SERT TIM 2 Executive Summary

The University of Alabama in Huntsville
Propulsion Research Center
UAH 2000-01

Space Solar Power Exploratory Research &
Technology (SERT) Technical Interchange Meeting 2

SERT TIM 2
Executive Summary

Submitted to

Joe Howell, COTR
Grant No. NAS8-H-32056D
Mail Code FD02
Marshall Space Flight Center, AL 35812

Prepared by

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and

Dr. Clark W. Hawk
Propulsion Research Center
The University of Alabama in Huntsville
March 17, 2000
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAT</td>
<td>Architectural Assessment Tool</td>
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<tr>
<td>ASAP</td>
<td>As Soon as Possible</td>
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<tr>
<td>ACT</td>
<td>Advanced Communication Technology</td>
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<td>ACRE</td>
<td>Advanced Chemical Rocket Engine</td>
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<tr>
<td>AIAA</td>
<td>American Institute of Astronautics and Aeronautics</td>
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<tr>
<td>amp/cm²</td>
<td>Amperes per square centimeter</td>
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<tr>
<td>AU</td>
<td>Astronomical Unit (Distance from the Earth to the Sun)</td>
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<tr>
<td>ARC</td>
<td>Ames Research Center</td>
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<tr>
<td>B</td>
<td>Billion</td>
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<tr>
<td>BOL</td>
<td>Beginning Of Life</td>
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<tr>
<td>CDS</td>
<td>Conception Definition Study</td>
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<tr>
<td>C&amp;DH</td>
<td>Control and Data Handling</td>
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<td>CMG</td>
<td>Control Moment Gyro</td>
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<tr>
<td>COTS</td>
<td>Commercial-Off-The-Shelf</td>
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<tr>
<td>COTR</td>
<td>Contracting Officers Technical Representative</td>
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<td>CSA</td>
<td>Civil Service</td>
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<td>CSA</td>
<td>Canadian Space Agency</td>
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<td>DASA</td>
<td>German Aerospace</td>
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<td>dB</td>
<td>Decibels</td>
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<tr>
<td>DC/RF</td>
<td>Direct Current Radiation Frequency</td>
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<td>DOE</td>
<td>Department of Energy</td>
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<td>DOS</td>
<td>Department of State</td>
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<tr>
<td>EMF</td>
<td>Electromagnetic Frequency</td>
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<td>EMI</td>
<td>Electromagnetic Interference</td>
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<td>EP</td>
<td>Electrical Power</td>
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<td>EPRI</td>
<td>Electrical Power Research Institute</td>
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<td>EOL</td>
<td>End of Life</td>
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<td>ESA</td>
<td>European Space Agency</td>
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<tr>
<td>ETO</td>
<td>Earth to Orbit</td>
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<tr>
<td>EVA</td>
<td>Extra Vehicle Activity</td>
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<td>Ex ante</td>
<td>Preexisting</td>
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<tr>
<td>FMCA</td>
<td>Functional Mission Concept and Architecture</td>
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<td>FR</td>
<td>Frequency Range</td>
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<tr>
<td>FY</td>
<td>Fiscal Year</td>
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<tr>
<td>GEO</td>
<td>Geostationary Earth Orbit</td>
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<tr>
<td>GHz</td>
<td>Giga Hertz</td>
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<tr>
<td>GN&amp;C</td>
<td>Guidance, Navigation, and Control</td>
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<tr>
<td>GPS</td>
<td>Global Positioning Satellite</td>
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<td>GRC</td>
<td>Glenn Research Center</td>
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<td>GRC</td>
<td>General Research Corp</td>
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<tr>
<td>GW</td>
<td>Giga watts</td>
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<tr>
<td>HALO</td>
<td>Earth-Sun L-2 Orbit (1.5 Million km from Earth—see figure page 58)</td>
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<tr>
<td>HEDS</td>
<td>Human Exploration &amp; Development of Space</td>
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<tr>
<td>HET</td>
<td>Hall Effect Thruster</td>
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<td>HFET</td>
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<tr>
<td>HRST</td>
<td>Highly Reusable Space Transportation</td>
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<tr>
<td>HTS</td>
<td>High Temperature Superconductor</td>
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<tr>
<td>IAAM</td>
<td>Integrated Architecture Assessment Model</td>
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<td>IPT</td>
<td>Integrated Product Team</td>
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</table>
**SERT TIM 2 Executive Summary**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ER</td>
<td>Infrared IRR (Internal Rate of Return)</td>
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<tr>
<td>ISP</td>
<td>In-Space Propulsion</td>
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<td>s</td>
<td>Specific Impulse</td>
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<td>ISS</td>
<td>International Space Station</td>
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<td>ITAR</td>
<td>International Trade Administration Regulations</td>
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<td>ITU</td>
<td>International Telecommunication Union</td>
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<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
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<td>JSC</td>
<td>Johnson Space Center</td>
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<tr>
<td>kg</td>
<td>Kilograms</td>
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<td>KSC</td>
<td>Kennedy Space Center</td>
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<tr>
<td>km</td>
<td>Kilometers</td>
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<tr>
<td>kW</td>
<td>Kilowatts</td>
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<tr>
<td>kWt</td>
<td>Kilowatts Electrical</td>
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<tr>
<td>kWh</td>
<td>Kilowatt Hours</td>
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<tr>
<td>LaRC</td>
<td>Langley Research Center</td>
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<tr>
<td>LCC</td>
<td>Life Cycle Cost</td>
</tr>
<tr>
<td>LDC</td>
<td>Less Developed Countries</td>
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<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
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<tr>
<td>LMBG</td>
<td>Multiple Band Gap</td>
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<tr>
<td>MEO</td>
<td>Medium Earth Orbit</td>
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<tr>
<td>mm</td>
<td>Millimeter</td>
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<tr>
<td>MPD</td>
<td>Magnetoplasmodynamic</td>
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<td>MSC</td>
<td>Model System Category</td>
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<tr>
<td>MSFC</td>
<td>Marshall Space Flight Center</td>
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<tr>
<td>MWe</td>
<td>Megawatt Electrical</td>
</tr>
<tr>
<td>N/A</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>NASDA</td>
<td>National Aeronautics and Space Development Agency (Japanese Space Agency)</td>
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<tr>
<td>NRA</td>
<td>NASA Research Announcement</td>
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<tr>
<td>NRC</td>
<td>National Research Council</td>
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<tr>
<td>OMV</td>
<td>Orbital Maneuvering Vehicle</td>
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<tr>
<td>OTA</td>
<td>Office of Technology Assessment—US Congress now defunct</td>
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<tr>
<td>PMAD</td>
<td>Power Management and Distribution</td>
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<td>PRC</td>
<td>Propulsion Research Center</td>
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<td>POD</td>
<td>Point of Departure</td>
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<tr>
<td>POP</td>
<td>Perpendicular to Orbit Plane</td>
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<tr>
<td>POST</td>
<td>Trajectory Model</td>
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<tr>
<td>PV</td>
<td>Photovoltaic</td>
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<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
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<tr>
<td>RF</td>
<td>Radio Frequency</td>
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<tr>
<td>RLV</td>
<td>Reusable Launch Vehicle</td>
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<td>RMS</td>
<td>Root Mean Square</td>
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<td>R&amp;T-WG</td>
<td>Research &amp; Technology Working Group</td>
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<tr>
<td>R&amp;T</td>
<td>Research and Technology</td>
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<tr>
<td>RTG</td>
<td>Radioisotope Thermal Generator</td>
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<tr>
<td>SAIC</td>
<td>Science Applications International Corp</td>
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<td>SAIM</td>
<td>System Analysis Integration &amp; Maintenance</td>
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<tr>
<td>SD/PV</td>
<td>Solar Dynamic versus Photovoltaic (power generation)</td>
</tr>
<tr>
<td>SE&amp;I</td>
<td>Systems Engineering and Integration</td>
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<tr>
<td>SEPS</td>
<td>Solar Electric Propulsion System</td>
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<tr>
<td>SERT</td>
<td>Space Solar Power Exploratory Research &amp; Technology</td>
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<tr>
<td>Si</td>
<td>Silicon</td>
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<tr>
<td>SIC</td>
<td>Silicon Carbide</td>
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<tr>
<td>SI-WG</td>
<td>Systems Integration Working Group</td>
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<tr>
<td>SMSM</td>
<td>Self-Mobile Space Manipulator</td>
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<tr>
<td>SMSA</td>
<td>Standard Metropolitan Statistical Area</td>
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</table>

4 March 21, 2000
SERT TIM 2 Executive Summary

SOTA  State-Of-The Art
SMOC  Senior Management Oversight Committee
SPS   Space Power Satellite
SSM   Space Segment Model
SSP   Solar Space Power
STUS  Space Transportation Upper Stage
TBD   To Be Determined
TIM   Technical Interchange Meeting
TPS   Thermal Protection System
TRL   Technology Readiness Level
OOMV  Tug Orbit to Orbit Maneuvering Vehicle
UAH   University of Alabama in Huntsville
UNESCO United Nations
US    United States
V-ac  Volts alternating current
V-de  Volts direct current
V/m  Volts per meter
VRC  Virtual Research Center
Vs.  Versus
WHO  World Health Organization
W/m²  Watts per square meter
W/kg  Watts per kilogram
WPT  Wireless Power Transmission
Abstract

The University of Alabama in Huntsville’s (UAH) Propulsion Research Center hosted the Space Solar Power Exploratory Research & Technology (SERT) Technical Interchange Meeting (TIM) 2 in Huntsville, Alabama December 7-10, 1999 with 126 people in attendance.

The SERT program includes both "in-house" and competitively procured activities, which are being implemented through a portfolio of focused R&D investments—with the maximum leveraging of existing resources inside and outside NASA, and guided by these system studies.

Axel Roth, Director of the Flight Projects Directorate NASA MSFC, welcomed the SERT TIM 2 participants and challenged them to develop the necessary technologies and demonstrations that will lead to Space Solar Power (SSP) International implementation.

Joe Howell, NASA MSFC, reiterated the SERT TIM 2 objectives:

1) Refining and modeling systems approaches for the utilization of SSP concepts and technologies, ranging from the near-term (e.g., for space science, exploration and commercial space applications) to the far-term (e.g., SSP for terrestrial markets), including systems concepts, architectures, technology, infrastructure (e.g., transportation), and economics.

2) Conducting technology research, development and demonstration activities to produce "proof-of-concept" validation of critical SSP elements for both the nearer and farther-term applications.

3) Initiating partnerships Nationally and Internationally that could be expanded, as appropriate, to pursue later SSP technology and applications (e.g., space science, colonization, etc.).

Day one began with the NASA Centers presenting their SERT activities summary since SERT TIM 1 and wound up with a presentation by Masahiro Mori, NASDA, titled "NASDA In-house Study for SSP Demonstration for the Near-Term.

Day two began with the SERT Systems Studies and Analysis reports resulting from NRA 8-23 followed by presentations of SERT Technology Demonstrations reports resulting from NRA 8-23. Day two closed with John Mankins presentation on "Technology Roadmapping" and the delivery of the charge to the Work Breakout Sessions.

Day three began with the eleven Work Breakout Session which was the major function of this TIM 2 and day three ended with reports by the Chairs of the eleven Work Breakdown Sessions.

Day four began with the six Integrated Product Team (IPT) meetings and ended with closing plenary panel sessions.

Background and Introduction

The University of Alabama in Huntsville’s (UAH) Propulsion Research Center hosted the Space Solar Power Exploratory Research & Technology (SERT) Technical Interchange Meeting (TIM) 2 in Huntsville, Alabama December 7-10, 1999 with 126 people in attendance.

Dr. Kaya demonstrated Wireless Power Transmission at the beginning of SERTS TIM 2, which was the same demonstration as at the July 1959 TAF.

Axel Roth, Director of the Flight Projects Directorate at NASA MSFC, welcomed the SERT TIM 2 participants and challenged them to develop the necessary technologies and demonstrations that will lead to Space Solar Power (SSP) International implementation.
Day 1

SERT TIM 2 Objectives

Joe Howell, NASA MSFC, provided the following SERT TIM 2 objectives:

1) Refining and modeling systems approaches for the utilization of SSP concepts and technologies, ranging from the near-term (e.g., for space science, exploration and commercial space applications) to the far-term (e.g., SSP for terrestrial markets), including systems concepts, architectures, technology, infrastructure (e.g., transportation), and economics.

2) Conducting technology research, development and demonstration activities to produce "proof-of-concept" validation of critical SSP elements for both the nearer and farther-term applications.

3) Initiating partnerships Nationally and Internationally that could be expanded, as appropriate, to pursue later SSP technology and applications (e.g., space science, colonization, etc.).

SERT Program Overview

John Mankins, NASA Headquarters, presented the SERT Program Overview:

During 1999-2000, NASA is conducting a SERT program which will conduct preliminary studies and strategic technology research and development across a wide range of areas to enable the future development of large multi-megawatt SSP systems and wireless power transmission (WPT) for government and commercial markets (in-space and terrestrial).

This program will allow informed decisions regarding future SSP and related R&D investment by both NASA management and prospective external partners. In addition, the SERT program will guide further definition of SSP and related technology roadmaps including performance objectives, resources and schedules; including "multi-purpose" commercial missions, Earth and Space science, exploration, and other government applications, such as national defense.

The SERT program currently includes both "in-house" and competitively procured activities, which are being implemented through a portfolio of focused R&D investments—with the maximum leveraging of existing resources inside and outside NASA, and guided by system studies. The Portfolio consists of three complementary elements:

1) System Studies and Analysis
2) SSP Research and Technology
3) SSP Technology Demonstrations

SERT Integration, Analysis and Modeling

Connie Carrington, NASA MSFC, and Harvey Feingold, SAIC, presented the status of the "SERT Integration, Analysis, and Modeling" which included the following:

Overview of Systems Integration Working Group (SIWG)
Points of Departure (POD)
Alternate Concepts (PODs)
Modeling/Analysis Status and Selected Results
Identified Issues and Technology Needs
Accomplishments and Status
NASA Centers Activities Summary

Next the NASA Centers presented their SERT activities summary since SERT TIM 1:

Ames Research Center (ARC) presentation was made by Hans Thomas, who used a computer generated presentation and he did not leave an electronic copy nor a hard copy. All efforts to contact Hans Thomas have been unsuccessful to date; but these efforts to contact Hans Thomas will continue until his material is in hand!

Sheila Bailey made the Glenn Research Center (GRC) presentation and she included:

- Power Management and Distribution Activities
- SiC High Power and High Temperature Electronics Research

The Status report by Professor Krishna Shenia, University of Illinois at Chicago, was moved from Day 2 to Day 1 due to a previous travel commitment. The title of Professor Shenia’s presentation was “Defect Engineering and Reliability Study of SiC High Power Devices.”

Steve Kant made titled “SSP Platform Systems” the Goddard Space Flight Center (GSFC) presentation.

The following people made the Jet Propulsion Laboratory (JPL) presentations:

- Wireless Power Transmission (WPT) by Richard Dickinson
- Inflatable Structures Technology Development by R. Freeland
- Space Power Robotics by Gregory Hickey
- Science Applications by Henry Harris (Actually Presented by Richard Dickinson)

The following people made the Johnson Space Center (JSC) presentations:

- Microwave System Analysis for the 5.8 GHz Wireless Power by Dickey Arndt
- Robotic Assembly, Maintenance, and Servicing by Chris Culbert (Do not have a copy of Chris’s presentation as of to date).

The Kennedy Space Center (KSC) did not participate in SERT TIM 2, but we included Carey McCleskey’s SERT Technology Mini-Workshop conducted at NASA Headquarters November 9-10, 1999.

The Langley Research Center (LaRC) presentation was given by Chris Moore and was titled “Structures, Materials, Controls, and Thermal Management.”

The following people gave the Marshall Space Flight Center (MSFC) presentations:

- Ground Power Systems by George Kusic
- Space Transportation Infrastructure by John Olds
- Functional Mission Concepts & Architecture by Lanny Taliaferro
- Environmental Safety and Health by Marvin Goldman
- Space Solar Power Applications by David Smithener

An Economic Assessment of Satellite Solar Power Technology as a Source of Electricity for Space Based Activities

John Fini, Strategic Insight, presented “An Economic Assessment of Satellite Solar Power Technology as a Source of Electricity for Space Based Activities.”
NASDA In-house Study on SSP Demonstration for the Near-Term

Day 1 wound up with a presentation by Masahiro Mori, NASDA, titled “NASDA In-house Study on SSP Demonstration for the Near-Term.

Day 2

SERT Systems Studies and Analysis reports resulting from NRA 8-23

Day 2 began with the following SERT Systems Studies and Analysis reports resulting from NRA 8-23:

1) System Studies and Analysis by Jay Penn, Aerospace Corp.
2) Systems Studies and Analysis by Seth Potter, Boeing
3) Power With Out Wires (POWOW) by Henry Brandhorst, Auburn University
4) Advance Design Concepts for SSP by Geoffrey Landis, Ohio Aerospace Institute
5) Application of SSP Technology to Space Transportation for HEDS Missions by Steve Hoffman, SAIC.
6) Market Analysis & External Factors by Carie Mullins, Futron
7) Assessment, Outreach, and Future Research of Environmental and Safety Factors Related to SSP by Margo Deckard, Space Frontier Foundation
8) AIAA Assessment: (1) International Cooperation, (2) Applicability to Terrestrial, Civil Space, and Military Space Programs, and (3) Technology by Jerry Grey, AIAA
9) Economic and Market Analysis to Ascertain the Potential Impact of SSP on a Specific Locale by John Fini, Strategic Insight

SERT Research & Technologies resulting from NRA 8-23

Day 2 continued with presentations of SERT Research & Technologies resulting from NRA 8-23:

1) Advanced High-Voltage Solar Array Design Guidelines from Soar Tile Testing by Brian Reed, Boeing
2) Multi Band Gap High Efficiency Converter (Rainbow) by C. William King, Essential Research
3) Effects of Hypervelocity Impacts on High Voltage Solar Arrays by Henry Brandhorst, Auburn University
4) Low Mass Phased Array Antenna for Wireless Power Transmission by James McSpadden, Boeing Phantom Works
5) Development of Inflatable Space Frame by Dilip Darooka, ILC Dover, Inc.
6) Innovative Deployable Radiator for Space Solar Power Systems by Roger Giellis
7) Fabrication of Very High Efficiency 5.8 GHz Power Amplifiers using AlGaN HFETs on SiC Substrates for Wireless Power Transmission by Gerry Sullivan, Rockwell Science Center
8) High-Voltage, Modular, DC-to-DC Converter by David Fox, Hamilton Sundstrand Aerospace
9) Rectenna Development for Wireless Power Transmission by Bernd Strassner, Texas A&M University
10) 5.8 GHz Circular Polarized Dual Rhombic Loop Antenna for Space Power Applications by Bernd Strassner, Texas A&M University
SERT Technology Demonstrations resulting from NRA 8-23

This was followed by presentations of SERT Technology Demonstrations resulting from NRA 8-23:

1) Wireless Power Transmission for Science Applications by James Benford, Microwave Sciences, Inc.
2) Ultralightweight Fresnel Lens Solar Concentrators for Space Power by Mark O’Neill, ENTECH, Inc.
3) Skyworker Assembly, Inspection, and Maintenance of SSP Facilities by Red Whittaker, Carnegie Mellon University
4) Space Solar Power Technology Demonstration for Lunar Polar Applications by Mark Henley, Boeing

“Technology Roadmapping” and delivering the charge to the Work Breakout Sessions

Day 2 was closed with John Mankins presenting “Technology Roadmapping” and delivering the charge to the Work Breakout Sessions which begin tomorrow (day 3). John Mankins presented the following technology challenges for SSP:

- Solar Power Generation
- Wireless Power Transmission
- PMAD
- Structural Concepts, Materials, and Dynamics
- Thermal Materials and Thermal Management
- Controls and Operations cannot be worked as yet
- In-Space Transportation, propellant availability and cost are unresolved issues

John Mankins presented the following Model System Concept 1 (MSC 1) fundamental decision points assuming that MSC 1 POD is launched for testing in the 6-7 year timeframe:

Near-term decision points
- Mission and capabilities
- Delta V
- Payload
- On-board utilities
- Solar power generation
  - PV versus Solar Dynamic (current recommendation is PV of some sort)

Mid-term decision points (in the next 2-3 years)
- System configuration
  - Single spacecraft or mother/daughter
  - Program/system cost goals/constraints
- Solar array type
  - Planar
  - Thin film
  - Concentrator (e.g., POD 1.1 or POD 1.2)
- Wireless power transmission
  - Frequency?
  - If microwave
ERT TIM 2 Executive Summary

2.45 GHz; ± 8 GHz? Other RF
If visible
IR; green; other?
Power management and distribution: Operational voltage
300 V or higher?
Energy storage on board?
Structural concept, materials and dynamics
Mix of structural concepts
Integrated, erectable, deployable, inflatable
Platform systems
Autonomy and operations approach: Traditional or intelligent systems
Earth-to-orbit transportation and infrastructure
One launch or several
One element or several with in space assembly
In-space transportation and infrastructure
Space transportation R&T goals?
On-board propulsion (primary? and/or an experimental package?)
Robotic assembly, maintenance and servicing
Assembly approach
Use of international Space Station or not?
Astronaut compatibility?

Later decision points (prior to CDR)
System configuration
Lifetime
Number of MSC 1 units and/or flights
Wireless power transmission
Microwave or visible?
If microwave
Solid state
Magnetrons
Klystrons
If visible
Lamps and reflectors (spot light approach)
Lasers?
Power management and distribution
If energy storage, what type?
Structural concepts, materials and dynamics
GN&C/attitude control design (e.g., momentum wheels? Station-keeping?)
Robotic Assembly, maintenance and servicing
Resident robots or not? Roles?

John Mankins also presented the above type of material for MSC 2 and MSC 3 as part of his charge to the eleven Work Breakout Session groups.

Day 3

Work Breakout Sessions meeting
Day 3 began with the eleven Work Breakout Sessions meeting in parallel until 3:00 pm

1) Systems Integration, Analysis, and Modeling co-chaired by Harvey Feingold and Connie Carrington.
2) Space Transportation and Infrastructure co-chaired by David Way and Mike Nicks
3) Wireless Power Transmission co-chaired by Richard Dickinson and Jim McSpadden
4) Platform Systems co-chaired by David Maynard and Seymour Kant
5) Robotics, Assembly, and Servicing co-chaired by Chris Culbert and Red Whittaker
6) Structures, Materials, Controls, and Thermal co-chaired by Chris Moore and Mike Gilbert
7) PMAD and Ground Power Systems co-chaired by Jim Dolce and Tom Lynch
8) Solar Power Generation co-chaired by Shelia Bailey and Nick Mardesick
9) Environmental and Safety Factors co-chaired by Marvin Goldman and Gayle Brown
10) International Issues and Opportunities co-chaired by Jerry Grey and Mark Henley
11) SSP Applications co-chaired by David Smitherman and Ken Cox

The Work Breakout Session reports
Day 3 ended with reports from the eleven Work Breakdown Session chairmen.

Work Breakout Session 1 Report
The Work Breakout Session report from group 1, Systems Integration, Analysis & Modeling, chaired by Connie Carrington and Harvey Feingold was as follows:

Objective:
Address the SIWG role in achieving the near to long term goals of SERT and SSP
Update and/or develop technology roadmapping products for the SERT systems function (WBS element B.12)

Session results:
New “Bubble Chart” created
Uses modified version of technology roadmap template
Chart driven by systems information that must be provided to RTWG’s, leading to required system studies and analyses.
Identified product is system level characterization and documentation of performance, cost, schedule and risk for defined candidate concepts.
Will be used to update last year’s Systems Integration “Bubble Charts”

Reviewed MSC 1 and MSC 3 decision points
Used to determine if the system level information or analyses would be needed to support the identified configuration or technology decisions.
Decision points can be used to develop system integration, analysis and tool development schedules analogous to technology development schedules that lead to MSC 4.
Cost of identified systems support still to be determined.

SIWG recommendation on MSC 1 fundamental decision points:
Near-term decision points during SERT
These decisions depend upon the particular mission scenario, and the mission and technology development objectives. An additional decision point should be added: If microwave, what frequency is suitable.

Mid-term decision points within the next 2-3 years:
Technology breakthroughs may determine solar array type. WPT decisions will depend on the mission scenario, as does the GN&C approach, on-board propulsion demo status, and the assembly approach. We recommend that the transmitter technology decision be made in mid-term, since it is a design driver for configuration and subsystems. We prefer 300 V solar arrays to direct drive SEP thrusters, with the capability to use DC-DC conversion only if lower S/S voltages (120 V) can be achieved. The decision about the need for on-board energy storage will depend upon the selected configuration and mission application. Structural technology decisions should be based on lifetime cost considerations, rather than mass (unless mass is a showstopper). The decision on traditional versus intelligent systems should be
based on the state-of-the-art at this time (off-the-shelf technology). We recommend scaling the mission to minimize the number of launches, and would use in-space assembly only if absolutely necessary. We do not recommend use of ISS or astronaut compatibility for assembly or maintenance.

Later decision points prior to CDR
Lifetime decisions should consider follow-on applications, perhaps commercial, after the primary mission objectives are met. Microwave vs. laser decisions will be greatly influenced by international policy. The transmitter technology decision should be made earlier, since it is a driver for many other decisions and will delay development if deferred. The decision on robotic demonstrations should also be made earlier, since it will impact configuration and mission design as well as operations, and the decision should depend on cost impacts to the program. Energy storage technology, in any, will depend on the selected mission scenario. GN&C design decisions should be made earlier, although sensor selection could be made at this latter period.

SIWG recommendations on MSC 3 fundamental decision points:

Near-term decision point within the next 4-5 years
These decisions should use knowledge determined from system studies and the MSC 1 program. We expect to have more insight into technology readiness levels, high voltage issues, and cost impacts of technology decisions. We will have a better understanding of the concepts, and insights into spin-off applications and commercial applicability. We hope to have a better understanding of projected launch rate capabilities, and insight into future launch infrastructures.

Mid-term within next 8-9 years and later pre-CDR decision points
These decisions should be made from lessons learned during the MSC 1 program. At the same time, they should address the critical technology needs from MSC 4 (with implications that many decisions on MSC 4 will have to be made concurrently). As in MSC 1, the technology selection for WPT should be made in mid-term rather than later, since it is a primary driver for many other subsystems, configurations, mission scenario, operations, kind regulations/safety requirements. Propulsion technologies should also be made in mid-term since it is a primary driver for MSC 3 configurations.

Work Breakout Session 2 Report
The Work Breakout Session report from group 2, Space Transportation and Infrastructure co-chaired by David Way and Mike Nix was as follows:

Charge from John Mankins
What data needs to be exchanged between teams?
What data will need to be provided in the near future?

Database, structured properly, could address needs
Data (documented with assumptions of what is included in estimates
Modeling results
Algorithm

Problem: Some teams do not have even basic information needed to start analysis
E.g., Structures team does not have loads

Concept proposers should take responsibility for providing schemes for assembly, component packaging, etc.

Assembly complexity vs ETO launch sizing (do we need to optimize?):

March 21, 2000
Currently assuming 20 to 40 MT per launch (5 lb/cubic foot) for transportation
Larger payload units could simplify assembly, but launch vehicle availability is a consideration
Transfer vehicle could become part of on-orbit structure
How fast does transportation need to provide materials? Driven by economic considerations
High flight rate is better, from transportation point-of-view
SIWG can provide number of launches per satellite (Current assumption is one SSP per year, but economic considerations will require a fleet of SSP satellites in perhaps a 5 year period of time)

Recommendations:
1) Get SIWG, transportation, structures, and robotics teams together ASAP to establish assembly philosophy baseline.
2) Decide ASAP on a LEO-GEO transportation philosophy baseline

Interactions between Systems and Transportations Teams:
Questions:
Do we need a depot for storing materials, tools, etc?
Does each package deliver itself to GEO (maybe higher, due to GEO station keeping considerations), or do we have tug deliver launch packages?
1) Deploy SSP arrays for LEO-GEO transportation (load on structures, degradation, PMAD, and high voltage considerations, etc.)
2) Transportation has traded expendables, reusable, and autonomous SEP approaches for transportation considerations only
3) Autonomous SEP approach appears favorable to transportation, but oversizes/overdesigns the on-orbit SSP configurations, structures, PMAD, etc.

Do we need LEO transportation nodes?
1) May need three/or orbit phasing considerations
2) Will need equatorial launch sites (build our own island?)

What is the lifetime of this system?

What transportation needs from SIWG?
- Density and dimensions of the payloads
- Launch rates
- Payload mass
- Assembly sequence
- Maintenance estimates

Information needed by Systems and transportation teams from the following other teams:
- Propulsion needs
  - Efficiency vs specific impulse vs propellant type
  - Specific mass of propulsion unit
- Solar array needs
  - Specific power with or without structure
  - Degradation (thermal and radiation)
  - Efficiencies (BOL and EOL, to aid in lifetime estimates)
- Robotics needs
  - Robotic capability for assembly
  - Reliability
  - Mass and cost including all support
  - Type of robots
- Wireless Power Transmission (solid state, magnetrons, klystrons, lasers)
  - Characteristics: Mass, configuration, performance with assumptions
  - Efficiency chains (space segment, atmospheric, ground rectenna)
- Platform Systems needs
  - Reliability data for all hardware (SSP satellites, robotics, ground systems)
  - Mass and cost data for platform systems with all assumptions
  - Communications and computers with all assumptions

14 March 21, 2000
Structures needs
- Mass estimate for solar arrays, transmitter array, reflectors/bearings, integrating structure
- Number of control actuators and sensors, mass, power, and cost estimates
- Assembly approach and deployment
- Packaging
  - Thermal mass, radiator configurations and locations
PMAD Needs
- Voltage levels, AC or DC, radiator temperatures
- Mass distribution of components for configuration, design recommendations
- PV to SEP switching information
SSP applications
- Missions
- Requirements
- Spin off applications that could impact systems and transportation decisions, such as lifetime
Environmental, safety and health needs
- Allowable power densities
- Stake holders such as exclusion zones and cost impacts

**Missing element in Work Breakout Sessions**

Operations
- Command and control (ground and space)
- Hierarchy, control sites, etc
- Role of government and private industry

**Work Breakout Session 3 Report**

Work Breakout Session group 3, Wireless Power Transmission, co-chaired by Richard Dickinson and Jim McSpadden report follows:

**Solid State needs**
- Two filters per element, many filters, large volume and large mass
- Establish EMC requirements
  - Currently large uncertainty
- More emphasis in laser systems area
- Effects of weather on system

MSC 1 R&T goals (launched in 6-7 years timeframe)
- Free flyer turnace
- Photon sail
  - Microwave and laser
  - Micrometeoroid arc
  - Beam turner mirror with slew tracking
  - Pilot beam steering
  - Safety beam de-phasing, etc.
- Two to three years more study of options for flight in 6-7 years

MSC 3 R&T goals (launched in 15 years timeframe)
- More and bigger MSC 2
- $300 Million

**Work Breakout Session 4 Report**

Work Breakout Session group 4, Platform Systems, co-chaired by David Maynard and Seymour Kant report:

**High level task functions**

**Reliability methodology**

**Goals**
- Identify methodologies and risk mitigation techniques to support mission assurance
Identify failure modes
Predict lifetimes of year 2020 configurations
Determine lifetimes of new technologies (MTBF > 40 years)
Derive maintenance requirements

Approach
Identify components reliability drivers
Include damage modes
Define functional relationships of subsystems
Characterize uncertainties
Apply probabilistic failure assessment methodologies

System monitoring and health management

Goals
Define satellite communications requirements
Incorporate high bandwidth telecommunications
Provide high capacity computing and data management
Determine communications subsystems
Evaluate command and control linkage (C&DH)
Accommodate robotic systems and operations

Approach
Identify operational and situational factors
Define communication frequency domains
Construct communications subsystems and apply to concept architectures
Configure hierarchical operations decisions tree
Provide “hot” change-out of components

Technology sharing

Goals
Capture advantages of current and emerging technologies
Employ technologies to minimize mass and cost ($100-$200/Kg)

Approach
Identify opportunities for utilizing technology
Development from other programs (NASA, other agencies and industry)
Map technology insertion opportunities
Facilitate synergisms of function and integration of operations
Consider alternative configurations for SSP components, subsystems and systems
Evaluate interfaces and identify areas requiring emphasis
Leverage on-going activities to minimize effort duplications
Focus on critical elements

Concept architectures, technology, integration and emerging R&T needs
Alternate architectures

Thermal analysis

Goals
Define heat rejection requirements
Evaluate heat transfer and radiator concepts

Approach
Define environmental and structural factors
Characterize SSP operation affecting thermal design (transient, load rejection, and shadowing)
Compare candidate thermal subsystems (efficiency, mass, maintenance, cost, etc)

Controls

Goals
Define control schemes for each MSC
Develop two-tier, ultra-high precision, extremely large flexible-surface control technology

Required surface flatness /40RMS/20RMS
Subarray tilt angle to within 2 arc -minutes RMS

March 21, 2000
SERT TIM 2 Executive Summary

Subarray size to 4MX4M
Applicable FR frequency to 500 M diameter range to 5.8 GHz
Applicable antenna size

Approach
- Identify performance criteria for concepts structures
- Define control approaches for various configurations
- Characterize multifunctional control for thrust/non-thrust modes, antenna, control, and solar array drives

Work Breakout Session 5 Report

Work Breakout Session Group 5, Robotics, Assembly, and Servicing, co-chaired by Chris Culbert and Red Whittaker report:

Robotics Technology Challenges
- Maintenance during continuous operations
- Environmental issues (robot operating conditions)
  - Micrometeorite impact, heat, RF and high voltage
- Stick to grasp anything (minimize scarring)
- Walk/manipulate softly
- Wiring, plumbing, and connecting work
- Coordinated operations with ground (levels of autonomy)
- Satellite to robot power and communications
- Robot state assessment
  - "Migrant" construction robots?
- Inspection approaches
  - Extended operations for autonomous robots (MTBF of robot)
- New and/or unique robot physiologies
- Simulation and studies
- Cooperative robots (coordinated activities)
- Material logistics

Interfacing challenges
- Facility mobility
  - Hardpoints, grapple, etc
  - Spots to minimize reaction forces
- Facilitate reaction control
- Facilitate maintenance
  - Design for robot only maintenance
    - Smart structure, self-diagnosis, and component changeout
- Clearance and accessibility (pathways)
- Location/marking/components bar-coding
- Communication and data (diagnostic facilities)
- Robotic infrastructure/toolshed, or warehouse

Robotics Technology Demonstration Opportunities
- General philosophy: Develop basic technologies through ground demos leading to specific capabilities demonstrated on-orbit in MSC 1 through MSC 4
- Ground demonstrations
  - Robotic component to inspect and calibrate a ground phased array structure
  - Robotic assembly of a ground based array structure
  - Grasping and manipulation tests (to develop grasp anything concepts)
  - Basic environmental studies (heat and EMF affects on robots)
  - Connectors and plumbing fittings handled by robot
  - Develop extended operations concepts and procedures
  - Autonomous robot docking, self-charging, and self-maintaining
Mobility approaches that lead to "walking softly"
Cooperative control of multiple robots: information sharing
Robot state awareness capabilities

Flight demonstrations
- Robotic assembly techniques
- Environmental tests
- Zero g mobility tests
- Automated rendezvous and docking

MSC 1
Well suited for inspection demonstration and simple maintenance
Onboard inspection system capable of traversing and inspection the vehicle and providing status information to the ground

MSC 3
Begin testing initial assembly concepts. Target areas such as plumbing connections, wiring routing, etc.
Demonstrate full-scale inspection and maintenance
Once core vehicle mission has been completed, use robotic maintenance to keep sub-elements functional over an extended period of time.

MSC 4
Demonstrate significant portion of robotic assembly capability, including coordination between multiple robots.
Refine inspection and maintenance approaches
Demonstrate long-term operational processes

Short Term Future Work
- Study to characterize robotics assembly and maintenance activities and visualize scenarios
- Integrated project to demonstrate cooperating robots performing assembly with visual service as needed
- Study "stick-to" approaches (Van de Waals forces, etc)
  - Non-goopy, sticks to glass, in vacuum, under thermal variance

Work Breakout Session 6 Report

Work Breakout Session group 6. Structures, Materials, Controls, and Thermal co-chaired by Chris Moore and Mike Gilbert report:

SSP Inflatable Structures Roadmap
- Develop a database of properties for rigidizable materials
- Characterize structural performance of inflatable columns
- Develop inflatable truss concept with scaling laws
- Build and test proof-of-concept trusses
- Integrate inflatable in prototype SSP structures

Logic diagram for multifunctional structures
- Structural/thermal load carrying panels with embedded heat pipes
- Structures/PMAD load carrying PMAD backbone
- Interconnects
  - Mechanical
  - Thermal
  - Electrical

Demos
- Structural/PMAD
- Thermal/WPT
- Antenna module
- Module assembly
- Thermal logic diagram
- High k materials
- TPS
Nanotubes
c-f
Loop heat pipes
  High temperature wicks
  Liquid metals
Advanced radiators
  Carbon-carbon, etc
  Deployable
  Heat pipe radiators
  Coatings
  Louvers
  Electrochromic
Demos
  Integrated heat pipe/radiator
  Central thermal bus
  Waste heat regen
    Heat engine
    TPV
    Thermoelectric cooling
Control
  Architecture
  Control algorithm
    Modeling
    Design
    Simulation
Sensors and actuators
  Attitude
  Structural sensing
  Metrology
  Momentum actuators
  Strain actuation
  Differential GPS
  Networking communications
  Avionics
  Inflatable structural control
Demos
  Integrated structural/attitude control
Technology needs for ABACUS concept
Structures
  Modular rigid abacus structure
  Lightweight deployable solar arrays
  Modular antenna structure
  Lightweight RF reflector
  Integrated structure/PMAD/thermal
  500 meter rotary bearing
  Autonomous modular assembly
  In-space manufacturing
Thermal management
  Lightweight deployable radiators
  High-temperature loop heat pipes
  Management of viable thermal loads
Control
  Distributed attitude control and structural control
  Pointing of RF reflector
  Shape control of RF reflector (1.3 mm accuracy)
  Solar array tracking
**Work Breakout Session 7 Report**

Work Breakout Session Group 7, PMAD and Ground Power Systems, co-chaired by Jim Dolce and Tom Lynch report:

PMAD design risks

- **100 KV operation**: Test prototype transfer and cable segment to validate design baseline
- **MTBF for 30 years**: Evaluate design for thermal/voltage stress and other factors
- **HV shielding**: Test design concept in ground test facility
- **Failure detection and recovery**: Analyze design concept for subsection failure by shorting. Can design withstand failure and stop propagation?
- **High temperature electronics**: Develop program parts list suitable for 200 °C to 300 °C operation. Find and characterize candidate parts. Predict MTTBF for these parts.

PMAD experiments

- **Cable usage at high current density**: Determine realistic SSP guidelines for individual wires in 0 K space environment. Can 160 A per square cm be exceeded?
- **Transfer-to-antenna heat load isolation**: Test thermal isolation capability of transformer to antenna with candidate insulation technique.
- **Protection switch for 25KA at 80 V**: Design and fabricate turnoff switch for 25 KA. Determine sharing, extendibility, power density for candidate design.
- **Transfer operation at 100 KV**: Design and fabricate 10 KW transformer for 100:1 ratio at 10 KHz and 1000 V peak drive. Test for corona, dielectric stress and leakage inductance.
- **Cable transient response**: Fabricate test model and measure step response with simulated drive and load. Develop analytic simulation model from test data.

Ground power issues

- **Utility grid acceptance of SSP power**: Less than 20 GW must transport DC power to remote grid. Federal government controlled.
- **Power drop out**: Site specific alternate power sources. Alternate SSP.
- **Grid fault, Rectenna operations**: What happens to Rectenna voltage and SWR?
- **Site selection**: Desert, volcano caldero.

Shielding

- **Protection of cable and distribution**

R&T needs:

- **High current breakers**
- **SiC power devices for high temperature**
- **AC cable drive**
- **AC rectifier/transformer**
- **LAN communication tower and antenna**
- **Superconductor**: Cryogenic in space with MTBF
- **High temperature passive components**

**Thermal management and recovery**

- **High power**: Near term 10-100 KW, midterm 1-10 MW, and far term 1-10 GW
- **Power density**: Near term 50 W/Kg, midterm > 100 W/Kg, and far term > 200 W/Kg
- **Low cost**: $1-$2
- **Long life**: MTBF > 20-30 years
- **HV switching**: 25,000 A at 1-5 KV
- **AC HV cable**: 100 KV at 10 KHz
- **HV solar array**: 6,000 V
- **Hot change of PMAD**

**PMAD Risks**

- **HV switching (1 KV-5 KV)**: Forced to new components
- **Mass (1 Kg/KW)**: Configuration dependent
- **High voltage (100 KV)**: Distribution and component risks
- **Lifetime (MTBF)**: Temperature and thermal transients affects life; forced to new materials
Work Breakout Session 8 Report


Size-Graded Self-Assembled Quantum Dot Solar Cell

Definition
A Si quantum dot cell utilizes the solar spectrum from 1.1 eV to 4.1 eV representing 80% of the solar emission spectrum.

Accomplishments
Size graded Si quantum dots have been fabricated and characterized.

Future
Optimize laser ablation parameters for sized graded dot arrays
Characterize optical properties to determine absorption range
Determine size distribution
Build prototype devices

Solar Dynamic Power Generation

Near term priorities
Evaluate PMAD impacts associated with SD (high voltage AC)
Address spacecraft integration issues: i.e., pointing and tracking, power distribution, attitude control (torque), and electric propulsion operations
Continue to develop/refine concentrator designs; i.e., largest mass, highest cost, greater uncertainty.

Proposed tasks
SD PMAD architecture design for SSP
In-house SD integration studies
Refractive Secondary concentrator development
Refractive Secondary hot test
Concentrator pointing test

Demonstrate overall concept feasibility: design, build (CY2000), and test (CY2001) a 100 watt, fully integrated SD power system with advanced concentrator and Stirling converter

Ultra Lightweight High Efficiency Thin Film Cell Growth Using Low Temperature Processing

Objective is to produce high power-to-weight ratio photovoltaic solar arrays on flexible substrates.

Task Descriptions
Develop and screen single source precursors
Optimize low-temperature thin-film deposition on flexible substrates
Demonstrate >5% AMO thin-film solar cells
Demonstrate pre-pilot production deposition of thin-film solar array materials
Keep related industries informed for eventual technology transfer

21 March 2000
SERT TIM 2 Executive Summary

Milestones/Products
- July 1999 Optimized single source precursor for CuInS2
- August 1999 Low-temperature deposition of ZnO, CdS, CuIn, Ga(1-x)S, Se
- September 1999 Synthesize thin-film heterojunction solar cell on flexible substrate
- November 1999 Install and test precursor analysis and characterization tool
- January 2000 Produce 5% efficient prototype small-area cells

Future Plans
- Develop and screen single source precursors for the low-temperature deposition of CuInSe2, Cu(In, Ga)(1-x)S, Se
- Produce 5% efficient thin film prototype small area solar cells with each of the above absorber materials
- Complete a design study for a multi-junction high-efficiency solar cell
- Produce a 10% efficient thin film solar cell on a flexible substrate

Rainbow
Accomplishments
- Assemble prism assembly
- Prototype mirror/prism/cell assembly test
- Prototype 55% AM0 prism cell

Future Plan
- Test mirror/prism/cell
- Fabricate and test five cell array
- Fabricate and test prism/cell array system
- Test system with mirror and/or lens
- Design and fabricate 28 volt array
- Demonstrate system design requirements

Advanced High Voltage Solar Array Design Guidelines from Solar Tile Testing
Accomplishments
- 40 Volt solar tile available for plasma testing
Begun prediction analysis and test plan
- Designed solar cells for 500 volt tile

Contract Completion
- 500 Volt solar tile tested in vacuum-plasma
- Developed general design guidelines for high voltage solar arrays

Follow-on Suggestions
- Design, build and test a 1,000 volt solar tile (higher voltage & higher efficiencies)
- Thermal cycle 500 volt & 1000 volt tiles
- Crack cover slide and test again
- Develop updated guidelines
- Develop arc detection and mitigation technologies
- Cross-technology development design/build/test 500 volt concentrator array

Stretched Lens Aurora
Accomplishment
- Module test 25% AM0 and 28% AM1
- Aurora Integration (Array)

Current Performance
- >300 watts/square meter
- >300 watts/Kg panel
- >150 watts/Kg array
Future Performance
- 400 watts/square meter
- 1000 watts/Kg panel
- 500 watts/Kg array

Follow-on Possibilities
- High voltage receivers demonstration
- Start next generation R&D (1000 watts/Kg)
- Larger Ground test panel (LaRC)
- Array integration
- Rainbow Receiver

Work Breakout Session 9 Report
Work Breakout Session group 9, Environmental and Safety Factors co-chaired by Marvin Goldman and Gayle Brown report:

Critical path environmental analysis
- Ionosphere
- Atmosphere
- Orbital space
- Beam safety
- Long term exposure
- Ecology
- Orbit slot allocation
- Environment impact statement process
- Frequency allocations
- Rectenna
- Large scale demos

Prioritize research needs for future years
- Dual site use (rectenna)
- Identify environmental costs
- Power density vs site
  - Land use
  - Safety
  - Ecological costs
  - Quality of life
- Exposure issues
- Debris mitigation

Work Breakout Session 10 Report
Work Breakout Session group 10, International Issues and Opportunities, co-chaired by Jerry Grey and Mark Henley report:

ITAR constraints
- Action is needed to mitigate constraints on SSP technical interchange
  - NASA needs an umbrella SSP technologies list
  - NASA needs to submit a rational for technical SSP interchange as a research activity for Department Of State approval via headquarters.

International cooperation mechanisms
- Create International Working Group (IWG) on SSP (our preference is a sub committee of the IAF Power Committee)
  - The IWG will identify demo projects, some of which may need international agreements.
Companies seeking joint efforts will apply for Technical Assistance Agreements (TAAs).
The IWG will seek to mitigate current ITAR constraints.
UNESCO World Solar Program
- Identify specific need of developing countries (e.g., SPS-2000)
- Promote SSP as a supplement to terrestrial solar systems
Energy demand projections
- Seek long-term energy demands scenarios from all sources

Address International Issues (non-technical)
- The IWG will create an “action” agenda to address each of the issues identified at Unispace 3

Mechanisms for International Information Exchange
- Set up SSP International Wing of VRC (Badged access, but on ITAR sensitive information) to publish and review work in all countries.
  - Alternative: Create international Internet communication network using VRC-like software.

Public Education and Information
- Identify and publicize demos having general public interest
- Seek public participation in demo projects (e.g., control of rovers)
- Create awards, essay contests, toys, etc

Work Breakout Session 11 Report
Work Breakout Session group 11. SSP Applications, co-chaired by David Smitherman and Ken Cox report:
Applications to Space Science Missions
- High power laser beaming to asteroids and planetary surfaces to determine chemical content
  - Power for long duration sample return
Economics
- Improved remote analysis of materials
- Standardized high power systems
Power for lunar-based telescopes
Technologies for large space telescopes
- Optics
- Power
- Propulsion
- Structures
- Robotics
- WPT to interstellar probes
Economics
- Continuous non-nuclear power supply
- Common technology development path
- Identify Earth crossing asteroids

Application to HEDS
- SEP stages for space transfer
- Power plug in space
- High power for processing raw materials
- Surface power beaming instead of power lines
WPT to surface systems
- Landers and science instruments
- Rovers
- Habitats
- Power to surface solar power systems in shadow
Power beaming to cold traps in shaded areas to release water and gases
High power radar mapping for resources mapping on planetary bodies

Application to Space infrastructure Development
- High power to micro satellites
- High power for electromagnetic launch systems on lunar and planetary bodies
- Orbital debris removal
  - Power to robotic maneuvering vehicle
  - Deorbit by direct laser beam to debris

Dual Use Technologies
SSP Technology
- PMAD
  - Thin film Fresnel lens
  - Ultra light solar arrays (efficient thin film flexible solar arrays)
  - High temperature RF electronics and materials (phased array to replace dish antennas)
  - High efficiency solar cells (terrestrial power including solar cells on roofs)
  - Robotics (convenience robots and construction robots)
  - Remote assembly
  - WPT and tall towers for receivers above the atmosphere
Next generation commercial aircraft and future RLVs
Space telescope lenses
Satellite solar arrays

**GRC presentation at the Work Breakout Session**

GRC presented 73 VUGHRAPHS at the Work Breakout Session and Pat George furnished copies of these charts for the SERT TIM 2 record and they include the following subjects:

1) High Voltage SSP Issues by Dale Ferguson
2) Application of Superconductors to SSP Satellites by James Powell
3) Solar Electric Propulsion by GRC
4) PMAD Accomplishments and Future Plans by GRC

**Day 4**

**Integrated Product Team (IPT) meetings**

Day 4 began with the following six Integrated Product Team (IPT) meetings until 11:00 am:

- **IPT 1.** Systems Engineering, Integration, Analysis, and Modeling: Cost Estimation and Space Transportation & Infrastructure co-chaired by Harvey Feingold, Connie Carrington, and David Way

- **IPT 2.** WPT & Reception: Ground Power Systems: Environmental & Safety Factors co-chaired by Richard Dickinson, Jim McSpadden, and Marvin Goldman

- **IPT 3.** Solar Power Generation and PMAD co-chaired by Shelia Bailey and Tom Lynch

- **IPT 4.** Structural Concepts & Technologies co-chaired by Chris Moore and Mike Gilbert

- **IPT 5.** Space Platforms and Operations co-chaired by David Maynard and Greg Hickey

- **IPT 6.** SSP Applications: Space & Terrestrial Markets, International Issues and Opportunities co-chaired by Jerry Grey, Mark Henley, Ken Cox, and David Smitherman
Day 4 ended with closing plenary panel sessions

**IPT Reports**

**IPT 1 Report**

IPT 1, Systems Engineering, Integration, Analysis, and Modeling: Cost Estimation and Space Transportation & Infrastructure co-chaired by Harvey Feingold, Connie Carrington, and David Way

Charge from John Mankins
- What data needs to be exchanged between teams?
- What data will need to be provided in the near future?

Database, structured properly, could address needs
- Data documentation with assumptions of what is included in estimates
- Modeling results
- Algorithms

Problems:
- Some teams do not have even basic information needed to start analysis
  - E.g., Structures team does not have loads

Interaction between systems and transportation
- Concept Proposers should take responsibility for providing schemes for assembly, component packaging, etc.

Assembly complexity vs ETO launch sizing (do we need to optimize?)
- Currently assuming 20 to 40 MT per launch (5 pounds per cubic foot) for transportation
- Larger payload units could simplify assembly (but launch vehicle failure is a consideration)
- Transfer vehicle could become part of an-orbit structure
- How fast does transportation need to provide materials? (Driven by economic considerations)
- High flight rate is better, from transportation point-of-view

SIWC can provide number of launches per satellite (currently assume on SSP satellite per year, but economic considerations will require a fleet of SSP satellites in perhaps a 5-year period of time)

Interactions between systems and transportation
- Recommendation 1: Get SIWG, transportation, structures, robotics teams together soon to establish assembly philosophy baseline
- Recommendation 2: Decide soon on a LEO-GEO transportation philosophy baseline

Interactions between systems and transportation
- Question 1: Do we need a depot for storing materials, tools, etc.
- Question 2: Does each package deliver itself to GEO (maybe higher, due to GEO stationkeeping consider stationkeeping), or do we have tug deliver launch packages?
  - Deploy SSP arrays for LEO-GEO transportation (loads on structures, degradation, PMAD and high voltage considerations etc.
  - Transportation has traded expendable, reusable, and autonomous SEP approaches (for transportation considerations only)
  - Autonomous SEP approach appears favorable to transportation, but oversizes and overdesigns the on-orbit SSP configurations, structures, PMAD, etc

Question 3: Do we need LEO transportation nodes?
- May need 3 for orbit phasing considerations
- Will need equatorial launch sites (build our own island?)

Question 4: What is the lifetime of this system?
Transportation needs from SIWG
- Density and dimensions of the payloads
- Launch rates
- Payload mass
- Assembly sequence
- Maintenance estimates

Propulsion needs
- Efficiency vs. specific impulse vs. propellant type
- Specific mass of propulsion unit

Solar array needs
- Specific power with or without structure
- Degradation both thermal and radiation
- Efficiencies (BOL and EOL) to aid in lifetime estimates

Robotics needs
- Robotic capability for assembly
- Reliability
- Mass, cost including all support
- Type of robots

WPT technology needs (solid state, magnetrons, klystrons, and lasers)
- Characteristics: mass, configuration, performance with assumptions
- Efficiency chains (space segment, atmospheric, ground rectenna)

Platform System needs
- Reliability data for all hardware (SSP satellites, robotics, and ground systems)
- Mass and cost data for platform systems
- Communications and computers

Structure needs
- Mass estimates for solar arrays, transmitter array, reflectors/bearings, and integrating structures
- Number of control actuators and sensors: mass, power and cost estimates
- Assembly approach and deployment
- Packaging
- Thermal mass, radiator configurations and location

PMAD needs
- Voltage levels, AC or DC and radiator temperatures
- Mass distribution of components for configuration design and recommendations
- PV to SEP switching information

SSP Applications needs
- Missions
- Requirements
- Spin-off applications that could impact systems and transportation decisions (lifetimes etc)

Team for Environmental Safety and Health needs
- Allowable power densities
- Stake holders
- Exclusion zones (cost impacts)

Missing Elements in WBS
- Operations
SERT TIM 2 Executive Summary

Command, Control and Data handling (ground and space)
Hierarchy, control sites, etc
Roles of government and private industry

IPT 2 Report
IPT 2, WPT & Reception: Ground Power Systems: Environmental & Safety Factors co-chaired by Richard Dickinson, Jim McSpadden, and Marvin Goldman

Safety
- Locate receiving stations in restricted airspace sites when possible
- Site requirements
  - Two radars
    - One for low slow moving small airplanes
    - One for high fast moving commercial and corporate planes
  - Detectors for beam scatter
  - Tie in with FAA ATC system
  - Redundant computers
- What do you want to protect?
  - All spaces
  - Other (land use, medical devices, etc)
  - Need more chronic long-term exposure data
  - Satellite Protection
  - Need analysis of fleet of beaming power stations at GEO
  - Rectenna maintenance
  - Protective suits
  - Auditory effects
- Beam pulsing possible? Probably not

Land use considerations
- Siting of microwave
  - Not is SMSAs
- Need flyway corridors superimposed on beam map
  - Birds, aircraft, and other migratory animals
- Reservations
  - Indian
  - National parks
  - Military
  - Wetlands
- Land costs
- Societal issues (e.g., construction worker support infrastructure)
- Microclimate effects
- Siting of lasers
  - $10^5 - 10^6$ receiving sites for 1 GW
  - May require neighborhood homogeneity
  - Public comfort factor (could look like a weapon)
    - Minimal problems with birds and planes flying through beam
  - PV material scarcity

Minority report 1
- Economics ($/KWh$) is the ultimate figure of merit for SSP. Microwave WPT at this point of time and for the next several decades is much better than laser WPT.
  - Lowest cost of electricity has been shown to be delivered from large antennas to multiple recentenas

Minorities report 2

March 21, 2000
Laser emitters can be designed so that they deliver power at about the intensity of natural sunlight in a distributed manner.
Laser emitters can be designed so that they can not be turned into a weapon system without major changes.
Efficiencies of 36% for a high quality beam have been demonstrated.
Higher efficiencies appear accessible (upper limit is 1001 - kT/kW) www.osa.org

**IPT 3 Report**
Interface Questions and Issues
- WPT voltage level and regulation
- Propulsion voltage level
- Structures, control and thermal: Mass and pointable structure, grounding, thermal regulation, and housekeeping power
- Robotics: Replacement of damaged components
- Space environment and safety: Charge dissipation

**IPT 4 Report**
IPT 4. Structural Concepts & Technologies co-chaired by Chris Moore and Mike Gilbert
IPT 4 did not meet; therefore they had no report.

**IPT 5 Report**
IPT 5. Space Platforms and Operations co-chaired by David Maynard and Greg Hickey
Functions
- Hierarchy of control
  - Granularity of control
  - Command and control schemes
  - Distribution of knowledge
- Assembly
  - Task order driven (repetitive)
  - Preventative
  - Adaptive scheduling
- Repair
  - Highly flexible
  - Responsive
  - Do we repair everything?
- Diagnostics/Health monitoring
  - Define needs
  - Non contact/point contact ports
  - Smart structures

System needs
- Efficient highways for mobility/operations
- Design forgiveness in system for assembly and operations
- Modularization
  - Similarity of components
  - Similarity of subsystems
  - Common interfaces/connectors
  - Self-fastening interfaces
  - Magnitude of change out
- Trash disposal/reutilization

Open issues
Computational requirements
   Speed vs memory
   Distribution vs non-distribution
Thermally/electrically hot change out
Isolation of damaged/downed systems, subsystems, and components
Thermal management
   How is PMAD integrated into structure and its effect on assembly?
Centralized vs distributed
   Robotics
   Intelligence
   Information management

Technology challenges
   Maintenance during continuous operations
   Coordinated operations with the ground (level of autonomy)
   Platform to robot and communications
   Health monitoring system
   Ad hoc network
   Inspection approaches/definition
   Extended operations for systems
   Simulation and studies
   Material logistics

Interfacing challenges
   Facility mobility
      Hard points, grapple, etc
      Spots to minimize reaction forces
   Facility reaction control
   Facility maintenance
      Design for robot only maintenance
      Smart structure, self-diagnosis, component change out
   Clearance and accessibility (pathways)
   Location/marking/component bar coding
   Communications and data (diagnostic facilities)
   Robotic infrastructure/tool shed and warehouse

IPT 6 Report
IPT 6. SSP Applications: Space & Terrestrial Markets, International Issues and Opportunities co-chaired by Jerry Grey, Mark Henley, Ken Cox, and David Smitherman
   What factors drive conversation to SSP?
      Economics
      Environmental benefits
      Fossil fuel depletion (plastic resources)
      Unique electricity markets e.g., electric cars
      Nuclear concerns

   Common issues
      Terrestrial power
      Space applications

Terrestrial power
   Major market: Developing nations
   Applications: Peaking power, base loads, or niche?
Integration with utility infrastructure
How to incentivize energy companies to put SSP in their strategic planning
Would offshore oil development model work for SSP?

Space missions
Scientific exploration
Orbital debris removal
Planetary defense
Nonterrestrial materials resources

Other Subjects
Environmental effects of electric propulsion effluents (xenon)
New people in this field would benefit from 1980 DOE/NASA study: Need copies
Environmental community is a major potential ally: Review Space Frontier Foundation’s presentation

John Mankins’ summarization
First end-to-end review of SSP with architectures, systems, technology, and demos.
Excellent interchanges among diverse organizations and groups
Good synthesis of relationships and issues
Something else to do
Concepts>database>R&T> applications Need to better more explicitly document traceability of specific technology efforts to concepts
We will be inverting the matrix
Space Applications
Need to continue to work hard on this subject
Will need to engage R&T teams to broaden perspective
For Example:
Infrastructure dual-use
Technology dual-use
Alternative systems use
Information dual-use

A lot of work to do

List of Attendees

1. Anderson, Dave
   Boeing
2. Anderson, Jeffrey
   NASA MSFC ED44
3. Arndt, Dickey
   NASA JSC
4. Bailey, Sheila
   NASA GRC
5. Balbaa, Ibrahim
   Ontario Power Technologies Canada
6. Baker, William
   Naval Research Lab
7. Beaudoin, Greg
   Strategic Insights
8. Benford, Gregory A.
   Microwave Sciences, Inc
9. Benford, James N.
   Microwave Sciences, Inc
10. Blanks, Hal
    United States Alliance Corp
    Auburn University December 7th & 8th
12. Brown, L. Gayle
    University Space Research Association (USRA)
13. Brown, Gardner
    Strategic Insights
14. Brown, Mike
    NRL
15. Cacace, Ralph
    Honeywell
16. Campbell, Jon
    NASA MSFC FD02
17. Carrington, Connie
    NASA MSFC FD02
18. Carroll, Kieran
    Dynacon Enterprises Limited Canada
19. Charania, Ashrof
    Georgia Tech

March 21, 2000
<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
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# Agenda for Day 1

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<tbody>
<tr>
<td>0730—0800</td>
<td>Registration UAH University Center UC 133</td>
<td>Dr. Hawk</td>
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<td>0800—0810</td>
<td>Welcome/Dr. Kava's WPT Demo</td>
<td>Axel Roth</td>
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<tr>
<td>0810—0820</td>
<td>Introduction</td>
<td>Joe Howell</td>
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<td>0820—0830</td>
<td>SERT TIM 2 Objectives</td>
<td>John Mankins</td>
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<td>0830—0910</td>
<td>SERT Program Overview</td>
<td>Carrington / Feingold</td>
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<td>0910—0950</td>
<td>SERT Integration, Analyses, &amp; Modeling</td>
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<td>0950—1000</td>
<td>ARC</td>
<td>Hans Thomas</td>
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<td>1000—1010</td>
<td>Intelligent Systems, Robotics, &amp; Other Environmental</td>
<td>Jay Skiles</td>
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<td>1010—1040</td>
<td>GRC</td>
<td>Pat George</td>
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<td>1040—1110</td>
<td>Solar Power Generation</td>
<td>Sheila Bailey</td>
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<td>1110—1130</td>
<td>Defect Engineering &amp; Reliability Study of SiC High Power Devices</td>
<td>Jim Dolce</td>
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<td>1130—1150</td>
<td>GSFC</td>
<td>Jim Andary</td>
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<td>Lunch</td>
<td>D. Maynard/Steve Kant</td>
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<td>1250—1320</td>
<td>JPL</td>
<td>Richard Dickinson</td>
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<td>1320—1340</td>
<td>WPT System Activities</td>
<td>David Maynard</td>
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<td>1340—1410</td>
<td>Science Applications</td>
<td>Brett Kennedy</td>
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<td>1410—1430</td>
<td>JSC</td>
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<td>Robotic Assy, Maint and Servicing</td>
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<td>1450—1505</td>
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<td>1600—1615</td>
<td>MSFC Ground Power Systems</td>
<td>George Kusic</td>
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<td>1615—1630</td>
<td>Space Transportation Infrastructure</td>
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<td>1630—1650</td>
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<td>Commercial Applications</td>
<td>David Smitherman</td>
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<td>1740—1800</td>
<td>Independent Economic &amp; Market Analysis</td>
<td>John Fini</td>
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<td>1800—1830</td>
<td>NASA In-House Study of SSP Demo</td>
<td>Mori Masahiro</td>
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<tr>
<td>1830—1850</td>
<td>Plans for Day 2</td>
<td>Joe Howell</td>
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**SERT Activities Summaries**

**ARC**
- Intelligent Systems, Robotics, & Other Environmental

**GRC**
- Solar Power Generation
- PMAD

**Defect Engineering & Reliability Study of SiC High Power Devices**

**GSFC**
- Space Platforms

**JPL**
- WPT System Activities
- Science Applications

**JSC**
- Robotic Assy, Maint and Servicing
- HEDS Applications and Other

**KSC**
- Spaceport Operations

**LARC**
- Struct, Materials & Control, and Thermal

**MSFC**
- Ground Power Systems
- Space Transportation Infrastructure
- FMCA
- Environmental & Safety Factors
- Commercial Applications

**Independent Economic & Market Analysis**

**NASDA In-House Study of SSP Demo**

**Plans for Day 2**
## Agenda for Day 2

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<th>Time</th>
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<tr>
<td>0800-0830</td>
<td>Aerospace System Studies &amp; Analysis</td>
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<td>SSP Systems Studies &amp; Analysis</td>
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<td>0900-0925</td>
<td>System Study for POWOW</td>
<td>Auburn University</td>
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<td>0940-0955</td>
<td>Application of SSP Technology to HEDS</td>
<td>SAIC</td>
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<td>0955-1015</td>
<td>Assessment of SSP Risk &amp; Uncertainty</td>
<td>Futron</td>
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<td>Assessment of Environmental &amp; Safety Factors related to SSP</td>
<td>Space Frontier Foundation</td>
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<td>1055-1110</td>
<td>Economic &amp; Market Analysis of Specific Locale</td>
<td>Strategic Insights</td>
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<td>SERT Research &amp; Technologies NRA 8-23</td>
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<td>1130-1145</td>
<td>Adv. High Voltage Solar Array Design</td>
<td>Boeing Phantom Works</td>
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<td>1145-1205</td>
<td>Solar Cell Development &amp; Array Design for RAINBOW Concentrator</td>
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<td>1205-1300</td>
<td>LUNCH</td>
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<td>Low-Mass Phased Array Antenna for WPT</td>
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<td>Ultra-Lightweight Inflatable Boom Dev</td>
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<td>Innovative Deployable Radiator Design for SSP</td>
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<td>Fabrication of Very High Efficiency 5.8 GHz Power Amplifiers for WPT</td>
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<td>1420-1440</td>
<td>High Voltage Modular DC to DC Converters</td>
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<td>R&amp;D of High Gain, High Efficiency, Circular Polarized rectenna</td>
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<td>WPT for Science Applications</td>
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<td>SSP Technology Demonstration for Lunar Polar Applications</td>
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<td>SERT PROCESS</td>
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<td>Charge to Work Breakout Sessions</td>
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## Agenda for Day 3

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<td><strong>SERT Work Breakout Sessions</strong></td>
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<td><strong>UC 126 C</strong> Space Transportation &amp; Infrastructure</td>
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<td>David Way, Mike Nix</td>
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<td><strong>Tech Hall N302</strong> Special Topics</td>
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<td>1500—1530</td>
<td>Break—Move back to UAH UC Exhibit Hall</td>
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<td>Reports from SERT Work Breakout Mtgs. (10 MINUTES EACH)</td>
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<td><strong>SSP Applications: Independent Economic &amp; Market Analysis</strong></td>
<td></td>
<td>David Smitherman</td>
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<tr>
<td>1730</td>
<td>Plans for Day 4</td>
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<td>Joe Howell</td>
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March 21, 2000
## Agenda for Day 4

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
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<tr>
<td>0730—0800</td>
<td>Registration UC 133</td>
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<tr>
<td>0800—1100</td>
<td><strong>SERT Integrated Product Team Meetings</strong></td>
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<tr>
<td></td>
<td>UC Exhibit Hall A</td>
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<td>Harvey Feingold</td>
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<td>Systems Engineering, Integration, Analysis Modeling: Cost Estimation and Space Transportation and Infrastructure</td>
<td></td>
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<td>WPT &amp; Reception: Ground Power Systems: Environmental &amp; Safety Factors</td>
<td></td>
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<td>UC 146</td>
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<td>Chris Moore/Mike Gilbert</td>
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<td>Jerry Grey/Ken Cox</td>
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<td>1100—1200</td>
<td>Lunch</td>
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<td><strong>Closing Plenary Panel Sessions</strong></td>
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