

The University of Alabama in Huntsville
Propulsion Research Center
UAH - 5

Space Solar Power Technical Interchange Meeting 2
SSP TIM 2

Executive Summary

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List of Acronyms:

ACT	Advanced Communication Technology
AIAA	American Institute of Astronautics and Aeronautics
amp/cm ²	Amperes per square centimeter
ARC	Ames Research Center
Borealis	Sun Sync Orbit
C&DH	Control and Data Handling
CMG	Control Moment Gyro
COTS	Commercial-Off-The-Shelf
COTR	Contracting Officers Technical Representative
CSA	Canadian Space Agency
DASA	German Aerospace
dB	Decibels
DC/RF	Direct Current Radiation Frequency
EMF	Electromagnetic Frequency
EMI	Electromagnetic Interference
EPRI	Electrical Power Research Institute
EOL	End of Life
ESA	European Space Agency
ETO	Earth to Orbit
EVA	Extra Vehicle Activity
Ex ante	Preexisting
FMCA	Functional Mission Concept and Architecture
FY	Fiscal Year
GEO	Geostationary Earth Orbit
GHz	Giga hertz
GN&C	Guidance, Navigation, and Control
GW	Giga watts
HRST	Highly Reusable Space Transportation
HTSC	High Temperature Superconductor
IAAM	Integrated Architecture Assessment Model
IPT	Integrated Product Team
IRR	Internal Rate of Return
ISP	In-Space Propulsion
I _{sp}	Specific Impulse
ISS	International Space Station
ITU	International Technical Union
JPL	Jet Propulsion Laboratory
kg	Kilograms
km	Kilometer
kW	Kilowatts
kWe	Kilowatts Electrical
kWh	Kilowatt Hours
LaRC	Langley Research Center
LCC	Life Cycle Cost
LDC	Less Developed Countries
LEO	Low Earth Orbit
LeRC	Lewis Research Center
MBG	Multiple Band Gap
MEO	Medium Earth Orbit
mm	millimeter
MPD	Magnetoplasma Dynamics
MSFC	Marshall Space Flight Center

Mwe	Megawatt electrical
N/A	Not Applicable
NASA	National Aeronautics and Space Administration
NASDA	National Aeronautics and Space Development Agency (Japanese Space Agency)
OMV	Orbital Maneuvering Vehicle
PMAD	Power Management and Distribution
PRC	Propulsion Research Center
POST	Trajectory Model
R&D	Research and Development
RLV	Reusable Launch Vehicle
R&T	Research and Technology
SD/PV	Solar Dynamic versus Photovoltaic (power generation)
SE&I	Systems Engineering and Integration
SEP	Solar Electric Propulsion
Si	Silicon
SOTA	State-Of-The Art
SSM	Space Segment Model
SSP	Solar Space Power
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
US	United States
V-dc	Volts direct current
V/m	Volts per meter
VRC	Virtual Research Center
Vs.	Versus
WHO	World Health Organization
W/m ²	Watts per square meter
W/kg	Watts per kilogram
WPT	Wireless Power Transmission

Abstract

SSP TIM 2 was conducted September 21st through 24th with the first part consisting of a Plenary session. The summary results of this Plenary session are contained in part one of this report.

The attendees were then organized into Working Breakout Sessions and Integrated Product Team (IPT) Sessions for the purpose of conducting in-depth discussions in specific topic areas and developing a consensus as to appropriate study plans and actions to be taken. The second part covers the Plenary Summary Session, which contains the summary results of the Working Breakout Sessions and IPT Sessions. The appendix contains the list of attendees.

The objective was to provide an update for the study teams and develop plans for subsequent study activities.

This SSP TIM 2 was initiated and the results reported electronically over the Internet.

The International Space Station (ISS) could provide the following opportunities for conducting research and technology (R&T) which are applicable to SSP:

- Automation and Robotics
- Advanced Power Generation
- Advanced Power Management & Distribution (PMAD)
- Communications Systems & Networks
- Energy Storage
- In Space Propulsion (ISP)
- Structural Dynamics & Control, and Assembly
- Wireless Power Transmission

1.0 Introduction and Background

MSFC is conducting a Space Solar Power Concept Definition Study for NASA Headquarters in response to strong interest expressed in SSP outside the Agency.

UAH Propulsion Research Center hosted SSP TIM 2 to facilitate International participation (Japan, Canada, and Germany) and open discussions with all data freely exchanged.

This TIM was conducted making maximum use of the Internet and the MSFC Online Project Management System, Virtual Research Center (VRC). For instance, the announcement, invitations, and agenda were put on the net. Other invitees not registered on the VRC were contacted by electronic email.

The 550 Vu-graphs presented at this TIM will be made available through Joe Howell, MSFC Project Manager telephone No. (256) 544-8491, and Fax No. (256) 544-6669 or email joe.howell@msfc.nasa.gov.

A list of SSP TIM 2 attendees with their email addresses is contained in the Appendix. This Executive Summary will be distributed by email and put on the MSFC Online Project Management System, VRC.

2.0 Objectives

The objectives of the NASA SSP study is to identify and refine commercially viable approaches and to enable choices that preserve and create options for:

- Technology Investment
- Regulatory Strategies
- Industry Relationships
- International Participation

Part I Plenary Session Summary Results

3.0 Systems Integration, Analysis, and Modeling

3.1 Accomplishments Since SSP TIM 1...Parker

- Focused subsystem and system-level teams
- Developed relationships among technical, economic, and market factors
- Developed “tall tentpoles” for Technology Roadmaps
- Issues and trades have been identified and are being resolved

3.2 Launch Vehicle Changes since SSP TIM 1...Parker

- Standardized Payload Volume to 226 cubic meters
- Updated POST trajectory data
- Increased Thermal Protection System (TPS) mass to reflect updated heating models
- Added 10% mass margin to key structure to increase airframe life to 1000 flights per airframe
- Added 5% mass to subsystems to reflect use of Commercial-off-the-shelf (COTS)
- Derated engines to 90% maximum thrust for normal operations to enable 500 flights per engine

3.3 SAIC Concept Definition Study...Feingold

SAIC presented a summary of study results and listed the following issues to be resolved at this TIM:

- Input Cost Data for Models
- PMAD-Resolve Power Cabling Concept (LeRC Vs MSFC)
- In Space Transportation-Expendable SEP Modules Vs Reusable SEP
 - Orbit-MEO Vs GEO, Should GEO Sun Tower Replace MEO Sun Tower as Study strawman?

3.4 FUTRON Concept Definition Study...Christensen

Futron presented an economic assessment and made the points that cost is driven by concept, technology development timing whereas the markets drive prices. Significant cost data is needed to complete the models.

Technology roadmapping is a critical issue for cost estimating. One must consider whether current technology, evolutionary technology, or revolutionary (leapfrog) technology is postulated for SSP development. Revolutionary developments require a focused R&D program and R&D demonstration projects.

The purpose of the Futron SSP study is to enable choices that preserve and create options for:

- Technology Investment
- Regulatory Strategies
- Industry Relationships
- International Discussions

4.0 Supporting Infrastructure (Launch Vehicle Assessment)...Olds

Is the SSP mission and \$400/kg price a large enough carrot to interest the ETO community?

The Georgia Tech study goals are:

- Assess four HRST concepts including performance, weight, size, and Life Cycle Cost (LCC).
- Use consistent assumptions and analysis tools to “level” technology differences between concepts.
- Identify economic attractiveness of SSP for ETO
 - Do HRST vehicles make sense at \$400/kg?
 - What Government investment is required up front?

The following to date study results were presented:

- \$400/kg price may not be sufficient because baseline IRR is less than 8%
- Financing costs are significant economic drivers because debt service burden can be as high as operations cost even using a 10% interest rate.
- Trade studies show improvement for larger vehicle payloads

5.0 Wireless Power Transmission...Dickinson

Central phasing minimizes the need for structural rigidity

For a 1GW radiating phased array with no gaps between sub-arrays, the backside radiation levels will be no more than 40 dB below the front side. Thus for a peak front side power density of 33kW/m² (average 14kW/m², the backside radiation will be less than 3 W/m², but depending upon maintenance after meteorite impacts.

The backside of the DSN antennas have never been measured due to the complex support structure and the backlobes are of narrow angular extent on the small antenna dishes that have been measured.

The WPT efficiency = 0.303 for a 5.8 GHz MEO WPT system design example, whereas the WPT efficiency = 0.375 for a 5.8 GHz GEO WPT system design example.

6.0 Automation, Robotics, and Assembly...Hickey

SSP robotic functions are:

- Assembly
- Inspection
- Maintenance

The approaches to robotic functions are:

- Multiple robots
- Maneuver capsule, robotic arm/tooling and gantry robot
- Maintenance and inspection by N-pod, free flyers, track rider, and arm

The issues are:

- What is structure
 - Tasks for free flier Vs structure based robot
 - Can expanded structures act as support?
 - Significant disturbance rejection issues
- What can we do?
 - Self assembly Vs robotic assembly
 - Repair Vs replace

- Size/scalability issues

7.0 Structural Concepts, Dynamics & Control, and Assembly

7.1 Automated Assembly, Maintenance, and Operations...Thomas

The strategy is:

- Design precision into the structure via self alignment, not into the robot
- Minimize point failures in system
- Keep it simple

The critical technologies to invest in are:

- Simulators
- Legged locomotion
- Robust control including on-line parameter identification and failure adaptation subsystems
- Execution, fault diagnosis and error recovery subsystems
- Power subsystems

7.2 Structural Concepts, Dynamics, and Control...Moore

The Sun Tower mass breakdown is as follows:

- Solar Collectors 30%
- RF antenna 27%
- Propulsion 26%
- Power conversion 10%
- Power backbone 3%
- Attitude control 3%
- Others 1%

Solar collector assumptions are:

- Planar arrays with 35% conversion efficiency, 2.56Mwe unit power, and size 200 meters x 40 meters
- Thin-film substrate and photovoltaic cells
- Two structural concepts
 - Elliptical inflated, rigidizable torus with thin-film Fresnel lens concentrator
 - Rectangular inflatable/deployable center mass with linear concentrator elements

Transmitting antenna-working assumptions are:

- 300 meter diameter array
- Surface off-normal slope allowed (10 to 15 degrees)
- 4 to 5 mm piston deflection allowed
- One mm maximum gap between elements
- 49,000,000 phased array elements
- Plus or minus 15 degrees pointing capability
- Microwave frequency is 5.8 GHz

Attitude control propellant estimates for momentum management and seasonal roll control is:

- Momentum buildup about vehicle y and z-axes must be dumped using orbit transfer SEP thrusters ($I_{sp} = 5000$ seconds)
- Y-axis secular torque produces pitch momentum (3 million Nm per orbit)
- Z-axis secular torque produces roll momentum of 2.6 million Nm over three months

- Seasonal roll control for solar beta angle tracking requires 50 kg per year of propellant
- Do not expect to have to reboost at 12,000 km altitude
- Station keeping propellant is not included

Identified technology development needs are:

- Power backbone
- Solar collectors
- Transmitting antenna
- Attitude and pointing control

8. Power Management and Distribution (PMAD)...Dolce

The primary distribution concept uses massively parallel simplex coaxial cable with the following characteristics:

- Separate conductor pair from each generating station
- No micro-meteoroid protection
- Graceful degradation
- 25 kV dc distribution
- Deployable

9. Advanced On-Board Propulsion...Olson

The mission assumptions to deliver each 2-5 MW Node from 300 km orbit 28.5 degree to a 12,000 km orbit 0 degree operating orbit are as follows:

- Impulsive Hohmann transfer for chemical propulsion
- Spiral transfer, thrusting only in sunlight for electric propulsion option
 - Drag estimates show electric propulsion thrust/drag ratio is greater than 3 at 300 km orbit under solar max conditions

System assumptions are:

- Node photovoltaic array subsystem and propulsion subsystem packaged node not deployed until 12,000 km altitude orbit arrival
- Power subsystem for electric propulsion option
 - Add a 200 kW power subsystem dedicated for propulsion and disposed of on arrival at 12,000 km orbit
 - Array/structure/mechanisms 500 w/kg and 200 W/m²
 - PMAD 2000 W/kg
 - Radiation resistant arrays

Conclusions to date:

- Electric propulsion allows substantial payload mass increase per launch vehicle
- Electric propulsion can start at 300-km drop off orbit
- Trade studies show that the 50 kW Hall thruster is best choice

10. Solar Dynamic Power Generation System...Flood

This system has been demonstrated in relevant environment with the following results:

- 2 kWe orbit power
- 29% cycle efficiency
- 17% orbit efficiency
- 750 hours of operation

Solar dynamic power generation has the following benefits for SSP:

- Demonstrated system efficiency
- Existing high power infrastructure
- Long life components
- Inherent radiation tolerant
- Suitability for mass production
- Well defined technology development plan to achieve system mass goals

11. Photovoltaic Conversion Technology...Flood

Photovoltaic Conversion Technology as per LeRC

Technology	Parameter	SOTA	Near Term	Mid Term	Far Term
Rigid Planar	Cell Efficiency	21.5%/MBG	24.5%/MBG	26.5\$/MBG	35%/MBG
	Array W/kg	40 to 60	45 to 70	50 to 80	65 to 105
	Array W/m ²	240	285	310	405
	Geo Lifetime/Loss	10yr/15%	10yrs/15%	10yrs/15%	10yrs/15%
Flexible Planar	Cell Efficiency	17%/Thin Si	18% InP/Si	22%/MBG InP	30%/same
	Array W/kg	130 to 150	130 to 150	170 to 195	230 to 265
	Array W/m ²	200	210	255	350
	Geo Lifetime/Loss	10yrs/25%	10yrs/5%	10yrs/5%	10yrs/5%
Concentrator	Cell Efficiency	24.5%	26.5%	30%/MBG	40%/MBG
	Array W/kg	60 to 70	70 to 80	80 to 90	105 to 120
	Array W/m ²	300	330	375	500
	Geo Lifetime/Loss	10yrs/5%	10yrs/5%	10yrs/5%	10yrs/5%
Flexible Thin Film	Cell Efficiency	N/A	10%/CIGS	13%/CIGS	20%/ADV
	Array W/kg		200	260	400
	Array W/m ²		110	150	220
	Geo Lifetime/Loss		10yrs/0%	10yrs/0%	10yrs/0%

Worldwide photovoltaic Module Manufacturing Activity

- 1988 35 MW/p
- 1989 42
- 1990 48
- 1991 54
- 1992 58
- 1993 62
- 1994 72
- 1995 83
- 1996 90
- 1997 122
- 1998 147-160 Forecast

12. Boeing End-to-End Architecture Study...Willenburg

20% of total mass is carried as program reserve

The key issues for the Sun Tower concepts are:

- Orbit selection to minimize radiation and orbital debris
- Orbit selection to maximize commercial utilization of power
- Transmitting antenna mass, complexity, and thermal control
- Tether thermal expansion/contraction from Earth's shadow
- Tether length minimization (15 km Vs 100 km)
- Solar array and transmitting antenna attitude control
- Power conductor material (copper Vs aluminum Vs other)
- Power converter to power bus interface
- CMG saturation, momentum dumping via tether Vs thrusters
- Spacecraft assembly scenario
- Spacecraft segment deployment scenario
- Solar concentrator thermal control

The Boeing near term research and technology focus areas are:

- Efficient power conversion
- Efficient PMAD/Integrate PMAD and electric propulsion
- Efficient wireless power transmission
- Integrated technology demonstrators

The Boeing summary study results are:

- Sun Tower concept is evolving (identical segment design is under consideration)
- System efficiency is critical
- Pop-up launch is viable and should be considered
- "Borealis" orbit should be considered

13. Aerospace Corporation End-to-End Architecture Study...Penn

The following subsystem models are incorporated into the SSP space segment model:

- Power transmission
- Power collector
- Backbone
- Attitude control for transmitter and collector
- TT&C and C&DH for transmitter and collector
- Thermal for transmitter and collector
- Structure for transmitter and collector
- PMAD (Harnesses, power conditioning/conversion, and batteries)
- Propulsion (Transfer system and on orbit system)

The following three additional models have been developed at top level:

- Ground system
- Cost
- Economics

Aerospace Corporation's view of Technical/economic readiness of SSP is as follows:

- Existing communication satellites are mini SSP demonstrators
- Key differences are:
 - Scale 400,000 to 6,000,000 kW per SSP

- Production volume requires tens of million of identical parts per SSP so the automotive and consumer manufacturing processes can be adapted
- Specific mass reduction of an order of magnitude is required for SSP
- Efficiency: SSP requires ultra low End-to-End transmission losses
- ACT demonstrator could be designed to demonstrate SSP and advanced communication satellite

14. Schafer Elliptical Orbit Architecture...Poulos

The purpose of this study was to conduct an analysis of an alternative SSP architecture based upon elliptical orbits. The results of this analysis to date are:

- Compared to GEO
 - Smaller aperture for same spot size
 - Equates to less mass in orbit
- Compared to circular MEO
 - Fewer SSPs (Four SSPs provide 24 hour power to three sites)
 - Only need three ground sites for commercial operations
 - Radiation environment is less
- Better coverage for north latitudes
- Economically competitive
- May be used for proof of concept and technology maturation
- Ultimately SSP may consist of combinations of GEO, circular MEO, and elliptical architecture

15. Environmental Factors...Anderson

The following recommendations are made concerning frequency allocation and EMI issues:

- Recognize the complexity and seriousness of these issues critical path for demos and final system
- Establish a program focus
 - Design solutions
 - Operational solutions
 - Consensus solutions
- Begin now to identify and characterize sensitive receptors
- Don't work toward higher beam intensities
- Stay below 200V/m (peak) at the ground

Resolutions of orbital debris generation and mitigation issue recommendations are as follows:

- The number and size of SSP satellites drive the system toward a dedicated orbital altitude band
- All satellites operating within the SSP altitude band must maintain formation
 - Formation design is non-trivial
 - Must allow for growth
- SSP must exercise extreme care to not create operational debris within its orbit band
- SSP must assure safe end of mission disposal
- LEO assembly of SSP satellite is probably still OK

The current standards are:

- US and Canada: 10mW/cm² for 2.45 GHz (unlimited occupational exposure)
- Sweden, UK, Germany, France, and Netherlands: Almost same as US
- Russia: 0.1 mW/cm²
- Don't misuse microwave safety standards of 5 mW/cm² for microwave ovens based on episodic short term exposure versus continuous

- Conservative factors always used to reduce occupational standards to public standards to account for cumulative effects from other sources of similar exposures

The following environmental projects are recommended for consideration for FY99:

- Standardize terminology and units (Clear definitions and units)
- Determine appropriate standards
 - Occupational: 8 hours/day, 40 hours/week
 - Public: continuous
- Initiate Environmental Assessment
- Health risk assessment
 - Assists in standard(s) determination
 - Determine sensitivity to change.
 - Assist in establishing “degree of uncertainty” that is acceptable

Last words on environmental assessment:

- Be clear on “Risk versus Benefits” and be realistic
- Hazard = Exposure + Risk
- Trust and Credibility are everything to successfully working with the public
- Environmental is not “stand alone”. But is an integral part of the project

16. Independent Economics and Market Analysis Working Group...Schaal

The purpose of this group is to establish an independent objective framework for and understanding of the economics and market for SSP. The output of this group is to provide decision-makers with information on whether to pursue public and/or private sector investment in SSP technology development.

This group has developed the following additional “market” understanding since TIM 1:

- Lessons learned from experience with nuclear power
 - Ex ante (Preexisting) cost estimation vs. realized costs
 - Other engineering challenges
 - Licensing and permitting
 - Public risk perception and communication
- Implications of fusion as a competing technology
- Human health, safety, and environmental data required for EMF determination
- Public perception of potential EMF risk
- Future of terrestrial solar photovoltaics as competing/complementary technology

This group reported the following general cost findings:

- For 1996, US generating costs for new plants averaged 3.8 cents/kWh
- For 2020, a reference case for generation cost is 3.2 to 3.3 cents/kWh

Comparative estimates for the rest of the world, the relevant SSP, does not exist. Accordingly, this working group used the following working hypotheses:

- Deregulation of foreign electric power markets narrows international cost differentials
- Resources inputs (except for hydro) trade in a world market at world prices
- Globalization of investment and technology contributes to convergence of costs
- Interfuel competition holds costs down
- Our World Bank expert suggested an average generating cost in 2020 for rapidly growing economic of 5.5 cents/kWh
- Generating costs above this 5.5 cents/kWh are subject to market forces

Environmental Factors:

- Global climate change is not a major factor in current power investment decisions by Less-Developed Countries (LDCs); local pollution problems in large cities may add a premium for non polluting technology
- Willingness to pay for clean technology tends to rise with rising incomes, but in LDCs, clean energy may not be among the highest-ranking environmental concern (e.g., clean water; sewage; health care)
- External effects are much less than many think because new plants are more environmentally benign

Competing Technologies:

- Technology considered in analysis must be in existence today due to the lag from invention through commercialization and to gaining market share
- Evolutionary technology has well known technical characteristics and documented performance
- Revolutionary technology is not in widespread use today but could be significant share of power generation in next century. Technology and operations are “break with the past”; could redefine nature of market in the long run
 - Biomass gasification
 - Fuel cells
 - Photovoltaics

17 Dual Purpose Technology...Smitherman

Dual purpose technology applications:

- Propellant supply and transfer
- In-space transfer service
- Satellite component and orbital debris storage
- In-space assembly of large systems
- Satellite inspection, servicing, and rescue
- Electrodynamic tether technology
- Earth to orbit passenger travel
- Manufacturing in space
- Lunar and asteroid materials for propellant and construction materials use in space

18. AIAA Assessment...Grey

Preliminary General Conclusions:

- Viability of the SSP concept is driven by economics. Danger is setting too stringent price goals and early demonstrations need not be strictly price competitive
- Perception related issues could determine success or failure
- The architecture issues of narrowing the field without discarding promising options, MEO may not be right orbit, and IAAM should continue to be used for conceptual designs

Preliminary Technical Conclusions:

- ETO cost and reliability are the highest risk drivers for economic viability
- Logistic support is major area for attention
- Energy collection and conversion: Photovoltaics is only viable option
- Ground storage has no technical barriers, but needs attention to ensure economic viability

- PMAD: Main issue is breakdown due to space plasma and needs operational demonstration of HTSC
- Wireless power transmission: Improve efficiency through magnetron research and solid-state devices
- Structures: Inflatable have promise, but technology is immature
 - Tensioned structures are promising and deserve evaluation
- Operations and on-orbit assembly: Automation concepts require intensive development
- GN&C, Thermal Control, and C&DH have no serious technical issues
- Dual purpose applications for SSP technologies worth exploring:
 - Propulsion and power for outer-planets robot science missions
 - Large high power commercial communication satellites
 - Human exploration missions
 - Providing beamed power to lunar and planetary surfaces
 - Delivering beamed power to geocentric orbit satellites

19. ESA Study of SSP Offshore Rectenna Siting in Western Europe...Kassing

Selection criteria:

- Safe and economic operation of a rectenna site
- Physical planning (navigation, oil and gas industry, recreation, marine environment, fisheries, and military areas)
- Natural boundary conditions
- Geotechnical boundaries
- At least 20 km offshore
- 300-km limit to consumer centers
- Water depth less than 30 m

Design drivers:

- Satellite in geostationary orbit (GEO) to provide continuous power
- Distance is some 36,000-km between satellite and rectenna
- Frequency of 2.45 GHz to reduce losses in the atmosphere and to avoid interference with telecommunications systems
- Passive radiation cooling only sufficient if DC/RF converters are distributed over large area
- Safety considerations require low-density RF beam above rectenna
- Due to costs, the beam is not ideal; i.e., significant side lobes and scattering effects

Secondary use of rectenna sites

- ESA rectenna siting study assessed potential secondary uses for the large offshore antenna fields
- Since RF radiation density beneath the rectenna elements is extremely low, and sunlight penetrates by about 80%, it was suggested to use the area for fish farming and agriculture

Conclusions:

- Very difficult to identify suitable and acceptable sites on ground of industrial regions
- With today's dredging capabilities, it is however possible to accommodate rectenna off-shore
- Rectenna construction and operation will count for approximately 1/3 of total program cost
- Secondary uses may compensate the operations cost significantly

20. NASDA Space Solar Power Studies...Mori

Why SSP?

- Environmental protection and energy policy; SSP could contribute to protect the Earth's natural environment and resolve the issue of the fossil fuel shortage
- Politics and economics in Japan; SSP could contribute to realize the economic growth and the national energy security in Asia-Pacific countries
- SSP could contribute to the post ISS project

Purpose and scope of study:

- Goal is to develop one GW class operational SSP by 2025 through international cooperation
- SSP requires broad studies
 - System concept
 - Regulation
 - Economics
 - Safety
 - Social influence
 - R&D scenario
- Technical studies
 - Power generation, management, and distribution
 - Wireless power transmission
 - Large structures and dynamics
 - Attitude control and station keeping
 - Automation, robotics, and systems assembly/maintenance
 - System health self-monitoring
 - Rectenna
 - Technology demonstration satellite
 - Reusable space infrastructure

SSP experiments using ISS

- Development of Micro Wave (MW) or Laser type SSP experiments
- Assembly and verification of the experiment system on ISS by EVA and/or robotics
- Technology experiments of the power transmission to Earth from ISS
- Critical estimate of technologies

SSP major milestones:

- FY99 Technical research,
- FY00 Development research (TDS/SSPE-ISS)
- FY01 Development (TDS/SSPE-ISS)
- FY05 Launch and Technology Demonstration Operations (TDS/SSPE-ISS)
- FY06 Development research (SSP pilot system)
- FY07 Development research (SSP pilot system)
- FY14 SSP pilot operations
- FY15 Beginning of operational SSP development

21. SSP Sandwich Concept (Kobe University)...Kaya

The sandwich concept reduces the heat reduction (thermal control) by:

- Larger sandwich structure
- Higher temperature
- Higher efficiency of the solar cells
- Selection of solar spectrum

- Active cooling

Conclusions:

- Temperature 120 C
- Spectrum 0.6 – 0.9 micro meters
- Orbit geostationary

22 Canadian SSP Initiative—An Update...Steiber

The Canadian Space Power Initiative (CSPI):

- Goal: Identify and plan for an appropriate role
- Sponsor: Canadian Space Agency
- Cooperation: Maintain strong links with activities in other countries and international bodies

Area of interest:

- Robotics
- WPT/Rectenna
- Ground based WPT demonstrations
- Space to ground WPT
- Large space antenna

Conclusions:

- Canada should have a role in the development of SSP
- Efforts of an exploratory and scoping nature is underway to determine role
- International cooperation will be an important aspect of the Canadian activity

Part II Plenary Summary Session

23. Systems Integration, Analysis, and Modeling IPT...Feingold

The following Systems Engineering and Integration (SE&I) issues (questions) were identified:

- How do we complete our models
- When will we get cost estimates
- What are we modeling, GEO or MEO Sun Tower
- What sensitivities/architecture should we run
- Resolution of systems issues
- Run a case study with SEP infrastructure, currently using non-reusable
- Ground Systems costs
- New concepts and architecture
- Reliability issues have not been considered
- How do we handle new concepts in the final report
- Contributions of this group to the final report
- Work on outline from SE&I
- How does FMCA fit in
- Document the pathway to the final design-audit trail. And methodology
- Technology roadmaps
 - Understand the as-is and the to-be
 - Also must understand the associated degree of difficulty/technology difficulty of new technologies

The SE&I final report outline is as follows:

1. Concept and architectures
 - A. Study strawman
 - i MEO 400MW
 - ii GEO 1.2 GW
 1. One 1.2 GW
 - 2 Three 400 MW
 - B. Other orbits
 - i LEO SS
 - ii Elliptical
 - C. Options-technology/system
 - D. Case Studies
2. Modeling
 - A Model description (detailed including all assumptions)
 - i SSM
 - ii IAAM
 - iii Aerospace
 - B. Case study results
3. Sensitivity analysis of key drivers/results
4. New concepts and architectures
 - A. White papers in standard format
 - B. Proposed process for evaluation and selection of technology options
 - i Decision criteria
 - ii Methodology
5. Technology roadmap (levels A and B)
 - A. Guidelines
 - B. "The Roadmap"
6. FMCA

The following action items were generated by this IPT:

- Working groups: Review/update technology assessment forms
- Working groups: Make sure modelers get data
- Dennis Wingo: Write white paper on addition of COMSAT capability to the space platform

This group recommended the following for FY99 study:

- Study to determine feasibility of selecting flight-demo sites that will help sell the SSP program
 - Remaining infrastructure complements the operational system
 - A politically correct location
- A Study to determine suitable international partnering

24. System Architecture and Modeling IPT...Fiengold

This Team put forth the following costing assumptions:

- 1998 dollars
- No reserve
- Separate breakout of technology development and demonstration costs

This Team also put forth a "Recommended Data Input Process" as follows:

- At regularly scheduled team telecons discuss and resolve the data requirements on the data input sheets
- The day after your telecon, the Systems Integration team will hold a telecon to collect your data.

This Team put forth the following data requirements:

Subsystem	Data Source	Desired Units	Resolution
Propulsion	MSFC, SAIC, LeRC	\$/W	Steve Olesin
Power Generation			
Concentrator Arrays	LeRC, JPL	\$/W	Jim Dudenhoefer
Thin Films	LeRC, JPL	\$/W	Jim Dudenhoefer
Solar Dynamic	LeRC	\$/W	Jeff Shreiber
C&DH and Telecom	MSFC	Adjusted Costs	Scott May
Transmitter Array	JPL	\$/element	Richard Dickinson
Attitude Control	MSFC	\$/kg	Connie Carrington
PMAD Cable, S-A interface, Xmt interface	LeRC	\$/kg	Jim Dolce
Manufacturing	MSFC	Adjusted Costs	SEER Model
Structure	LeRC JPL	\$/kg	Chris Moore Mike Gilbert Bob Freeland Billy Derber
Robotics	ARC	Kg \$/kg	Mike Sims Hans Thomas

25. FMCA...Parker

The following three timeframes are being examined to structure scenario planning:

TRL 6/7 in 2010 Accelerated Technology Readiness	TRL 6/7 in 2015 Moderate-Paced Technology Readiness	TRL 6/7 in 2020 Deferred Technology Readiness
System Possible as early as 2015	Inspection Possible as early As 2020	System Possible as early as 2025 - 2030
	Baseline for Roadmap Definition	

26. Infrastructure IPT...Nix

The major in-space transportation issues are:

- a. Propulsion Systems (Dual purpose; i.e., integration of SEP with PMAD)
 - Direct array power (direct drive)
 - Non xenon powered Hall Electric Thrusters
 - Ionic Propulsion Units
 - MPD
 - Pulse Inductive Thrusters
- b. Component protection during transit
 - Radiation
 - Debris
- c. Rendezvous
- d. Berthing/Docking
- e. Guidance and Control
 - Avoidance of interference with existing in space assets
- f. Component Check Out @ 300 km or more
- g. Disposal
- h. Space Based Reusable Orbital assembly Vehicle
Rendezvous and Recapture by RLV
- i. Low cost expendable stage

27. Wireless Power Transmission...Dickinson

This team put forth the following alternatives:

GEO sandwich

- a. One Beam
 1. Active cooling
 2. Passive cooling
- b. Multi beam
- c. Wireless Power Transmission Technologies
 1. 2.45 GHz
 2. 5.8 GHz
- c. Laser (Solar pumped device)
- d. Optical Reflectors
- e. ND4WM

28. Automation, Robotics, and Assembly IPT...Sims

This IPT Team defined the following robot types:

- OMVs for maneuvering payloads
- Walker/manipulator
- Freely flying inspection

The following logistics drivers were offered for considerations:

- Assembly
 - 1.2 GW in GEO/ very large shipments
 - Drop off area must be cleared and shipments stowed frequently
 - Large number of shipments is in transit at once
- Maintenance TBD

Some Robotics issues:

- Logistics
 - Orbital dynamics for berthing/docking, unloading, etc
 - Warehousing (new and bad parts)
 - Replacements
- Full access from rear or grappling fixtures on front (No connecting cables on rear of antenna tiles)
- Berthing/docking & undocking ops for tethered elements and large components

29. Structural Concepts, Dynamics and Control IPT...Gilbert

This IPT listed the following technology development needs:

- Power Backbone
 - Autonomous rendezvous and docking of tethers
 - Integral debris and plasma shielding
 - Lightweight, flexible power conductors
 - Deployment of power conductors
 - Large power connectors
 - Large deployable trusses
- Solar Collectors
 - Inflatable solar array/inflatable truss
 - Inflatable solar concentrators (Fresnel lens/reflectors)
 - Space-durable materials (UV and radiation resistant)
- Transmitting Antenna
 - Autonomous assembly of antenna modules
 - Integrated power distribution/structure
 - Efficient thermal management
- Attitude and Pointing Control
 - Distributed attitude control
 - Structure/actuator integration
 - Distributed rejection
- Mechanisms
 - Large rotary joints
- Integrated Design and Analysis Tools

This IPT offered the following thoughts on ground testbeds and space demonstrations:

- Ground Testbeds
 - Simulation of system dynamics
 - Distributed control of flexible structures

- Robotic assembly of antenna modules
- Large inflatable/deployable structures
- Space Demonstrations
 - Deployment of inflatable solar array
 - Autonomous rendezvous, berthing/docking, and deployment of tethers
 - Modular assembly of antenna
 - Sub-scale SSP system

30. PMADs IPT...Dolce

This IPT presented the following summary:

- GEO orbit is more benign than MEO
 - Eliminate insulation. Gold plate exposed conductors limit conductors field strength < 50,000 V/cm
 - Minimize local plasma generation near conductors ($p < 10E-7$ torr, charged particle density < 10,000 particles/cm³)
- Use 160 amp/cm² maximum conductor current density
- No more debris flux than in LEO
- There are three primary distribution concepts
 - Massively parallel simplex cable (one line, one return)
 - Massively parallel triplex cable (3 lines, 1 neutral)
 - Triplex main conductor (3lines, 1 return)
- Transmitter Distribution from GEO
 - Investigate 17,000 V distribution to magnetrons
 - Develop transmitter module replacement concept

31. Power Generation IPT...Dudenhoefer

This IPT listed the following issues:

- Array Voltage < 300 V
- Array orientation
- Array structural integrity
 - Assembly
 - Repair
 - Performance
- Eclipse
 - Thermal
 - Electrical
 - Optical (Concentrators)
- Safety (Power on/off)
- Array current collection
- Power transfer > 1000 V
- Detailed comparison SD/PV at system level
- EOL performance of Hi N cells

This IPT generated the following action for considerations:

- Complete GAP analysis: STA to SSP
- Generate thin film layout with current collection
- Complete roadmaps with consensus to use the "Technology Roadmapping Approach" templates
- Generated roadmap for 40% quantum well solar cell (Frank Little)
- Add "Dillard" concept to pool of new ideas
- Initiate weekly "Power Generation" telecon
- Roadmap material development to filter sunlight at concentrator (Mike Watson)

32. International Partners...Steiber

The International Team meeting is summarized below:

International Issues

- Establish understanding of how to share technology
- Coordinate planning and resources
- Commercial communication satellite industry is a good paradigm for resolving international issues

International organizations with SSP interest

- International Telecommunication Union
 - Assigns bandwidth through biennial conference held by WRC
 - Coordinate activities to request frequency allocation for demonstration
 - One in microwave regime and one in laser regime
- World Health Organization
 - Studies effects of radio frequency transmission on biological systems
 - Perform literature search of prior research on biological effects
- UNISPACE
 - Run by the Committee on Peaceful Uses of Outer Space
 - Will meet in Vienna in summer of 1999
 - Prepare proposal to address international aspects of a SSP demonstration program

Model for Early Demonstrations

- A 20 year SSP program plan is suggested as a good roadmap for international development
 - 10 kW Technology Demonstration Satellite by 2001 (microwave or laser)
 - SSP Experiments on ISS by 2005
 - 10 MW class pilot system with rectenna site by 2014
- Find a mechanism for developing a valid demonstration project with international participation, support, and acceptance
 - Current mechanisms not optimal
 - Technical, financial, development participation

International Experiment Proposals

- Eurospace proposing an experiment of WPT from an Ariane upper stage to an inflatable rectenna
- DASA proposing an experiment to use Inspector to map beam pattern of an ISS-based transmission
- NASDA has developed a 20-year plan for SSP development
- Contact other nations (industry and national agencies) to identify additional interest in international cooperation

Dual Purpose Applications

- Propulsion and power for outer planet robot science missions
- Large, high power commercial communication satellites
- Human exploration missions
- Provide beamed power to lunar and planetary surfaces
- Delivering beamed power to geocentric orbit satellites

UNISPACE Initiative

- Initiate contacts
- Organize a discussion session
- Propose a resolution to all relevant United Nations organizations:
 - ITU recommendation for scientific research allocation or orbital slots and bandwidth
 - WHO recommendation for environmental assessment
 - International Panel on Global Climate Changes

Recommendations for the NASA Report to the US Congress

- SSP will be a global enterprise
 - Markets
 - Environmental issues
 - Regulatory issues
- Interest in collaboration expressed by ESA, CSA, and NASDA. International effort to investigate and demonstrate all relevant factors (technical and environmental) should begin soon and should include the following:
 - Demonstration of key technical systems
 - Wireless power transmission through the Earth's atmosphere
 - Long term effects on biological system
 - Mitigating strategies
 - ISS should be considered as a supporting testbed for SSP demonstrations
- Space agencies and utilities should cooperate in system studies and technology development
- Ultimate developer likely to be energy agencies in collaboration with industry
- Other nations should be actively solicited (especially developing nations)
- Preparations should begin now for international agencies
 - UNISPACE
 - ITU frequency allocation

33. Independent Economic and Market Analysis IPT...Fini

The outcomes of this IPT are as follows:

- The long term trend of commercial electricity cost has been downward, and is likely to continue that way
- Top level requirements: All teams and team members must address the implication of the cost trends on commercial electric output
- Other concepts should be explored
 - Premature to foreclose on options at this time
 - Creates learning opportunities

34. Structures Control, Assembly, & Transportation IPT...Carrington

This team came up with the following questions and issues for consideration:

- Redundancy/Reliability philosophy
- Repair/replacement of components: Reliability of transmitting antenna elements must increase
 - Servicing, inspection, accessibility to components
 - In situ repair versus component removal
 - Issues with freeflyer(s): Removal and replacement of solar collectors
 - Logistics/Supplies: Is a nearby storage and maintenance facility required?

- Trade service life, technology level, and design to match component life with service life of system: Plan for upgrades and growth
- Trades for staging and drop-off of payload packets at one km from SSP during assembly (local OMV for docking, assembly by robots)
 - Proximity Ops
 - Tug logistics
 - Varying orbits
 - Balance assembly with goal of maintaining cg at specific altitude
 - Packing debris
- Disposal of debris, refuse discards, and broken components
 - Temporary storage
 - Down mass transportation issues
- Emergency and contingency operations and equipment
- Trades on interchangeability versus optimization of components
 - 3–4 types of transmitting antenna tiles, conduction cables, and nodes
 - Consider launch losses in assembly sequence, and logistics planning
- Payload density needs to be defined for transportation planning
 - Will determine number of launches
 - Will impact assembly logistics and scheduling

35. Special Projects IPT...Harris

This IPT suggested the following for time period 2000 to 2005:

- Technology demonstration with US Air Force
- Ground to ground demonstration of technologies to mitigate technology concerns
- Hitchhiker payload DSI PV elements, DS4 PV system
- Modification and extension of Goldstone demonstration
- Replace klystron in “Moonstruck” with phased array to power rover
- Use existing reflectors to perform “first light” space to ground low power demonstrations
- Test beds for SSP element such as PMAD, phased array radar technologies, tracking and pointing, photovoltaics, rectenna performance, environmental effects, etc

2006 to 2010

- Transition to demonstrations in LEO
- ISS 100 kW co-orbiter
- Supplement ISS arrays and test materials/ technologies on ISS
- Space to Earth demonstrations
- Commercial applications
- Science applications

2011 to 2015

- 10 MW demonstration
- SSP for Moon and Mars applications
- 100 MW near full scale prototype

2016 to 2020

- Pilot plant—Full scale

36. Terrestrial Energy Storage for SSP System...Merryman

These are the planning for a workshop that were initially presented at SSP TIM 1 June 29, 1998.

The objective:

- Review the current state-of-the-art in terrestrial energy storage
- Assess range of energy storage system applicable to SSP
- Assess technical barriers
- Review Interface with rectenna and utility grid
- Recommend the most cost effective system

Some key issues:

- Scaling potential
- Energy densities and comparisons
- Performance, robustness, and life
- Match with expected energy input rate and format
- Infrastructure Locations
- Interface with rectenna and utility grid
- Technical limitations
- Costs

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