in about 10 years, subsequent to additional technology development and maturation.

During the 1980s, technology development in range of relevant areas continued – particularly in the area of solar power generation of broad applicability in commercial and scientific spacecraft. Also during the 1980s and early 1990s, low level international interest in the SPS concept emerged, including wireless power transmission flight experiments in Japan and other activities in Europe and Canada. In the U.S., activities were largely limited to generic research and to modest systems studies of potential applications of SSP technology to space science and exploration missions.

Recent NASA Efforts

In 1995, NASA undertook a reconsideration of the challenge of large-scale SSP systems. This effort, the "Fresh Look Study," sought to determine whether or not technology advances since the 1970s might enable new SSP systems concepts that were more viable—both technically and programmatically. The Fresh Look Study reviewed, revised or created some 29 SSP system and architecture concepts (emphasizing gigawatt class power for terrestrial markets). The general finding of this preliminary assessment was that there did appear to be a number of promising SSP systems concepts – distinct from those of the 1970s – that were enabled by recent or projected advances in relevant technologies. The Fresh Look Study also concluded that the prospects for power from space were – although still exceptionally challenging – more viable than they had been at the end of the DOE-NASA study in 1980.

During 1998, NASA conducted the SSP Concept Definition Study following the suggestion of the House Science Committee. This study was a focused 1-year effort that tested the results of the previous Fresh Look Study. The 1998 effort engaged a wide range of technologists from outside the Agency as well as within. In addition, NASA funded an independent economic and market analysis study, led by Dr. Molly Macauley of the Washington D.C.-based non-profit, Resources For the Future. The 1998 SSP Concept Definition Study found that SSP did appear more viable than in the past—results that largely validated the findings of the "Fresh Look Study," while invalidating some of the specific systems/architecture concepts that had emerged from the earlier effort. A principal product of the effort was the definition of a family of strategic research and technology (R&T) road maps for the possible development of SSP technologies.

Beginning in spring, 1999, and continuing through fall, 2000, NASA has been conducting the Space Solar Power (SSP) Exploratory Research and Technology (SERT) Program. This program, which will be completed later this fall, has further defined new systems concepts (including space applications), better defined the technical challenges involved in SSP, and initiated a wide range of competitively-selected and in-house R&T activities to test the validity of SSP strategic research and technology road maps.

The SERT Program, led by the NASA Marshall Space Flight Center has involved technologists from across the U.S. Participants include eight NASA Field Centers, as well as a number of external organizations through a diverse family of some 31 individual, competitively-procured projects created as a result of a 1999 NASA Research Announcement. Funded by NASA at a level of about $22M (approximately $15M in FY1999 and $7M in FY2000), SERT Program participants have included large and small companies, other Agencies and laboratories, universities, and several international organizations. Attachment 1 provides a summary list of SERT Program participating organizations. Overall participation by private industry has been substantial, with significant technical contributions being made by small business.

SSP Strategic Research and Technology Challenges and Progress

Systems Integration and Analysis. Effectively integrating information on scores of technology options across a dozen systems concepts has been a major challenge for the SERT Program. A broadly constituted Systems Integration Working Group has operated as the "heart" of the effort to meet this challenge. SERT systems integration and analysis activities have provided a framework for modeling various SSP systems concepts and included formulation of a progressive family of "model system concept" options as stepping-stones to large-scale SSP systems. An integrated model has been used to capture technology metrics and systems data concerning these several Model System Concept options and to place these into an overall economic framework. As a part of these efforts, a series of technical interchange meetings have been held during the course of the SERT Program, involving both systems analysts and technologists from inside and outside the Agency (see Appendix 1). One important result of the SERT systems integration and analysis effort has been the identification of several new approaches that apply low-energy, solid state lasers for wireless power transmission as an alternative to microwave approaches.

Solar Power Generation. During the 1995-1997 SSP Fresh Look Study, solar power generation was identified as a major technology research challenge. The SERT Program has pursued several innovative solar power generation approaches at the component and breadboard level that suggest this challenge can be met successfully. Component level progress from previous technology efforts has been focused and extended—resulting in several "firsts". For example, a linear Fresnel lens-based concentrator solar array has been demonstrated at the panel level in a test chamber with sunlight to voltage conversion efficiency almost 30% (about 375 watts/m^2) and a power per unit mass of greater than 375 watts/kilogram. In application, this SERT-demonstrated technology should be capable of achieving about 170 watts/kilogram – a better than three-fold advance on the current state-of-the-art solar array (which is about 45 watts/kilogram). Other areas have also been pursued, including multiple-bandgap thin film solar arrays, the so-called "rainbow" concentrator array, testing of a high voltage solar panel, and others.

Wireless Power Transmission. A variety of approaches to safe and efficient wireless power transmission have been investigated, including microwave phased arrays using magnetrons or solid state transmitters, as well as visible light transmission using solid state lasers and associated optics. To assure beam safety, "center-of-beam" power intensities have been limited to the general range of 100-200 watts/m^2 during the SERT Program for both microwave and visible light transmission (corresponding to between 10% and 20% of the intensity of normal noon time summer sunlight). Good progress has been made and no show-stoppers have been identified – although resolution of potential spectrum management issues associated with power beaming applications with appropriate U.S. and international organizations continues to be an important issue. The SERT Program has conducted an important first-of-a-kind demonstration in a test chamber of the use of microwave power beaming to drive an innovative woven Carbon-filament "sail" such as might someday be used to send robotic probes beyond our solar system.

Power Management and Distribution. Power management and distribution continues to be a major challenge for large-scale SSP systems. A major feature of the 1979 SPS Reference System was the presumption of very high solar array voltages (e.g., 40,000 volts) that would largely eliminate the requirement for massive power management for the system. The findings of the SERT Program suggest that this feature is not technically feasible for reasons of interactions with the space environment at these voltages and that lower voltages must be used. However, a great disparity exists between the cost of terrestrial voltage converters (about $0.20 per watt) compared to voltage converters in space (about $20 per watt). Studies are continuing to better understand the reasons for these differences and to formulate affordable and effective power management and distribution concepts for large-scale SSP systems. Also during the SERT Program, an option identified during the SSP Fresh Look Study—the use of superconducting power cabling at lower voltages—has resurfaced as one potential solution.

Structural Concepts and Materials. Affordable and very low mass structures are critical. Several innovative types of inflatable structural concepts have been researched as a part of the SERT Program, including a simple truss structure that is deployed by an inflated column. The integrated consideration of structural concepts and materials as well as SSP system design concepts has been found to be critical to effective progress as a result of the SERT program.

Thermal Materials and Management. Specific requirements for thermal materials and management have been determined to be highly concept dependent. In general, however, simpler deployment and higher temperature operations have been identified as important advances for various SSP systems (e.g., to reject heat from a microwave transmitter array). The SERT Program has made good advances in these areas with the development of an inflatable radiator concept using the chemical Toluene as a working fluid that could operate at a higher temperature (and hence with lower mass) than typical radiators.

Robotic Assembly, Maintenance and Servicing. The SERT Team found that the definition of preliminary SSP design concepts was vital in order to guide and focus developments in robotic assembly, maintenance and servicing. Of particular importance is early and coordinated definition of structural systems, interconnections and packaging. Several examples of innovative robotic "physiology" have been advanced as a result of the SERT program, including a miniature walking manipulator system, the anthropomorphic "robo-naut", a highly-flexible "snake" robot, and the new "Skyworker" mobile crane system concept.

Platform Systems. The SERT team has determined that essentially all advanced space platform systems technologies – including areas such as central data systems, avionics, etc. – will be advanced effectively through ongoing technology development efforts inside NASA, other US Government Agencies and industry. These programs include the ongoing NASA Cross-Enterprise Technology Program, the New Millennium Program, developments by the Defense Advanced Research Projects Agency and others.

Ground Systems. The interface of a beamed power receiver into a local power grid is an important overall aspect of an operational SPS system in the far term. Several low-level efforts have been implemented as part of the SERT Program to examine these issues. For example, a small case study was conducted examining the possible insertion of SPS power into the local power market place in Vera Cruz, Mexico. Another small effort has examined possible requirements for energy storage systems in conjunction with terrestrial market use of power from space.

Earth-to-Orbit (ETO) Transportation. Affordable, large-scale Earth-to-orbit transportation is a key capability for any substantial future activities relating to the exploration and development of space, including SSP systems. How low these costs must be depends entirely on the type of future missions and markets that are contemplated. SERT results suggest that recurring launch costs in the range of $100-$200 per kilogram of payload to low-Earth orbit are needed if SPS are to be economically viable. The current National Space Transportation Policy as implemented in NASA's Integrated Space Transportation Plan and Space Launch Initiative, provide a solid strategic and programmatic foundation for achieving launch costs in the range that is projected to be required during the coming 20 years.

In-Space Transportation. Affordable and timely in-space transportation beyond low-Earth orbit is of equal importance to ETO transport for many exploration and development of space goals, such as SSP. There remains a significant challenge in achieving very low-cost, highly reliable and timely in-space transportation beyond low-Earth orbit. SERT results suggest that recurring in-space transportation costs in the range of $100-$200 per kilogram of payload from low-Earth orbit to geostationary-Earth orbit are needed if SPS delivering power to terrestrial markets are to be economically viable. Several approaches continue to be examined as part of the Integrated Space Transportation Plan and the NASA Aerospace Base technology program.

Environmental and Safety Factors. A variety of environmental considerations and safety-related factors continue to be examined by NASA's SERT Program team. Topics under consideration include the possible effects of SSP system launch, space environmental impacts on SSP systems, and possible effects of wireless power transmission from space-to-ground on the Earth's environment. Although there is no evidence of negative environmental impacts from either microwave or visible light approaches to wireless power transmission at the power intensities considered by NASA's recent SSP studies, environmental and safety factors continue to be given careful consideration.

The possible environmental benefits of power from space are also being assessed, vis-a-vis the long-term environmental impacts of other, non-solar base-load power generation approaches, such as fossil fuels. In this vein, NASA team members participated in a special workshop during summer 1999 at the third United Nations Conference on the Peaceful Uses and Exploration of Outer Space (UNISPACE-III) to discuss the possibility of power from space as a future global energy option.

Space Applications Studies. A wide range of important potential space applications of SSP technology and systems concepts has been identified in three important areas: space science, space exploration and commercial development of space.

In the area of space science, an immediate application emerges in the form of higher power, lower cost and longer lived solar-electric power and propulsion systems. Many ambitious potential space science mission goals – such as landing on Jupiter's moon, Europa, a rendezvous with Saturn's rings, and others – depend upon high-performance propulsion such as could be achieved with solar-electric power and propulsion systems in the 50-kilowatts-and-higher power class. In the very far term, the ambitious goal of sending robotic probes beyond our solar system – first to the Kuiper belt, then to the Oort Cloud and beyond – will only be viable if extraordinarily low-cost and high-performance propulsion systems can be developed. SSP technologies and system concepts—and in particular, wireless power transmissions--offer one important path to such future missions.

SSP technologies are also broadly applicable to a number of system and architecture options for the future human and robotic exploration of space. For example, advanced solar arrays could be used in low-Earth orbit for evolutionary upgrades of the International Space Station – reducing array sizes and reducing re-boost propellant logistics costs. Solar-electric power and propulsion systems in the 100-300 kilowatts class may be used to affordably transfer exploration systems of 10-50 metric tons from low-Earth orbit to other locations of interest in the Earth's neighborhood – such as the Earth-Moon or Sun-Earth Libration points. Systems in the 1-megawatt class have been identified as a important option for transporting large payloads of 100 metric tons or more from low-Earth orbit to high-Earth orbit as one phase in a non-nuclear approach to human interplanetary missions. In addition, systems in the 1-10megawatt class may enable reusable interplanetary transports for cargo (and perhaps people). Once at a target destination – for example in Areosynchronous Mars orbit – such interplanetary transports could also serve as "mini-SPS", beaming abundant and affordable power down from space to provide non-nuclear energy to planetary or lunar surface outposts and operations.

Finally, in prospective commercial development of space markets, several potential applications have been identified. For example, geostationary Earth-orbit-based communications satellites have grown substantially in size during the past 20 years. The most recently deployed systems have approached a level of 20 kilowatts operating power. Preliminary studies suggest that – based on current market projections –during the next 10-20 years, "mega-communications satellites" in the 100-kilowatt class, based in geostationary Earth orbit, could become economically viable. SERT studies suggest that the barriers to such growth – principally related to launch vehicle size constraints – might be surmounted through the application of SSP technologies and concepts. Several other potential commercial space applications have also been identified, ranging from the concept of a "power plug in space" – i.e., a space-to-space power beaming system – to on-board power for future commercial space business parks.

Market Analyses and Economic Studies. Building on results of the 1998 SSP Concept Definition Study independent analysis of prospective terrestrial markets for power from space, the SERT Program is supporting an analysis of potential space markets for an SSP-derived "power plug in space". (Preliminary results from these analyses have been promising.) In addition, a workshop is planned that will consider further the challenges and prospects for SSP technology-enabled "mega-communications satellites" during the coming years.

Strategic R&T Road Map for Space Solar Power

An important planned product of the SERT Program will be an update of the strategic research and technology (R&T) road maps for space solar power that were originally formulated in November 1998. The following is a brief synopsis of that updated strategic R&T road map.

By the 2006-2007 time frame, advances in a number of technology areas important to abundant and affordable power in space could be achieved. During this timeframe, early demonstrations of wireless power transmission could be implemented. For example, a 100-kilometer range power relay demonstration could test wireless power transmission using a reflector suspended from an airship at 20-km altitude. Similarly, initial technology flight experiments could be conducted, for example at the International Space Station, to test revolutionary solar power generation and management technologies.

In addition, the technologies for an initial in-space SSP platform bus in the 100-kilowatt power class could be demonstrated at the system breadboard level. Such a demonstration would be consistent with large-scale geostationary communications satellites, solar electric power and propulsion systems for space science and near-Earth exploration applications, and continuing commercial development of low-Earth orbit, including demonstration of wireless power transmission from central power stations to other spacecraft. Also, during this time frame, the technology could be demonstrated for a planetary or Lunar surface "wireless power grid" in the 5-20-kilowattpower class (a.k.a., "MSC-2", as explained in Footnote 5.). This prospective demonstration would be consistent with exploration and/or initial commercial development in these locations.

By the 2011-2012 time frame, these initial advances could be leveraged to demonstrate the technology for a 1-megawatt class SSP platform bus, including validation of space-to-space and space-to-surface wireless power transmission. As noted previously, once at a target destination such a system could also serve as a "mini-SPS", beaming power from space to provide non-nuclear energy to planetary or lunar surface outposts and operations. Substantial demonstrations of power beaming from ground-to-space might also be achievable during the next decade (for example, to transmit power to an electric orbital transfer vehicle operating in Earth orbit).

Within the next 15-20 years, the technologies and breadboard systems for an intermediate-scale in-space SSP platform in the 10-megawatt power class could be developed and demonstrated. This class of concept (a.k.a., MSC-3) is consistent with ambitious applications in space exploration, such as interplanetary transportation systems, or in space development, such as sub-scale SPS pilot plants or full-scale in-space power plants. If successfully developed, these technologies could find broad applicability on Earth and in space. For example, ultra-high efficiency solar arrays and energy storage systems (developed in cooperation with the Department of Energy and other Agencies) would find diverse uses terrestrially and in commercial and scientific space applications. Both power beaming from space-to-ground for planetary or lunar surface power (described above) as well as power relay concepts – beaming power from Earth-to-space-to-Earth – could be demonstrated in this timeframe.

By the 2025-2035 time frame, the technologies needed for a full-scale in-space SSP platform producing 1-2 gigawatts of power could be demonstrated at the system prototype level. This concept (characterized as "Model System Concept-4" in the SERT Program) is consistent with an initial solar power satellite "pilot plant" that could demonstrate base load power transmission for terrestrial markets. This time frame is consistent with current plans for the development of very-low-cost Earth-to-orbit space transportation systems (e.g., in the $100-$200 per kilogram recurring cost range).

Ultimately, in the post-2050 time frame, very large-scale, in-space SSP platforms in the greater than 10-gigawatt power class could become viable (a.k.a., "MSC-5"). Such systems might find application in providing very-large-scale power to terrestrial markets, for the industrial development of space resources, or in powering robotic probes to near-interstellar space during the latter portion of this century.

Overall, the updated strategic R&T road map for SSP suggests that significant advances could be achieved during the next several decades – with important applications in space science, exploration, commercial space and on Earth. Major technical, regulatory and conceptual hurdles continue to exist, nevertheless. Systematically, the technologies that might enable future large-scale SSP systems are sufficiently challenging that they will require several decades to mature. However, this is approximately the same time frame during which new space transportation systems, commercial space markets, etc. could advance. The question of ultimate SPS economics remains open, with key issues now appearing to revolve around the prospects for achieving "terrestrial-class" production costs for large space systems.

Technical hurdles have been better explored and characterized as a result of the SERT Program, and important progress has been achieved. Nevertheless, significant and highly challenging research and technology development must be conducted successfully across a wide range of areas in order for affordable and abundant space solar power to be realized.

The research and development cost of the strategic research and technology road map outlined above would be substantial. These activities have not been prioritized against other NASA programs and funding is not included in NASA’s FY 2001 budget request.

Power Relay Options

Many of the space solar power concepts and technologies that have been examined could be applied to the development of power relay systems and/or infrastructures. However, achieving economic viability continues to appear challenging. Early terrestrial demonstrations, as mentioned previously, (e.g., over a 100-kilometer distance) using microwave wireless power transmission may have applicability in specific regions. However, using current concepts for a geostationary Earth-orbit-based relay, a microwave wireless power transmission system is expected to be either too large on the ground (or in space) to be viable. On the other hand, it appears possible that ground-space-ground power relays may be viable in the case of visible light transmission concepts, which would be smaller in size than microwave systems. Investigation of these options – which are also useful for a number of ground-to-space and space-to-space power-beaming applications – continues.

Near-Term Plans

At this time, the National Research Council, Aeronautics and Space Engineering Board is initiating an independent assessment of the space solar power strategic research and technology road maps. The first meeting of the National Research Council SSP research and technology road map review committee will be held during the week of September 11, 2000.

During the next three months, NASA plans to complete the SERT Program as several research and technology efforts initiated in the past year are concluded. Consideration of a wide range of prospective applications of SSP technologies and concepts to human/robotic exploration and development of space missions and markets is continuing. Detailed systems analysis and sensitivity studies are being completed, including integrated economic analyses of various new SSP systems concepts for potential applications for power in space and for terrestrial markets. A final report from the SERT Program should be available early in calendar year 2001.

APPENDIX 1

Space Solar Power (SSP) Exploratory Research and Technology (SERT) Program Participating Organizations (Selected Examples)

NASA Field Centers

- Ames Research Center
- Glenn Research Center
- Goddard Space Flight Center
- Jet Propulsion Laboratory
- Johnson Space Center
- Kennedy Space Center
- Langley Research Center
- Marshall Space Flight Center (SERT Program Lead Center)

Other Government Agencies/Laboratories

- DOE/National Renewable Energy Laboratory (NREL)
- National Research Council (NRC) / Aeronautics and Space Engineering Board (ASEB)
- National Science Foundation
- USN/Naval Research Laboratory
- USAF/USAF Academy

US Companies

- Alpha Technology, Inc.
- bd Systems
- Bennett Optical Research, Inc.
- Bekey Designs, Inc.
- Boeing
- ENTECH
- Essential Research
- Futron Corporation
- George Kusic Company
- Global Solar Energy, LLC
- Hamilton Sundstrand
- Hughes SpectroLab
- ILC Dover
- L'Garde
- Lockheed Martin Corporation
- MagLev2000
- Microwave Sciences, Inc.
- PCS, Inc.
- Power Systems Consultants, Inc.
- PRIMEX Aerospace
- Programmed Composites, Inc.
- Rockwell Science Center
- SAIC
- Strategic Insight, Inc.
- Sverdrup
- TECSTAR
- Texaco
- TRW
- United Applied Technologies
- United Solar Systems Corporation

US Universities

- Arizona State University
- Auburn University
- Carnegie Mellon University
- Cornell University

- Fisk University
- Georgia Institute of Technology
- Howard University
- Rochester Institute of Technology
- Tennessee Technological University
- Texas A&M University
- University of Alabama, Huntsville
- University of California at Davis
- University of California at San Diego
- University of Cincinnati
- University of Colorado
- University of Houston
- University of Illinois, Chicago
- University of Louisiana, Lafayette
- University of Texas, Austin
- University of Southern California

Non-Profit Organizations

- Aerospace Corporation
- American Institute of Aeronautics and Astronautics (AIAA)
- Ohio Aerospace Institute (OAI)
- Resources For The Future (RFF)
- Space Frontier Foundation (SFF)
- University Space Research Association (USRA)
- USRA/Lunar and Planetary Institute (LPI)
- X-Prize Foundation

International Organizations

- CNES (French Space Agency)
- CSA (Canadian Space Agency)
- ESA (European Space Agency)
- Kobe University
- NASDA (National Space Development Agency of Japan)