THE FINAL REPORT OF THE
SPS SPACE TRANSPORTATION
WORKSHOP

January 29-31, 1980
Sheraton Inn — Huntsville
Huntsville, Alabama

October 1980

Prepared for the
Advanced Systems Office
Program Development Directorate
Marshall Space Flight Center
Huntsville, Alabama

Prepared by the
Johnson Environmental and Energy Center
The University of Alabama in Huntsville
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.
Satellite Power Systems (SPS)—Space Transportation Vehicles and Operations
This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States, nor any agency thereof, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use or the results of such use of any information, apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights. It is recommended that any organization or individual applying the information contained in this report be aware of local and state codes.
FOREWORD

Although this workshop was not intended to reach major decisions on satellite power system (SPS) transportation technology, it was expected to assist in mapping the next phase of work. In the opening words of Carl Schwenk, its purpose was to search the contemporary reference system for "show-stoppers" and to ask such questions as the following:

- Does space transportation pose insurmountable difficulties in realizing an economical SPS?

- Do space transportation operations create unavoidable environmental disasters?

- Can the aerospace community state with confidence that space transportation-systems technology will evolve to provide low-cost delivery of massive payloads to orbit?

- Will technology permit low-cost operations and maintenance of space-based transportation systems?

In addition, the workshop was asked to identify the dominant issues that call for the earliest, more detailed studies, and to assess the credibility of the prevailing plans for further efforts.

In all frankness, none of these tasks could be fully dispatched, initially because of the brevity of the meeting compared to the volume of relevant material to be digested, but fundamentally because the problems are not so simply defined.
Statements of technical viability and economic competitiveness are meaningful only when normalized in terms of all tangible and intangible benefits which derive from a successfully completed program, and in terms of full costs of alternative energy strategies. Neither parameter has been, nor likely can be, determined with any confidence over the projected development or operating span of the SPS at the present time.

What did clearly emerge from the vigorous discussions in the working groups, however, and persists through the resulting sections of this report, was that SPS is an attractive, challenging, worthy project, which the aerospace community is well prepared and able to address. The mature confidence and authority with which the assembly of contractors, agency delegates, and consultants dealt with the long succession of technical, social, economic and political issues left the clear impression that if some persuasive constellation of purposes--public or private, peaceful or military, national or international--should assign this particular energy strategy a high priority, it could be accomplished.

Robert G. Jahn
Chairman
ACKNOWLEDGMENTS

The SPS Space Transportation Workshop, held under the auspices of The University of Alabama in Huntsville January 29 through 31, 1980, at the Sheraton Motor Inn, addressed in two and a half days questions that will require the efforts of many workers for the next 5 to 10 years before a rational decision can be made concerning the variety of vehicles and transportation systems needed for the erection and operation of these potentially vital energy systems.

Approximately 60 participants, listed in the following pages, provided expert and devoted efforts that are presented in the body of this report. Their wholehearted participation represents an essential contribution to the ongoing development of an understanding of the promise of satellite power systems and, in particular, their space transportation aspects.

The administrative support of David L. Christensen, Kenneth Rossman, and David B. Cagle of the Johnson Environmental and Energy Center at The University of Alabama in Huntsville was essential to the success of the workshop. The secretarial assistance of H. Barbara Guillet, Marionette Bishop and Patricia Hein is gratefully acknowledged.

It is hoped that the workshop will assist in identifying further work necessary to the realization of SPS as a significant element in meeting future energy requirements of the Earth.

J. Preston Layton
Co-chairman
TABLE OF CONTENTS

FRONTISPICE
TITLE PAGE ........................................... i
NOTICE .............................................. ii
FOREWORD ........................................... iii
ACKNOWLEDGMENTS .................................... v
TABLE OF CONTENTS .................................... vii
LIST OF FIGURES ...................................... xi
LIST OF TABLES ....................................... xv
LIST OF WORKSHOP PARTICIPANTS ................... xvii
SUMMARY ............................................... xix

I. INTRODUCTION TO SPS SPACE TRANSPORTATION ....... I-1
   A. Historical Background ............................ I-1
   B. Description of SPS Concepts .................... I-3
   C. Current Status of SPS Program .................. I-3
      1. Reference Systems ............................ I-3
      2. Space Transportation Requirements .......... I-6

II. EARTH-SURFACE-TO-LOW-EARTH-ORBIT (ESLEO) TRANSPORT .......... II-1
   A. Vehicle Systems Concepts ........................ II-1
      1. Shuttle Transportation Systems (STS) ........ II-1
         a. Current baseline ........................... II-1
         b. Growth using liquid propellant boosters .... II-1
      2. Heavy Lift Launch Vehicles (HLLV) ............ II-3
         a. Shuttle derivatives ........................ II-3
         b. New vehicles ............................... II-8
         c. Critical vehicle technologies ................ II-13
            (1.) Reusable thermostructure ................ II-13
            (2.) Cryogenic tank insulation ............... II-18
            (3.) Other critical technologies ............. II-18
      3. Other Vehicle Concepts, Including the
         Advanced Single-Stage-to-Orbit (SSTO) Vehicle ...... II-19
         a. Baseline personnel launch vehicle .......... II-19
         b. Advanced PLV and HLLV concepts ............. II-20
<table>
<thead>
<tr>
<th>Section</th>
<th>Page No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. Propulsion Technology Options</td>
<td>II-24</td>
</tr>
<tr>
<td>C. Operational Considerations</td>
<td>II-29</td>
</tr>
<tr>
<td>D. System Support Requirements</td>
<td>II-31</td>
</tr>
<tr>
<td>1. Industrial Base</td>
<td>II-31</td>
</tr>
<tr>
<td>2. Logistics</td>
<td>II-34</td>
</tr>
<tr>
<td>3. Launch Facilities</td>
<td>II-35</td>
</tr>
<tr>
<td>III. ORBIT-TO-ORBIT (INCLUDING INTRA-ORBIT) TRANSPORT</td>
<td>III-1</td>
</tr>
<tr>
<td>A. Orbital Transfer Vehicle (OTV) Missions</td>
<td>III-1</td>
</tr>
<tr>
<td>1. Cargo Transport From LEO to GEO</td>
<td>III-2</td>
</tr>
<tr>
<td>2. SPS Module Transfer From LEO to GEO</td>
<td>III-4</td>
</tr>
<tr>
<td>3. Personnel Transport</td>
<td>III-4</td>
</tr>
<tr>
<td>4. Emergency Personnel and High-Priority Cargo</td>
<td>III-4</td>
</tr>
<tr>
<td>B. Chemical Rocket Orbital-Transfer Vehicles</td>
<td>III-5</td>
</tr>
<tr>
<td>C. Electric Orbital-Transfer Vehicles (EOTV)</td>
<td>III-14</td>
</tr>
<tr>
<td>1. Electric Thrusters</td>
<td>III-18</td>
</tr>
<tr>
<td>2. Power Conditioning</td>
<td>III-20</td>
</tr>
<tr>
<td>3. Solar Array</td>
<td>III-21</td>
</tr>
<tr>
<td>4. Alternative Electric Thruster Systems</td>
<td>III-22</td>
</tr>
<tr>
<td>5. SPS-Focused Technology Program</td>
<td>III-22</td>
</tr>
<tr>
<td>6. Field and Particle Interfaces</td>
<td>III-23</td>
</tr>
<tr>
<td>7. Ecological and Societal Impacts</td>
<td>III-25</td>
</tr>
<tr>
<td>D. SPS Station-Keeping and Attitude Control</td>
<td>III-25</td>
</tr>
<tr>
<td>1. Baseline Definition</td>
<td>III-25</td>
</tr>
<tr>
<td>2. Baseline Difference/Open Issues</td>
<td>III-25</td>
</tr>
<tr>
<td>3. Technology Issues</td>
<td>III-25</td>
</tr>
<tr>
<td>a. Electric ion thruster</td>
<td>III-27</td>
</tr>
<tr>
<td>b. Chemical thruster</td>
<td>III-28</td>
</tr>
<tr>
<td>E. Intra-Orbit Transport</td>
<td>III-28</td>
</tr>
<tr>
<td>F. OTO Advanced Propulsion and Vehicle Concepts</td>
<td>III-33</td>
</tr>
<tr>
<td>1. MPD Thrusters</td>
<td>III-34</td>
</tr>
<tr>
<td>a. Potential</td>
<td>III-34</td>
</tr>
<tr>
<td>b. Status</td>
<td>III-35</td>
</tr>
<tr>
<td>c. Needs</td>
<td>III-36</td>
</tr>
<tr>
<td>2. Nuclear Electric OTV</td>
<td>III-36</td>
</tr>
<tr>
<td>3. Gas-Core Reactor OTV</td>
<td>III-38</td>
</tr>
<tr>
<td>4. Mass Drivers</td>
<td>III-41</td>
</tr>
<tr>
<td>5. Other Concepts</td>
<td>III-43</td>
</tr>
<tr>
<td>Figure No.</td>
<td>Title</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>Frontispiece</td>
<td>Satellite Power System (SPS) - Space Transportation Vehicles and Operations</td>
</tr>
<tr>
<td>3</td>
<td>Satellite Power System - Space Construction Facility Detail</td>
</tr>
<tr>
<td>4</td>
<td>SPS Reference Systems - Late 1979</td>
</tr>
<tr>
<td>5</td>
<td>Alternate SPS Concepts - Early 1980</td>
</tr>
<tr>
<td>6</td>
<td>Shuttle Transportation System (STS) - Current (1980) Configuration</td>
</tr>
<tr>
<td>7</td>
<td>Shuttle Orbiter Personnel Payload Configuration</td>
</tr>
<tr>
<td>8</td>
<td>Liquid Propellant Rocket Recoverable Booster (LRB)</td>
</tr>
<tr>
<td>9</td>
<td>Heavy Lift Launch Vehicle - Shuttle Derivative - MSFC</td>
</tr>
<tr>
<td>10</td>
<td>Personnel/High-Priority Cargo Vehicle with Flyback Booster</td>
</tr>
<tr>
<td>11</td>
<td>Heavy Lift Launch Vehicle (HLLV) Concepts - Boeing</td>
</tr>
<tr>
<td>12</td>
<td>Reference Heavy Lift Launch Vehicle (HLLV) Configuration - Rockwell</td>
</tr>
<tr>
<td>13</td>
<td>Multiwall Thermal Protection System (TPS) Configuration</td>
</tr>
<tr>
<td>14</td>
<td>SPS Booster Maximum Radiation Equilibrium Isotherms</td>
</tr>
<tr>
<td>15</td>
<td>SPS Orbiter Maximum Radiation Equilibrium Isotherms</td>
</tr>
<tr>
<td>16</td>
<td>Heavy Lift SSTO Launch Vehicle with Winged Recovery - Rockwell &quot;Star Raker&quot;</td>
</tr>
<tr>
<td>Figure No.</td>
<td>Title</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>17</td>
<td>Dual Expander Rocket Engine Concept - LOX/RP-1/LH₂</td>
</tr>
<tr>
<td>18</td>
<td>Multicycle, Airbreathing Engine and Inlet Configuration - Rockwell</td>
</tr>
<tr>
<td>19</td>
<td>HLLV Site Plan - Cape Canaveral, Florida</td>
</tr>
<tr>
<td>20</td>
<td>Off-Shore HLLV Launch Site Installation</td>
</tr>
<tr>
<td>21</td>
<td>Personnel Orbital Transfer Vehicle (POTV) Configuration - Rockwell</td>
</tr>
<tr>
<td>22</td>
<td>Single-Stage Advanced Personnel/High Priority Cargo OTV - Boeing</td>
</tr>
<tr>
<td>23</td>
<td>Two-Stage Personnel/High-Priority Cargo OTV - Boeing</td>
</tr>
<tr>
<td>24</td>
<td>In-Orbit Propellant Processing Facility Concept</td>
</tr>
<tr>
<td>25</td>
<td>Advanced Space Engine (ASE) Characteristics</td>
</tr>
<tr>
<td>26</td>
<td>Electric Orbital Transfer Vehicle (EOTV) Configuration - Rockwell</td>
</tr>
<tr>
<td>27</td>
<td>Electric Orbital Transfer Vehicle (EOTV) - Boeing</td>
</tr>
<tr>
<td>28</td>
<td>Electric Rocket Propulsion System - Boeing</td>
</tr>
<tr>
<td>29</td>
<td>Ion-Thruster Technology Extrapolation - Boeing</td>
</tr>
<tr>
<td>30</td>
<td>Intra-Orbit Cargo Tug Concept - Boeing</td>
</tr>
<tr>
<td>31</td>
<td>SPS Maintenance Sortie Transportation Vehicle</td>
</tr>
<tr>
<td>32</td>
<td>Nuclear Electric OTV - Boeing</td>
</tr>
<tr>
<td>33</td>
<td>Nuclear Gas Core Reactor OTV - Rockwell</td>
</tr>
<tr>
<td>34</td>
<td>Mass Driver Reaction Engine Concept</td>
</tr>
<tr>
<td>35</td>
<td>SPS Space Transportation Costs</td>
</tr>
<tr>
<td>Figure No.</td>
<td>Title</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>36</td>
<td>NASA Space Transportation Technology Planning Scenarios (Assume Shuttle STS Baseline: 30 Tons Per Flight, 50 Flights Per Year)</td>
</tr>
<tr>
<td>37</td>
<td>NASA Space Transportation Planning - Reference Vehicles</td>
</tr>
<tr>
<td>Table No.</td>
<td>Title</td>
</tr>
<tr>
<td>----------</td>
<td>------------------------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>Merit Indexes for Candidate Materials</td>
</tr>
<tr>
<td>2</td>
<td>Orbit-to-Orbit Transfer Mission Requirements</td>
</tr>
<tr>
<td>3</td>
<td>Major EOTV Hardware Technology Areas</td>
</tr>
<tr>
<td>4</td>
<td>Baseline Systems - Station-Keeping and Attitude Control</td>
</tr>
</tbody>
</table>
LIST OF WORKSHOP PARTICIPANTS*

Carl A. Aukerman  
Larry B. Bassham  
Rudi Beichel  
M. W. Bell  
Ron Bergeron  
R. Boyland  
George Bremer  
James D. Burke  
George Butler  
David C. Byers  
David B. Cagle  
David L. Christensen  
C. C. Christman  
Earle Crum  
J. P. R. Cuffe  
Eldon Davis  
Gerald Driggers  
Richard Earhart  
Carl Ehrlich, Jr.  
Charles H. Eldred  
Dr. Krafft Ehricke  
Lester K. Fero, Chairman  
ES to LEO Workshop  
Dale A. Fester  
Joel S. Greenberg  
Gerald Hanley  
Robert D. Harris  
R. G. Jahn, Chairman  
Harold Kaufman  
Frank Kirby  
S. Lafazan  
J. Preston Layton,  
Cochairman, O-to-O Work-  
shop Chairman  
James Lazar  

NASA/Lewis Research Center  
Aerojet Liquid Rocket Company  
Rockwell International  
Gurman Aerospace  
North American Rockwell  
Jet Propulsion Laboratories  
McDonnell Douglas Aircraft  
NASA/Lewis Research Center  
The University of Alabama in Huntsville  
The University of Alabama in Huntsville  
Lockheed Missiles & Space Company  
NASA/Johnson Space Center  
Pratt & Whitney  
The Boeing Company  
President, L-5 Society, Consultant  
Battelle - Columbus  
Rockwell International  
NASA/Langley Research Center  
Consultant  
NASA Headquarters  
Martin Marietta Corporation  
ECON, Incorporated  
Rockwell International  
Aerojet Liquid Rocket Company  
Princeton University  
Colorado State University  
Rockwell International  
Aerospace Corporation  
Consultant  
Argonne National Laboratories

*For addresses and telephone numbers of workshop participants, see Appendix B.
Howard Macklis
Kathleen Maher
William McRae
Arthur Mensing
R. H. Nansen
Hans Paul
Eugene V. Pawlik
Robert Riebling
Richard Rodgers
Kenneth L. Rossman
Donald Rote
Bob Salkeld
F. Carl Schwenk
William R. Snow
J. W. Streetman
Ernst Stuhlinger
Myron Uman
A. R. Valentino
Frank Williams
Wayne Wilson
Gordon Woodcock

TRW Defense & Space Systems Group
Battelle - Columbus
Rockwell International
United Technologies Corporation
The Boeing Company

Consultant
Jet Propulsion Laboratory

NASA Headquarters
United Technologies Corporation
The University of Alabama in Huntsville
Argonne National Laboratories

Systems Development Corporation
NASA Headquarters
Princeton University
General Dynamics
Consultant

National Academy of Sciences
Argonne National Laboratories

Martin Marietta Corporation
The Boeing Company
The Boeing Company
SUMMARY

In the course of studies of SPS over the past 10 years, it has become apparent that the space transportation requirements are major elements in the technical and economic realization of the concept.

The space transportation system generally consists of a trajectory from Earth's surface to a low-Earth orbit (ESLEO) and a transfer from low-Earth orbit (LEO) to a geosynchronous altitude (GEO) or an orbit-to-orbit (OTO) transfer, which includes both a transfer through the Van Allen Belts and intraorbital operations.

A number of concepts have been studied for enhancing the capabilities of the current Shuttle Transportation System (STS) so its role can be extended to early SPS demonstrations. Beyond the growth and derivative versions of the present Shuttle concept lie the possibilities for relatively low-cost transportation for ESLEO, which is a major factor in the economic feasibility of SPS.

The initial steps in enhancing the operational capabilities of the Shuttle will probably include using the liquid-propellant boost module, derived from the Titan ICBM, and liquid-propellant, strap-on boosters to replace the current solid-propellant, strap-on boosters. Following this modification, there may come advanced versions employing boosters with aerodynamic surfaces. Such developments will be consequences of the direction that the national space program takes in the next two decades.

Entirely new heavy-lift launch vehicles (HLLV) will need to be identified before the economic and environmental problems of the prototype, or even demonstration, SPS can be resolved. The need for single-stage vehicles capable of
achieving low-Earth orbits, using either vertical or horizontal take-off and landing, remains to be determined by future analyses or the course development of events in booster technology. In any event, considerable analysis, research, and technology will be required before the choice can be made. Social impacts in environmental areas will need to be considered.

The ESLEO operational requirements and costs dominate the SPS space transportation scene. Launch-vehicle technology must be driven to a rather sophisticated extent to meet the needs as currently perceived and this perception is immature at the present time. The workshop decided that, although rather advanced technology and well-developed operational management would be required, it was proper to target the average cost of gross cargo payloads into LEO at $30 (1979)/kg for construction of the initial SPS. The further cost goal for repetitive construction of 30 to 60 SPS would need to be reduced to $15 (1979)/kg for all operational payloads for ESLEO and would require the use of advanced, long-lived vehicles with a sophisticated operational organization, probably utilizing offshore equatorial launch sites.

The wide variety of OTO missions in support of the SPS demonstration, construction and operation needs to be better defined before the vehicle concepts can be identified. Chemical orbital transfer vehicles (OTV) require further analysis, technology refinement and a reasonably early start on development to provide a capability that is needed in even the present STS. OTO, including intra-orbit, requirements of the 1980s need to be coordinated with SPS needs for chemical rocket OTVs in the 1990s and beyond. In-orbit propellant processing should be fully assessed for early employment.
Much work is needed on the conceptualizing and research on electric rocket propulsion systems for SPS applications. Mission analyses including optimized high- and low-thrust acceleration trajectories are needed that serve the SPS requirements. High-power ion thrusters and magnetoplasmadynamic (MPD) thrusters urgently need development to ascertain their characteristics. Much better coordination between research in the electric-rocket propulsion system technology planning and support, and the overall future requirement for this kind of propulsion, including the SPS, is needed.

More advanced propulsion systems such as dual-mode solid-core nuclear fission systems, gas-core nuclear rocket stages and mass driver reaction engines (MDRE) need sustained attention. OTO propulsion using high-power lasers should also be given attention.

The present ground-based exploratory development program in space transportation for SPS is inadequate and such content as it has needs to be restructured. Its primary efforts should be directed toward strengthening the present concepts but, at the same time and just as importantly, we should be careful not to close off any promising concepts or technologies. Operations and social impacts are also important considerations. If the program is intended to be the next phase for SPS, it needs to be reconceived from the ground up with an increase of an order of magnitude in funding.

A greatly increased program of SPS space transportation analysis, research and technology is clearly needed. Efforts must be devoted to areas of system analysis and technology readiness (including ground and space testing) that will reduce space-transportation cost uncertainties in the next five to ten years.
Although the consensus of the workshop supported the future prospects of the SPS, it was generally believed that much work is needed before space transportation choices can be made.
I. INTRODUCTION TO SPS SPACE TRANSPORTATION

A. Historical Background

The Sun provides the basis of all life on Earth and is the primary energy source. Man has been tapping the Sun's energy in various forms for many centuries. Dependence on different energy forms has varied as the demands of man's societies have changed and increased, especially in the past several hundred years. The rate of energy usage has increased exponentially under the global pressures of the industrial revolution and the pervasiveness growth of technology throughout the world.

It has been evident for some years that petroleum fuels, on which industrial activity and the standard of living of most countries depend, would reach the peak of their economic production within a few decades and be exhausted in a foreseeable time thereafter. Coal is a major fossil fuel with extended reserves, but also with economic and societal difficulties. At present, nuclear-fission energy is seen to have only a limited and special usefulness, while controlled-fusion concepts must still be found to be feasible and practicable.

The use of direct solar energy for base electrical utility power is being studied as a renewable source of almost limitless power and is believed to hold great promise; however, the state-of-the-art of the various system concepts has not yielded a clear direction for solar power systems development. A large number of technologies and systems are being studied and developed under the energy programs of the United States and elsewhere. Thermal and photovoltaic ground-based central power systems are both under development. The possibility of space-based, solar-utility power was first suggested in the late 1960s by Dr. Peter Glaser of Arthur D. Little, Inc. Early SPS design concepts are shown in Figure 1. These concepts were based on the use of solar photovoltaic (silicon) cells and microwave transmission to Earth.
Figure 1 Early Satellite Power System (SPS) Design Concepts
at the 10-GWe power level.

B. Description of SPS Concepts

A considerable number of SPS concepts have been studied in more or less detail (as shown in Figure 2) by Boeing Aerospace Corp. The photovoltaic designs are primarily planar with silicon solar cells in rectangular areas of 50 to 100 km² and a mass in geostationary orbit of 50 to 100 Gg. Other designs with thermal solar collectors and Brayton- or Rankine-cycle power conversion have similar areas and masses. Similar concepts have been studied by Rockwell International and others with essentially the same results. Rockwell has shown a preference for gallium arsenide photovoltaic cells.

Figure 3 shows SPS space construction detail that gives an appreciation of the scale of the undertaking. In this illustration a construction base in geostationary orbit is shown with surrounding SPS structure and heavy-lift and personnel vehicles.

C. Current Status of SPS Program

The SPS studies and analyses have been carried out on a very broad base under the direction of the Department of Energy (DOE) in a joint effort with the National Aeronautics and Space Administration (NASA). The work has been distinguished by the breadth of a long-term conceptual development and consideration of broad societal and environmental issues. Economic factors relative to competing energy systems have also been considered in the year 2000 and beyond.

1. Reference Systems
Figure 2 Various Satellite Power System Design Concepts - Boeing 1970s
Figure 3  Satellite Power System - Space Construction Facility Detail
In recent months two photovoltaic reference systems have been identified, as shown in Figure 4, to serve as mileposts in further consideration of SPS from the standpoint of basic feasibility and in competition with other energy systems in the early years of the 21st century.

Alternative concepts still need to be considered carefully in some detail before development is undertaken, and much research and technology effort, including ground and space tests, is required before a definitive conclusion can be reached or a system configuration selected. Two recent concepts are shown in Figure 5, and many others will need to be considered.

2. Space Transportation Requirements

All studies of the SPS have identified the space-transportation element as a major, and even critical factor in the overall prospects of the system. The frontispiece shows the variety of space vehicles and operations currently identified in the construction and maintenance of the SPS. The ESLEO-transportation requirement represents the most substantial challenge in advanced large chemical rocket vehicle technology and costs. The OTO requirement, especially from LEO to GEO, and intra-orbit operations are also very demanding and will necessarily involve new vehicle technology and operations. Space basing will certainly be required. Electric rockets and other advanced propulsion capabilities may be needed. The current status and future prospects for satisfying the SPS space-transportation requirements as viewed by the workshop participants are presented in the sections that follow.
Figure 4  SPS Reference Systems - Late 1979

Silicon Solar Cells

Gallium Aluminum Arsenide Solar Cells
Figure 5 Alternate SPS Concepts - Early 1980

FLAT-MIRROR CONCENTRATOR WITH SINGLE ANTENNA

PARABOLIC CONCENTRATOR WITH THREE ANTENNAE
II. EARTH SURFACE TO LOW EARTH ORBIT (ESLEO) TRANSPORT

A. Vehicle Systems Concepts

1. Shuttle Transportation Systems (STS)
   
a. Current baseline

   It was agreed that the baseline current (1980) Shuttle transportation system, as shown in Figure 6, will be capable of supporting space-data-acquisition projects necessary for SPS feasibility evaluation during the middle years of the 1980s. These early experiments would undertake to verify analyses and ground-based experiments essential to early demonstration of SPS feasibility. NASA has already established the Orbiter Experiments (OEX) program to perform this function. If it proves desirable to conduct a subscale SPS demonstration program during the early 1990s, substantial uprating of the Space Shuttle delivery capability is feasible. The approach taken in uprating will be impacted by early operational experience and actual recurring costs per flight.

b. Growth using liquid propellant boosters

   It is understood that near-term Shuttle performance growth capability will be provided by the Titan LBM. The LBM was originally conceived for use at the Western Test Range (WTR) to give the Shuttle a performance increase from a predicted 1984 capability of 10,885 kg (24,000 lbm) to over 16,325 kg (36,000 lbm) into a near-polar orbit (98-deg inclination). The LBM, to be available in mid-1985, can also be used at the Eastern Test Range (ETR) to raise the Shuttle payload from a predicted 1984 capability of 29,480 kg (65,000 lbm) to a 36,280 kg (80,000 lbm) equivalent payload on due-east launch. This increased payload capability will undoubtedly have utility in any SPS on-orbit system demonstration program, and its availability should be recognized and incorporated into SPS planning.
Figure 6  Shuttle Transportation System (STS) - Current (1980) Configuration
The LBM airborne configuration consists of the Titan 3 first-stage engine, a new thrust structure and modified fuel and oxidizer tanks. The LBM is a self-contained propulsion system which mounts on the aft of the external tank. It has a 200-sec burn time, starting 5 sec after Shuttle liftoff.

The LBM is currently in the program-definition phase with full-scale development anticipated to start in October, 1982, to support a June, 1985, first flight at the WTR. The development program contains testing of the structural and propulsion systems, as well as an LBM flight-duration demonstration. Further growth configurations of the LBM with additional engines and tankage are also being evaluated.

According to Rockwell studies, the basic Orbiter vehicle can be adapted to transport about 75 personnel to low-Earth orbit within the cargo bay. This capability should be adequate to support probable requirements of the SPS program well into the 1990s. This concept is illustrated in Figure 7.

Studies have shown the feasibility of increasing the Orbiter payload for SPS-scale demonstrations to nearly 54,420 kg (120,000 lbm) by replacing the present solid rocket boosters (SRB) with a pair of reusable liquid propellant rocket boosters (LRB) that would be recovered from the water and refurbished, in an operation similar to that planned for the SRBs. The largest uncertainties in this conceptual approach involve the operations for undamaged water landing, retrieval and turnaround, and the costs associated with achieving the required confidence level for these operations. The proposed LRB configuration is shown in Figure 8.

2. Heavy Lift Launch Vehicles (HLLV)
   a. Shuttle derivatives
Figure 7 Shuttle Orbiter Personnel Payload Configuration
The present STS hardware can be adapted to deliver heavy-lift class payloads. Several studies have indicated the feasibility of using the LRB, the external tank and a new recoverable propulsion module containing the Space Shuttle main engines (SSME) and appropriate elements of the STS guidance, navigation, flight control, data systems auxiliary power and reaction control systems. The configuration, illustrated in Figure 9, could deliver more than 68,000 kg (180,000 lbm) of payload to low-Earth orbit. This configuration provides an effective contender for intermediate SPS demonstration program support by utilizing an expendable shroud that would permit payload dimensions to exceed those now imposed by the Shuttle cargo bay constraints.

The Shuttle derivative concepts assume present specifications plus modest technology growth, such as the following:

- Space Shuttle main engine being fully in accord with current specifications
- A new liquid-propellant booster engine using current technology
- Shuttle-type thermal protection system (TPS)
- Automated diagnostics to facilitate maintenance operations
- Aluminum and titanium airframes with modest use of composites
- Cryogenic orbital maneuvering system (OMS)
- Off-line processing of palletized payloads to minimize loading time

These design assumptions lead to an expected vehicle life of 300 flights (500-flight design life with 0.1 per cent attrition per flight). Engine-life limitations would probably result in a substantial maintenance load and
Figure 8 Liquid Propellant Rocket Recoverable Booster (LRB)
Figure 9 Heavy Lift Launch Vehicle - Shuttle Derivative - MSFC
TPS refurbishment is an unknown quantity. Airframe spares of 0.18 per cent flight have been estimated with somewhat higher engine spares in accordance with the current SSME specification.

b. New vehicles

It was the consensus of the workshop that more ambitious goals in performance, reusability, and operations technology must be advanced, utilizing new vehicles to develop a potential for substantial reductions in projected transportation cost. This is a critical area in terms of overall SPS economics. To achieve significant reductions in costs, a representative set of goals must include the following items which require, in effect, new vehicles:

- Vehicle design life exceeding 1,000 flights with reduced attrition
- Improvements in engine life and maintainability beyond the SSME specification by major factors
- A TPS technology that would require only routine visual inspection and infrequent maintenance, and would offer very high confidence that catastrophic failure would not occur
- Vehicle and airframe subsystems requiring infrequent maintenance
- A means of leak detection (for propellants and hazardous fluids) that would obviate extensive pressure checking, purging, etc.
- More aggressive use of composites and other mass-reduction means
- Vehicle sizing and capabilities appropriate to alternative uses, so that the SPS program will not have to bear the entire development cost
Advanced operational capabilities similar to airline freight operations

Given the goal of an HLLV system capable of placing about 100,000 kg (220,000 lbm) into LEO, there is little reason to question our present ability with current technology, although new large vehicles, such as the flyback booster shown in Figure 10, would be required. With more massive payloads and a greatly reduced cost of payload to LEO, it will be necessary to utilize advanced technology and very large, completely reusable HLLVs, such as those shown in Figures 11 and 12. Although the conceptual designs need further study, it is essential that they have minimum costs for production, operation and maintenance.

Assuming that the cost to operate, primarily fuel cost, is about 15 per cent of the total over the vehicle lifetime, the costs of hardware (manufacturing and spares) and labor (maintenance and operating personnel) can be taken to be divided at 40-45 per cent each.

The key drivers of the technology, then, may be identified initially as those which reduce labor and hardware costs. Eventually, as these costs are minimized, the cost of fuel will become more significant, so attention must also be given to those technologies which will reduce it (i.e., improve performance).

The SPS studies performed by governmental and industrial teams have repeated to a considerable degree the findings of earlier pre-Shuttle studies performed between 1962 and 1969. The common denominator is to achieve "airline operation," high reliability, long time between failures, little delay between flights (i.e., maintenance relegated to scheduled periods, turnaround limited to refueling and mating with rapid payload installation, and launch).
Figure 10  Personnel/High Priority Cargo Vehicle with Flyback Booster

PAYLOAD ~ 200K LB
GLOW ~ 6M LB
BOOSTER THRUST (VAC) = 4 X 2.15M LB
Figure 11 Heavy Lift Launch Vehicle (HLLV) Concepts - Boeing
HLLV Mass Properties ($x10^{-6}$)

<table>
<thead>
<tr>
<th></th>
<th>kg</th>
<th>lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLOW</td>
<td>7.14</td>
<td>15.73</td>
</tr>
<tr>
<td>BLOW</td>
<td>4.92</td>
<td>10.84</td>
</tr>
<tr>
<td>Wp1</td>
<td>4.49</td>
<td>9.89</td>
</tr>
<tr>
<td>ULOW</td>
<td>2.22</td>
<td>4.89</td>
</tr>
<tr>
<td>Wp2</td>
<td>1.66</td>
<td>3.65</td>
</tr>
<tr>
<td>PAYLOAD</td>
<td>0.23</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Figure 12 Reference Heavy Lift Launch Vehicle (HLLV) Configuration - Rockwell
c. Critical vehicle technologies

The critical vehicle technologies, among others, must be emphasized early and aggressively if SPS goals, identified above, are to be met.

(1.) Reusable thermostructure

In the broad sense, thermostructure refers to both the TPS and the primary structure. The TPS, in particular, must require no inspection or refurbishment between flights; to do so would induce prohibitive labor costs considering the extended surface involved with these very large systems. This strongly suggests the use of metallic material for both the TPS and primary structure as shown in Figure 13. The TPS thickness and mass are dependent upon the allowable backface temperatures of the primary structure. High thermal-gradient joints are characteristics of the interfaces between hot external surfaces and cooler internal structures.

These requirements vary, with boosters or orbiters, since their thermal environments are different. Boosters stage at lower velocities and therefore have less energy to dissipate. The maximum temperatures are typically not greater than 1,090°C (1,500°F), as shown in Figure 14. The local temperatures are generally well within the realm of conventional heat-sink structure with perhaps some localized TPS. The design emphasis is on minimizing structural mass while not increasing manufacturing or maintenance costs.

Orbiters encounter much higher thermal environments with maximum temperatures of approximately 1,750°C (2,700°F), as shown in Figure 15. These temperatures exceed the capability of currently available materials which do not require special surface coatings (to retard oxidation) and which can experience repeated thermal cycles without degradation. Much work is needed to bring the candidate materials listed in Table 1 to full technology readiness.
Figure 13 Multiwall Thermal Protection System (TPS) Configuration
Figure 14  SPS Booster Maximum Radiation Equilibrium Isotherms
Figure 15  SPS Orbiter Maximum Radiation Equilibrium Isotherms
<table>
<thead>
<tr>
<th>TEMP RANGE</th>
<th>VEHICLE STRUCTURAL APPLICATION</th>
<th>CANDIDATE MATERIAL</th>
<th>PHYSICAL PROPERTIES (3)</th>
<th>TENSILE PROPERTIES (3)</th>
<th>CREEP RESISTANCE (212°C)</th>
<th>FORMABILITY (3)</th>
<th>WELDABILITY (3)</th>
<th>OXIDATION RESISTANCE (2)</th>
<th>LEADING CANDIDATE MATERIALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>150°C - 250°C</td>
<td>WING, TANKS BODY STRUCTURE</td>
<td>2219 T811</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6061 T6</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7075 T6</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BE 3816</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>AMS 2902</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SAI 2600 IV</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SAI 2554</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>250°C - 300°C</td>
<td>UPPER SURFACE PRIMARY AND SECONDARY STRUCTURE</td>
<td>HAYNES 25</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NICKEL BASE ALLOY</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>INCO 625</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>INCO 710</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>INCO 7001</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HASTELLOY B</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RENE 11</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>STAINLESS STEEL</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TO NICKEL</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>300°C - 350°C</td>
<td>LOWER SURFACE LEADING EDGE AND HEAT SHIELD</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TO NICKEL (200°F)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>COLUMBIUM (6°) ALLOY</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>G 43</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R 68</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>FS 85</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C 128</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MODERATELY HIGH MECHANICAL PROPERTIES</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cu 752</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>350°C - 400°C</td>
<td>LEADING EDGE</td>
<td>TANTALUM (6°) ALLOY</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9041 20W</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T 202</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ti 2N</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>400°C - 450°C</td>
<td>NOSE CAP</td>
<td>TUNGSTEN THORIA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TUNGSTEN</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ZIRCONIA NOSE</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

**NOTES**

1. MAXIMUM STRUCTURAL TEMPERATURE LIMIT
2. BASED ON 0.5 PERCENT CREEP AT SPECIFIED TEMPERATURE
3. RATING LEGEND AS FOLLOWS:
   - E - EXCELLENT
   - G - GOOD
   - S - SATISFACTORY
   - P - POOR
   - NA - NOT APPLICABLE
4. WITH OXIDATION PROTECTIVE COATING

**REFERENCES**

- AFFDL-TR-69-94

**REMARKS**

- GOOD FABRICABILITY AND STRENGTH
- GOOD WELDABILITY, MODERATE STRENGTH
- HIGH STRENGTH, WELDING NOT PRACTICAL
- NOT WELDABLE
- GOOD STRENGTH AND FABRICABILITY
- GOOD STRENGTH AND FABRICABILITY
- LOW STRENGTH, GOOD FABRICABILITY
- "HAYNES 25"
- ANNEALED MATERIAL WITH MODERATE TENSILE PROPERTIES, GOOD OXIDATION RESISTANCE TO 1500°F
- "INCO 625"
- MATRIX STRENGTHENED ALLOY WITH MODERATE TENSILE PROPERTIES, METALLURGICALLY UNSTABLE ABOVE 1400°F
- "INCO 710"
- AGE HARDENABLE ALLOY WITH HIGH TENSILE PROPERTIES, MODERATE CREEP RESISTANCE
- "INCO 7001"
- "HASTELLOY B"
- "REN 11"
- "STAINLESS STEEL"
- "TO NICKEL"
- "NOT PRACTICAL"
- "EXTREMELY BRITTLE MATERIAL AT ROOM TEMPERATURE"
- "TO NICKEL"
- "POOR WELDABILITY"
- "SUPERIOR DENSITY, COMPENSATED STRENGTH VALUES, POOR FORMABILITY AND WELDABILITY PROPERTIES"
- "COLUMBIUM (6°)"
- "Cu 752"
- "TANTALUM (6°)"
- "9041 20W"
- "MODERATELY HIGH MECHANICAL PROPERTIES"
- "TUNGSTEN THORIA"
- "TESTED IN ENTRY PROFILE"
- "LIMITED BY OXIDATION PROTECTIVE SYSTEM"
- "TESTED IN ENTRY PROFILE"
In addition, many of these materials have high densities, are very expensive, and are available only from foreign sources. Little or no effort has been expended in metallurgical development since the late 1960s. Therefore, a major development program is required to provide advanced thermostructures which meet the needs of the SPS and other advanced space transportation systems. Primary emphasis should be placed as follows:

- **Materials** - metallurgical development of new materials which are readily manufacturable, maintainable, reusable, highly damage resistant, and made from domestically available raw materials

- **TPS** - extensive development and evaluation of metallic thermal protection systems with or without nonmetallic insulative material. Active cooling or heat-pump systems are back-up candidates for local high-heating areas

- **Primary structure** - principal structural components which may be metallic, composite or metal matrix, and which may also be hot or cold. High-strength structural gradient joints must also be developed

(2.) **Cryogenic tank insulation**

The cryogenic tanks of both the boosters and orbiters must be designed so that they require little or no inspection other than normal maintenance cycles. Similar requirements are placed on the tank insulation. Whether the tanks are integral or nonintegral does not relieve this requirement significantly. Insulation systems must be developed which satisfy these requirements and prohibit cyropumping and eliminate external ice buildup. The latter is especially important for horizontal takeoff vehicles.

(3.) **Other critical technologies**

Efforts need to be made to identify all critical areas of vehicle technology and to be certain that they receive adequate attention to remove substantial problem areas. Propulsion, in all ESLEO applications, is discussed below.
3. Other Vehicle Concepts Including the Advanced Single-Stage-to-Orbit (SSTO) Vehicle

a. Baseline personnel launch vehicle

The requirement for the personnel launch vehicle (PLV) is to transport SPS construction and maintenance personnel. Roughly 600 people are required for the steady-state construction period while approximately 30 people per satellite are needed for maintenance. Assuming a three-month duty tour in space, annual man-trips start at 2,400 and approach 10,000 when 60 satellites are operational.

The payload and launch-rate requirements in the early program phases are compatible with a Space Shuttle system which incorporates modest payload uprating -- possibly the augmented STS or an uprated liquid rocket booster.

The total cost of personnel transportation within the overall SPS scenario is "relatively insignificant"--representing approximately 10 per cent of the total SPS transportation cost, or about 2.5 per cent of the total SPS cost.

The Shuttle-derivative approach provides a required capability at low investment cost and risk. The high operational cost associated with high HLLV traffic flow raises the possibility of substantial cost savings through personnel transportation on the HLLV. This approach, suggested by both study contractors, eliminates the requirement for all but occasional use of this vehicle but puts an additional man-rating requirement on the HLLV.

The relative total cost of the PLV compared to the HLLV is small, and thus the criticality of this system from a total cost standpoint is low. A modest uprating of the Shuttle can meet the initial requirements at low investment cost and risk. However, the PLV operational trips required and the tradeoffs need to be evaluated against the development of a new vehicle with
lower operational costs. The requirements and justification for such a vehicle would come not only from SPS but also from the broad range of other space activities--both civilian and military. Within that broad range of transportation requirements, it is quite likely that the development of a new PLV will be attractive.

b. Advanced PLV and HLLV concepts

The PLV and HLLV baseline concepts presented by the study contractors have emphasized low risks and low technology. Relatively little treatment has been accorded to options associated with alternate system concepts and/or the possible benefits to be derived from the incorporation of technology improvements. In trying to prove feasibility, the obvious motivation is to show a capability while using low-risk technology. However, the best system options will strike a balance between low risk and benefits/improvements to be derived from alternate vehicle concepts and/or technology advancements.

A new PLV/priority cargo vehicle must, first of all, be fully re-usable and meet a payload requirement in the range of from 20,000 to 50,000 kg (40,000 to 100,000 lbm). Beyond that there are concepts with a broad matrix of operational modes, staging options and propulsion system with potential application for a PLV. Key issues appear to be vertical vs horizontal takeoff, one vs two stages, and rocket vs air-breathing propulsion. Air-breathing propulsion is generally associated with horizontal takeoff.

Six PLV concepts are discussed below:

- Concept 1 - Two stages, vertical takeoff, and horizontal landing (VTOHL). All rocket propulsion is the most conventional approach offering potentially low risk
• Concept 2 - Single stage, VTOHL, all-rocket propulsion shares basic technology elements with Concept 1; however, it needs a high level of performance in order to become attractive. Potential benefits accrue in development, vehicle purchase, and operations by having a single vehicle.

• Concept 3 - Air-breathing, first-stage accelerator offers versatility of horizontal takeoff (HTO) operations. Large vehicle size, and propulsion system mass and cost are key issues.

• Concept 4 - A sled-assisted, rocket-powered HTO concept which shares many technology issues with Concept 2.

• Concept 5 - An air-launch assist by in-flight fueling which has many similarities to Concept 4.

• Concept 6 - A single-stage vehicle utilizing multicycle, air-breathing propulsion system offers great versatility; however, it also presents a very substantial challenge to the mass and performance of the propulsion system. A Rockwell concept of such a vehicle, called the "Star Raker" is presented in Figure 16. Although this vehicle employs very advanced technology, it represents the direct thrust of future aerospace development and may incorporate a substantial capability for a variety of missions after the turn of the century. However, it is too soon to determine how such a vehicle would fit into the SPS or other uses. Never the less, it is necessary that the essential technologies be pursued actively.
It is essential that a systematic evaluation of these various advanced concepts be included in order to identify the most desirable concepts and their associated technology requirements. A balanced series of system studies and technology is required to guide the development of the concept.

The proposed ground-based exploratory development (GBED) program contains a long list of detailed technology programs which support a rather specific set of reference vehicles. There does not appear to be enough depth in the systems-level studies to justify selection of these reference vehicles to the extent that critical technology requirements should be predicted for them. The GBED program should initiate adequately funded, feasibility studies of competitive systems: and parallel supporting-technology programs should be tailored appropriately. The system studies should initially consider multiple concepts and only later narrow to preferred concepts.

There are many areas of common technology requirements between the advanced PLV concepts and the baseline, two-stage, VTOHL rocket-powered concepts. Concepts 1 and 2 above do not create any basically new technology issues. However, the hybrid and single-stage concepts tend to require a higher level of performance than the VTOHL options. Although single-stage-to-orbit (SSTO) concepts are not baselined, the GBED program does include specific SSTO propulsion items.

The horizontal takeoff concepts as a group generate a number of technological implications not common to the baseline HLLV. These are most critical in the area of air-breathing propulsion and range from adaptations of existing turbojets to advanced-technology, multicycle engines operable to hypersonic speeds. Air-breathing propulsion applied to accelerator vehicles
Figure 16 Heavy Lift SSTO Launch Vehicle with Winged Recovery - Rockwell "Star Raker"
offers the benefits of high specific impulse; however, the penalties of propulsion-system weight create a special technology effort on reducing engine weight. The horizontal takeoff mode presents additional challenges in aerodynamic configuration and structural loading not required in the vertical-takeoff mode. The SSTO vehicles incorporate an aircraft-development approach which includes taxi, takeoff and landing, subsonic flight, supersonic flight, low- and high-altitude tests, etc.

The technology program of the baseline HLLV will create benefits to potential PLV system concepts. Additional activity related to PLV should focus on broad system/technology option assessment prior to committing substantial resources to specific developments.

B. Propulsion Technology Options

The propulsion systems used in the ESLEO SPS transportation are discussed in this section. The reference vehicles are the PLV and the HLLV. These vehicles use liquid oxygen/liquid hydrogen propellants for high-altitude operation and either oxygen/RP-1 or oxygen/H₂ propellants during the low-altitude operation. Engine-thrust levels in these two vehicles are not identical; and therefore there are potentially four different rocket engines while only one engine, the SSME, is currently under development.

One of the advancements in technology that should be pursued for the three new engines is to improve engine service life and reduce turn-around maintenance. It is also important to understand the sensitivity of engine performance and life and their impacts on transportation cost. Both of these affect the operational cost of SPS in terms of labor to perform maintenance and spares to overhaul or replace engines. Since labor and hardware are large per-
centage shares of the total SPS cost, research and technology funding in pro-
pulsion should be concentrated on them.

The next phase of the SPS program should address the features of the rocket engines of the reference vehicle that impact the operational costs. A generic approach to increasing life would apply across the board to all three new engines. However, there are specific areas that must be considered for the liquid oxygen/RP-1 engine that are not appropriate to liquid oxygen/liquid hydrogen. Carbon formation within the turbomachinery and in cooling circuits could be significant factors degrading performance and life of engines using RP-1 fuel. Techniques to clean the engine between flights without significant penalties to cost and time are necessary. Past programs with RP-1-fueled engines have relied upon purging and flushing the engines on the launch pad prior to launch. Technological advances in this area are expected to have great influences in reducing operational costs and should be included in the following program phase.

Research and technology associated with materials development and advancing fabrication techniques to increase engine life, reduce maintenance, lower weight, and reduce cost are not addressed in the present propulsion program. Initiation of new development programs needs an advanced technological base in these areas. There are numerous potential advances that could be applied in a development program if their feasibility is demonstrated. The reference SPS system does not depend upon advances of this type, but there should be significant returns if the subsequent program includes activity to permit assessment of these advances. There have been essentially no funds spent by NASA for rocket-engine research in this area for nearly a decade.
Ballistic recovery of the PLV liquid-propellant boosters assumes complete protection of the propulsion system from the sea. There is no research and technology (R&T) in the next program to assess the capability of the engine to survive a sea-water environment without increased maintenance. It could be a key factor in the decision between ballistic and fly-back boosters for the reference PLV. Therefore, it is recommended that the next program phase include this issue.

Alternate propulsion systems have emerged in SPS studies. Dual-fuel engines for SSTO vehicles, as in Figure 17, multiple-cycle, air-breathing engines for SSTO and HLLV, as in Figure 18, and LOX/CH₄, high-thrust engines are alternatives that are not yet developed. These propulsion systems may not be required for the reference-system performance, but it is strongly recommended that sufficient funds be invested in R&T of these systems because of their potential for ultimately reducing costs. By omitting alternate propulsion concepts, options are closed for future decisions on the best propulsion improvements on the reference SPS system. It is recommended that the next program phase be structured to give equal priority to all promising propulsion systems.

The major technology issue for the liquid-propellant rocket engines that may be utilized for the SPS transportation system is the means of achieving low-cost operation of a highly reusable, complex system. The implications of this issue demand long life for the engine and its components, ease of inspection and maintenance, basic reliability of components, and high confidence in the ability to avoid random catastrophic failures. An appraisal of existing, successful, and reusable propulsion systems provides a good model to adopt for minimizing the operating costs of the SPS transportation life cycle.
Figure 17 Dual Expander Rocket Engine Concept - LOX/RP-1/LH₂
Figure 18 Multicycle Airbreathing Engine and Inlet Configuration - Rockwell
These successful reusable systems are as follows:

- The automotive engine (a simple, low-technology system)
- The aircraft turbojet engine (a complex, high-technology system)

The engines initially introduced should perform to the conditions and limits identified up to the point of qualification. At the same time, additional operational experience will be accumulated on a test stand through the "fleet leader" concept. This approach accumulates additional experience far in excess of the operating fleet. This additional experience is the only way to identify certain types of random failures and weak points in the engine design. As the combined experience, inspection, and overhaul observations of the operational engine and the fleet leader are accumulated, the ultimate operational and maintenance procedures are developed, and the operational limitations can be expanded. As a result, the ultimate maximum life and minimum maintenance operations are developed to the desired level of confidence.

Since this approach is novel in the field of rocket propulsion, considerable new experience will evolve from the SSME, which is the nation's first reusable, high-performance engine. This experience with the SSME and serious attention to reuseability in the beginning of the SPS transportation system should develop the necessary operational results approaching the success of propulsion systems for aircraft and automobiles.

C. Operational Considerations

In the construction and maintenance phases of the SPS, one to two launches of an HLLV (of the 400 mg or 180,000 lbm payload variety) are required each day. A fleet consisting of five to six boosters and six to
seven orbiters is needed to place either the silicon (weighing $5\times10^6$ kg or $112.2\times10^6$ lbm) or gallium (weighing $34\times10^6$ kg or $74.8\times10^6$ lbm) satellites in LEO. It is estimated that the turn-around time for each of the HLLVs is approximately four to five days. The number of reuses is based on current Shuttle criteria.

Operating cost is driven significantly by the degree of reuseability and the amount of refurbishment required on launch vehicles. It is expected that over the next three to six years, the present STS will mature operationally through flight experience in much the same manner as does a new commercial airplane. Improvements in subsystem performance, reduced turn-around times and reduced refurbishment needs will all contribute to providing information for SPS. However, additional advances in vehicle design and life (engine, insulation, structure, etc.) could significantly reduce operational cost.

Results from examining nonspace systems (airline and water transportation), that have undergone significant changes in the past 25 years, lead to the conclusion that an HLLV system would benefit from automation and reduced manpower support by incorporation of on-board, self-test, and performance-monitoring equipment. Possible design features were also identified which could minimize operational flow and the manpower associated with launch operations.

In summary, key factors for low-cost operations include the following:

- Design for long life and maintainability throughout the life cycle
- Automation of preflight check-out and servicing
- On-board, self-test, and performance monitoring
Continual subsystem or component tests to gain experience and confidence for extending inspection intervals

Reduction of skill level for maintenance through simplified design

Streamlined management for maximizing productivity

D. System Support Requirements

This section discusses three key areas of SPS transportation system support. The first consideration is the capability of the industrial base to support the STS transportation system by providing as an example the liquid-propellant rocket industry's current and projected status. The logistics considerations provide an indication of the magnitude of the area of logistics support needed. Logistics alternatives must be addressed early as they are major contributors to life-cycle cost. Launch-facility definition and location, the last area, not only can have an impact on program planning and funding if located outside of the U.S.A., but also will have an impact on personnel, propellants, spares, and payloads. All three areas have received limited study by SPS transportation-system contractors and a minimum of discussion during this workshop.

1. Industrial Base

Industrial base concerns arise for the SPS transportation system due to the current low level of funding in view of projected requirements for the 1990s and beyond. In assessing the industrial base, the following questions must be answered:

- What industrial base is required for SPS transportation?
- Will it be in place when required?
What are areas of concern?

What is needed to maintain or develop these areas?

To illustrate the potential overall problem, the following discussion of the liquid-propellant rocket industry is provided. It is recommended that this area and others which are identified are properly addressed in any near-term planning for an SPS transportation system. The American Institute of Aeronautics and Astronautics (AIAA) has recognized the problem of this industry and is preparing a position paper based on the use of cross-cut techniques. The discussion below reflects the tenor of the study.

Space Shuttle is a step toward establishment of routine, low-cost space operations. However, it is not an end point, and continued progress in lowering the cost of space operations depends on continuing development of propulsion technology. Unfortunately, at present, propulsion technology and system development are at a low ebb. The extensive funding commitment required to bring the STS to fruition and funding constraints imposed by current national priorities have severely restricted propulsion R&D. This tight budget situation, placing a strain on the propulsion industry, is resulting in the loss of some previously developed capabilities.

SPS and other future missions need new propulsion capabilities not included in the present STS. R&D lead time for a propulsion system is 5 to 10 years; therefore, delays in needed R&D can have significant downstream effects. Mission-performance capabilities become frozen; and the impact of a lack of propulsion system progress will be felt on the SPS, on the space program, and on industry by limited payload or mission opportunities and flexibility.
Because of the vital role of propulsion in the evolutionary growth of SPS and other space mission capabilities and because of the adverse effects that inadequate R&D support is having on the liquid-propellant propulsion industry, there is a need to renew the commitment to liquid-propellant propulsion R&D and to support restoration of an adequately funded effort. That effort must focus on promising options in propulsion systems and must be keyed to future requirements such as SPS transportation. These requirements are identified below as typical R&D options that should be pursued.

Space Shuttle will provide low-cost transportation to LEO for manned and unmanned missions. Economic analyses have identified Shuttle modifications which could improve its cost effectiveness.

SPS transportation studies have identified technological options which should be pursued for HLLV or SSTO; advanced liquid-propellant rocket propulsion is a key requirement. Advanced, high-density, high-pressure, liquid-propellant rocket engines are required by HLLV to maximize specific impulse while minimizing engine system volume and weight. High-density fuel is required to minimize vehicle size. High levels of specific impulse, and either an advanced version of the SSME or an entirely new dual-fuel engine are needed by SSTO vehicles. Lead times, up to 10 years, are required for some areas of this technology.

The liquid-propellant rocket propulsion industry is currently in a state of decline when it is needed to advance technologies which support development of necessary propulsion systems to maximize STS utilization, STS payload systems, and the SPS transportation system. The low level of the R&D budget has forced universities to turn to other areas of research, government laboratories to reassign their propulsion staffs, and industrial
organizations to diversify and enter other markets or to leave the marketplace altogether. This situation has resulted in a rapidly declining liquid-propellant engine R&D capability, a national asset which took more than 30 years and billions of dollars to develop. This capability, if lost, will not be easy or cost effective to reestablish. It represents knowledge and experience not found in textbooks. If it is not supported by meaningful technology and development efforts at a significant funding level, it will be lost to SPS and other future space programs. The present austere planning of NASA and DOD, unless supplemented by a focus such as SPS, will not protect this technological base.

2. Logistics

In order to define the logistics requirements—both on Earth and in space and to establish the feasibility of meeting these requirements—a comprehensive, end-to-end analysis was conducted of space and ground operations for construction, operation, and maintenance of the Nth satellite and rectenna. From these analyses, the time-phase, personnel and material-flow requirements on Earth and in space were derived.

Within the context of the systems and mission timelines defined, no operational or technological barriers to performing the logistics functions were uncovered. There were, however, cost-sensitive issues highlighted which bear on the problem of space-transportation economics, e.g., costs of hydrogen at the launch facility. The two more promising near-term processes identified for liquid hydrogen production are coal gasification and water electrolysis. Coal gasification involves manageable but expensive logistics problems. Water electrolysis requires a lot of energy and costs more. It is recommended,
as a part of the GBD program, that technological studies of the more advanced liquid hydrogen production processes, such as thermochemical and photosynthetic processes, be undertaken.

3. Launch Facilities

The SPS reference system assumes use of Kennedy Space Center (KSC) at Cape Canaveral, Florida, as a launch site. Three potential limitations at KSC are space for the launch pads, noise and sonic booms, and other concurrent activities. These limitations together with the potential of performance improvements from equatorial launch sites led to an examination of alternate sites, primarily near the equator. The following discussion summarizes this examination.

Cape Canaveral can probably support an SPS emplacement up to approximately 10 GWe of power per year. A suggested site plan is shown in Figure 19. This figure has a high uncertainty, being dependent on achieving recycle rates for the pad. To the first order, it is not heavily driven by vehicle size. Vehicles smaller than the reference HLLV will alleviate concerns for noise and sonic booms.

Performance gains due to low-altitude launch are negligible with an electric-propulsion OTV. Reduction in $\Delta V$ is countered by increased shadowing by Earth for the EOTV. Appreciable gains are available (roughly 15 per cent) in chemical-OTV performance. The gains did not appear to offset the likely higher costs of remote site operations.

Low-inclination (23 deg) launch to an equatorial LEO provides frequent (about 15 times per day) launch windows and a lesser radiation environment for the crews.

No desirable equatorial land sites were found, given political,
LEGEND:

- - - EXISTING CHANNELS

Figure 19  HLLV Site Plan - Cape Canaveral, Florida
environmental, and safety considerations. However, a potentially attractive off-shore installation concept was developed with the characteristics shown in Figure 20. Other features studied include the following:

- Location off the west coast of South America in international waters at a latitude of some 3 deg
- Mild climatology, weather, sea states and low currents
- Water depth on the order to 600 ft (180 m), well within off-shore technology
- Brown and Root, Inc. examined moored, semisubmersible, and jacketed structures and projected an installation cost of $3 to $4 billion. Facilities and equipment costs are additive to this base structure cost. The structures provide areas for landing runways, processing, cargo hauling, propellant storage, and launch operations. Facilities and equipment would be installed on the structures in a continental shipyard before towing to the emplacement site
- Estimated cost of this approach is less than a remote, land-based facility

Further study is required in this area to refine system size limitations for KSC use and to develop credible cost data to support a launch site location trade-off study. An input to this study should be the results of a complete logistic study to define launch rates, material, propellant supply, and personnel supply rates.
Figure 20  Off-Shore HLLV Launch Site Installation
III. ORBIT-TO-ORBIT (INCLUDING INTRA-ORBIT) TRANSPORT (OTO)

This section provides an overview of OTO and intra-orbit transport and traffic requirements associated with the reference SPS concept. In addition, it directs attention to some important areas of uncertainty and issues bearing on OTO transportation requirements that require more thorough investigation which may lead to substantial changes and improvements in the definition of SPS and its operations. Based on these observations, it identifies some key items which should be treated in the next phase of the SPS program.

A. Orbital Transfer Vehicle (OTV) Missions

The SPS system is to be developed in three major overlapping phases according to the current reference systems:

- Orbital base construction (LEO and GEO) and on-orbit construction of electric orbital transfer vehicles (EOTV)
- Construction of the SPS satellites
- Operation and maintenance of the SPS satellites

The orbital transfer modes required by each of these three phases are as follows:

- Intra-orbit transfers (transfers typically less than a few kilometers, except during maintenance)*
- Personnel and cargo transfers between LEO and GEO
- Emergency personnel and high-priority cargo transfers directly to and from GEO orbit (The last transfer mode has not previously been included and probably should be considered as a side issue)

*The maintenance phase requires intra-orbit transfers between all deployed satellites (spaced 2 deg apart in GEO) at the rate of twice per year.
Table 2 summarizes the number of OTO transfer flights required for a two-satellite SPS system. A more detailed analysis of these parameters should be performed; ultimately these data could be used to determine the propulsion system characteristics.

Using Table 2, an overall timeline and sequence of activity can be developed. First, intra-orbit transfers at LEO must be performed for each HLLV and PLV. The second GEO intra-orbit transfer represents that required to perform SPS maintenance and corresponds to servicing 20 satellites in a period of 90 days. This 90-day servicing is performed twice a year as indicated by the two LEO-GEO-LEO transfers required. Personnel and cargo (4,000 klystron tubes, for example) are transferred to GEO by a single vehicle.

1. Cargo Transport From LEO to GEO

The LEO to GEO cargo transfers required for construction of the SPS satellites and vehicle returns in the reference system scenario are not performed in series, but overlap in their timelines. Even with this overlap, given a number of EOTVs in simultaneous operation, the 120-day transfer required seriously restricts the time to load and unload cargo and refurbish the EOTV vehicle and propulsion system. The requirement for priority cargo OTV with chemical rocket propulsion systems needs to be assessed, especially during the demonstration and construction periods.

In summary, the assumed SPS construction rate of two satellites per year is an overriding system driver and the resulting nominal timelines are probably unrealistic. It is suggested that OTO transfer traffic models should be developed as a function of transfer time (i.e., thrust acceleration levels), SPS deployment rate, and SPS mass required in GEO. With this, OTO transfer vehicles can be sized and optimized; and the mass rate required in LEO by HLLVs can be
<table>
<thead>
<tr>
<th>Mission</th>
<th>No. of Flights to Build Construction Bases and EOTVs</th>
<th>No. of Flights for SPS Construction (2-5 GW per Year)</th>
<th>No. of Flights for SPS Maintenance (one Year Period)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Personnel</td>
<td>Cargo</td>
<td>Personnel</td>
</tr>
<tr>
<td>a. LEO Intra-Orbit</td>
<td>32</td>
<td>118</td>
<td>30</td>
</tr>
<tr>
<td>b. LEO-GEO-LEO</td>
<td>6</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>c. GEO Intra-Orbit #1</td>
<td>5</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>d. GEO Intra-Orbit #2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>e. LEO Intra-Orbit</td>
<td>6</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>f.</td>
<td>1</td>
<td>N.A.</td>
<td>1</td>
</tr>
<tr>
<td>g.</td>
<td>N.A.</td>
<td>1</td>
<td>N.A.</td>
</tr>
</tbody>
</table>
accommodated. Accordingly, system timelines can then be developed including appropriate cargo transfer vehicle construction, cargo loading and unloading, and vehicle refurbishment.

2. SPS Module Transfer From LEO to GEO

While recognizing the importance of the reference SPS system concepts as a stepping-off point for technical and economic assessments, it is observed that areas of uncertainty exist, which should remain open as subjects for investigation and which could lead to substantial changes and improvements in the character of SPS and their operations.

The option of constructing SPS modules in LEO for transfer to, and final assembly in, GEO is a potentially competitive approach which could be technically and economically superior if:

- EOTV reusability cannot meet or exceed ten round-trip flights
- Solar-cell annealing capability cannot be reliably held above 50 per cent
- Operational factors are significantly different than currently foreseen, including the docking problem

3. Personnel Transport

The importance of transporting large numbers of personnel from LEO to GEO for construction of the SPS must receive full consideration from the initial to the final system and their subsequent operation. The vehicles configured for this use have chemical rocket propulsion to minimize transfer time, especially through the Van Allen belts, and are presented in the following section.

4. Emergency Personnel and High-Priority Cargo

The reference SPS concept does not include provision for emergency transfer to Earth or for quick-reaction delivery of high-priority cargo ("Federal Express")
The need for these mission capabilities should be assessed. The vehicles for this use have not yet been configured. Such vehicles should incorporate the capability for direct flights to Earth from LEO or GEO with airstrip landing.

B. Chemical Rocket Orbital Transfer Vehicles

A reusable cryogenic Shuttle upper stage has been considered to be part of the STS program for over 10 years. This program is more than twice as far away as it was seven years ago, as is shown in the following table.

<table>
<thead>
<tr>
<th>Concept</th>
<th>IOC Date</th>
<th>Δ Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space Tug (1973)</td>
<td>1979 (Initial)</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>1982 (Final)</td>
<td>9</td>
</tr>
<tr>
<td>Interim Upper Stage (1975)</td>
<td>1980</td>
<td>5</td>
</tr>
<tr>
<td>To be followed by Orbital</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transfer Vehicles</td>
<td>1983</td>
<td>8</td>
</tr>
</tbody>
</table>

The reasons for this increased delay shown above are a combination of lack of near-term funding (which will still be unavailable for a number of years because of the need to bring the Space Shuttle to operational status) and the decision to use the available time to go to the direct development of a "clean sheet" advanced system in 1992.

If STS upper stage and early OTV capability is to be obtained within a desirable future (say, within this decade), a feasible approach is to pursue an evolutionary program.

Such an evolved program would initially make maximum use of existing subsystems, which would be improved as technology became available and introduced as the capability was required.

Initially, the cryogenic stage would be used in an expendable mode. During
this time, experience in operating a $O_2/H_2$ stage from the Shuttle would be obtained. This stage would increase STS payload capability to GEO by a factor of approximately 2.5 over that of the Shuttle/IUS. With modification and operating at low thrust, initial experience can be gained in the erection and deployment of large structures in LEO and GEO.

This stage would then be modified to allow it to be returned in the Shuttle Orbiter payload bay and brought back to Earth for re-use. This re-use capability would provide operational experience, rather than economic pay back, and would include an improved cryogenic space insulation, in-orbit servicing and eventually manual operation.

The feasibility of the chemical OTV does not have to be established. Rather, the uncertainties facing the chemical OTV are in the realm of life and cost, not performance, and these are the issues that need to be better defined. The eventual approach to the design, development and operation of the chemical OTV engine will be nearer to commercial aero engine practice and possibly even the industrial gas turbine, rather than that used for the present generation of liquid-propellant rocket engines. The combination of low cost and long life engines therefore are expected to require the following actions:

- Reduce dependence on strategic materials
- Enhance reliability and life
- Extend in-service periods
- Employ fail-safe design
- Accelerate minimum cycle development

Requirements for space-based operation include use of condition monitors and engine diagnostic systems (EDS) techniques.
Three reference OTV missions are envisioned in the SPS program as follows:

- **Cargo OTV**, for transfer of intermediate cargoes from LEO to GEO and return
- **Large cargo OTV** from LEO to GEO and vehicle return (EOTV baseline)
- **Personnel/priority cargo OTV** for short turnaround between LEO and GEO. An emergency ballistic re-entry vehicle may also be required

Chemical rocket OTV options currently identified that could meet the personnel/priority cargo transport requirement are shown in the next three figures. Figure 21 shows a single-stage OTV and a crew module, which could also carry cargo, that are compatible with the payload bay of the baseline Shuttle. This vehicle would find use during the space test and demonstration phases of SPS. A growth version OTV is shown in Figure 22 that would find use during the establishment of the GEO construction base and the construction of the initial SPS. A derivative cargo STS is needed for transport of this space-based OTV which would be refueled for the return to LEO in GEO. The two-stage personnel/high priority cargo OTV, shown in Figure 23, is a fully developed concept that would find continued use between LEO and GEO throughout the construction phase and during the operation phase of the SPS. Such a vehicle would make effective use of the in-orbit propellant-processing facility concept presented in Figure 24.

A range of chemical rocket OTV engines will be required from low thrust (~4,500 Newton [1,000 lbf] for low acceleration and reaction control) to much higher thrust (~470,000 Newton [100,000 lbf] for primary propulsion of the above personnel/high priority cargo and intermediate cargo OTVs).

For some years NASA has had an advanced space engine (ASE) under development with the configuration and characteristics shown in Figure 25. The further development of such an engine should be continued but its cycle, thrust level and
Figure 21  Personnel Orbital Transfer Vehicle (POTV) Configuration - Rockwell
Figure 22  Single-Stage Advanced Personnel/High Priority Cargo OTV - Boeing
- **Payload Capability** = 400,000 KG
- **OTV Startburn Mass** = 890,000 KG
- **Stage Characteristics** (Each)
  - Propellant = 415,000 KG
  - Inerts = 29,000 KG
    (Including Nonimpulse Propellant)
- **280 OTV Flights per Satellite**

Figure 23 Two-Stage Personnel/High-Priority Cargo OTV - Boeing
INSULATED EXTERNAL TANK
FOR PROPELLANT STORAGE
WILL HOLD 1.5 MILLION LB
OF PROPELLANTS

PROCESSOR MODULE
PROCESS RATE OF
20,000 LB PER WEEK
ATTACHES TO EXTERNAL
TANK/ORBITER UMBILICALS
SHUTTLE DOCKING PORT
FOR WATER DELIVERY

SOLAR
POWER
ARRAY

SPACE
RADIATOR

SHUTTLE ORBITER
WITH WATER AS
CONTINGENCY PAYLOAD

Figure 24 In-Orbit Propellant Processing Facility Concept
THRUST (LB) 20,000
CHAMBER PRESSURE (PSIA) 2000
EXPANSION RATIO 400
MIXTURE RATIO 6.0
SPECIFIC IMPULSE (SEC) 473.0
DIAMETER (IN.) 48.5
LENGTH (IN.)
   NOZZLE RETRACTED 50.5
   NOZZLE EXTENDED 94.0

Figure 25 Advanced Space Engine (ASE) Characteristics
other characteristics must be reviewed so they are compatible with the perceived needs of the orbital transfer vehicles in the future U.S. space program including the SPS.

Certain low-thrust chemical rocket propulsion technological efforts have already been initiated to meet NASA and DOD requirements for transfer of acceleration-limited structures from LEO to GEO. These programs should be examined for their applicability to SPS and augmented where appropriate to meet those operating requirements that are peculiar to SPS. Systems analysis should be undertaken to evaluate promising concepts from the standpoint of life-cycle cost, mass, performance and environmental considerations.

Other programs in component technology should be undertaken in the areas of propellant-feed systems designed for maintainability and long operating times or intermittent operation, long-life reusable thrust chambers, control systems and utilization of low-cost materials. At the end of the next phase of the SPS, several low-thrust chemical rocket concepts will be defined to a sufficient degree to permit their evaluation for use in various SPS vehicles. Breadboard system demonstrations of the most attractive concepts could then be initiated to verify the technical merit.

A recommended program of activities is presented which will undertake to show the merits, potential and costs of chemical propulsion systems tailored to meet mission needs. The goal of this activity is to reduce uncertainties in the following:

- Performance, mass, lifetime, maintenance and on-orbit operation
- Cost comparisons and cost-estimating relationships
- Range of applicability of chemical rocket systems

With this goal accomplished, a comparison of chemical rocket and other candidate approaches (i.e., electrical and more advanced) can be conducted by the
systems contractors with the knowledge that the chemical-rocket data base will be at a high confidence level. It is recognized that the technology of other candidate systems is not as mature. Therefore, this base will serve as a measurement standard against which the performance characteristics of other candidates can be judged. Following these judgments, suitable trade-off studies can then be conducted and the lowest cost systems (including unreliability impacts) can be selected.

C. Electric Orbital Transfer Vehicles (EOTV)

It is the consensus of the working group that ion propulsion for transfer from LEO to GEO is feasible and may offer major cost savings relative to chemical propulsion. The cost savings result primarily from the reduced mass delivered to LEO. The feasibility of ion propulsion has been demonstrated in the development of a substantial body of technology, including space tests, during the past years. Since ion thrusters are more developed, they were selected for the initial systems analyses; however, other options that should be considered are described in Section F below.

Although a considerable amount of technical work must be performed before a suitable electric propulsion system is available for OTV application, the cost of this work will be small compared to the cost savings that can result. To be more specific, ion propulsion permits a reduction by a factor of 2 or 3 for the mass required at LEO to place a given payload at GEO. This major mass reduction has an associated reduction in overall cost.

EOTVs currently defined in the reference SPS by the major contractors are shown in Figures 26 and 27. A typical electric rocket propulsion system with 120-cm (46.8-in) diameter ion thrusters, using argon as the propellant, is shown in Figure 28.
Figure 26 Electric Orbital Transfer Vehicle (EOTV) Configuration - Rockwell
- INITIAL POWER = 296 MW
- ARRAY AREA = 1.5 Km²
- ELEC THRUST = 3345 N
- EMPTY MASS = 1462 MT
- ARGON = 469 MT
- LO₂/LH₂ = 46 MT

Figure 27 Electric Orbital Transfer Vehicle (EOTV) - Boeing
THRUSTER POWER SUPPLY
- DIRECTLY FROM ARRAY
- NO PROCESSING
- NO REGULATION

- NO PROCESSING
- ARRAY REGULATION
- PROCESS ALL POWER

- TYPE OF PROCESSING
  - MOTOR/GENERATOR
  - SOLID STATE

- PROCESSING THERMAL CONTROL
  - ACTIVE RADIATOR
  - 915 m²
  - LIMIT ELECTRONICS TO 200°C

Figure 28 Electric Rocket Propulsion System - Boeing
Because of the major advantages of ion propulsion for the OTV, it is clear that the following tasks should be adequately addressed at an early time:

- Demonstrate that system performance is verified and that operating constraints are quantified
- Define the operating interfaces of the system
- Establish the ecological acceptability of the system

1. Electric Thrusters

As indicated above, an argon ion thruster, of approximately 1-m diameter, with conventional power conditioning similar to solar electric propulsion system (SEPS), is the reference system for ion rocket OTV. Such a thruster extrapolated from current practice is presented in Figure 29. The performance of this thruster (thruster efficiency of over 60 per cent at specific impulses above 6,000 sec) is a major driver for system cost. Performance estimates that have been made in SPS studies to date have ranged from either conservative to overly optimistic. Adequate performance appears likely, but the extrapolation from present work is quite large.

The importance of ion thruster performance results in a requirement for ground tests of the ion thruster of the size planned. In the absence of adequate facilities, a space test would be required for verification. The facility requirements for an approximately 1-m thruster emphasize the need for preliminary tests with a smaller thruster at the earliest possible time. This smaller thruster should be significantly larger than existing 30-cm (9-in) thrusters and can be assumed to be roughly 50 cm (19.5 in) in diameter. The development of this intermediate-size thruster should permit extension and verification of scaling relationships.

Thruster lifetime is also a cost driver. The major thruster components involved in the lifetime are cathodes (both main and neutralizer) and ion optics (accelerator system or grids). Because of the larger size and mass, the ion optics
Figure 29 Ion-Thruster Technology Extrapolation - Boeing
are felt to be most important for cost. The problems involved in ion optics are replacement (refurbishment) and assembling and aligning ion-optic grids in GEO, a rather delicate operation, or replacement of ion optics complete with structural support sufficient to maintain alignment during transport from ground to GEO.

Lifetime tests should be conducted after adequate performance data have been obtained. These lifetime tests should be conducted both on the ground and in space. It is also felt that sufficiently sensitive diagnostic tests exist to permit adequate test duration to be of the order of 100 hr, if the thruster is recovered.

2. Power Conditioning

The power conditioning, like the thruster, represents a major extrapolation from present technology. To keep the cost low and reliability high, the module size of this power conditioning should be large, much larger than any existing in space or considered for any other space application. Heat rejection would, in the absence of other developments, result in modules having larger than present kg/kw ratios. A major need in power conditioning then, is to develop large, efficient and lightweight modules. A possible example of the type of development required is integration of heat pipes with the transformers.

The sequence of test proposed is, first, to develop thruster power-conditioning modules with adequate overall performance parameters. Then, at a lower priority, the interactions with an active load (ion thruster) should be evaluated and resolved.

A major reduction in power-processing mass (and perhaps also losses) could result from direct drive of ion thrusters from solar arrays. The largest power block is for the screen (ion beam) supply. The next largest block is for the discharge supply. The effective use of direct drive would be for the screen supply or for the screen and discharge supplies, with all other functions associated with conventional power conditioning.
The use of direct drive results in several interactions that should be evaluated. A major interaction is the dynamic one between the thruster and solar array. At the very least, switching of incremental array areas in and out of the circuit should be required for control. The voltages required for screen and discharge functions determine the sign and magnitude of associated array areas. The nature of interactions of these array areas with ambient and charge-exchange plasmas is thus partially determined by the choice of direct drive, if used. These plasma interactions are discussed below.

3. Solar Array

The basic, solar-array technology required for the SPS is assumed as an available base. The requirements discussed below are in addition to this base. The low end of the orbit-raising mission involves a high plasma density of \( \geq 10^5 \, \text{cm}^{-3} \). Plasma interactions with high voltage (2kV) array surfaces will therefore be more intense than at GEO. Near the thrusters there will be additional contributions to this plasma density due to charge exchange of escaping propellant atoms with beam ions. The propagation of this charge-exchange plasma is not well understood, nor are the effects of the space plasma on a high-voltage array. Other thruster/array interactions should also be included.

The plasma environment under some conditions will be sufficiently dense to assure near spacecraft-ground potential will exist outside all insulator surfaces surrounding solar arrays. Under such conditions, the insulators must continuously withstand the full local array voltage relative to the spacecraft ground. The large areas, the possibilities of manufacturing defects, defects due to poor handling during assembly, or micrometeoroid holes require that electrical breakdown failures be self-limiting. The physical processes involved in these breakdowns and the means of making them self-limiting are important areas for further experimental work.
The radiation degradation of the solar array in transfer from LEO to GEO is an important factor in solar array selection. This is in addition to the special plasma interactions faced by the OTV solar array. These special considerations for the OTV solar array indicate that serious consideration be given to a modified solar array design from that used in the SPS. For example, the inability to anneal radiation damage in silicon solar cells as indicated by the Boeing reference system, might make gallium arsenide a viable alternative for the ion rocket OTV, even if silicon cells are used on the SPS.

Environmental Interactions - Large quantities of ionized and atomic argon are expelled from the thrusters during orbit-raising operations. These large quantities raise the possibility of interactions with portions of the upper atmosphere. Because such interactions could be critical in the decision to use or not use an ion thruster, further study of these interactions is important. (See section on atmospheric effects of the SPS transportation system.)

4. Alternative Electric Thruster Systems

Other electric-thruster systems should be studied as possible alternatives. Emphasis here should be on propellants having minimal interactions with the upper atmosphere. Hydrogen appears to be a possible propellant from this viewpoint. Thruster concepts to be considered should include magneto-plasmadynamic (MPD) thrusters as discussed in the following section.

5. SPS-Focused Technology Program

The propulsion requirements for SPS require major extensions from the ion-propulsion system technology under development for planetary and geocentric applications. A focused program which would build upon the established technology is thus required to establish confidence in and define the performance envelopes of ion-thruster systems appropriate for SPS.
The three generic areas, as follows, require focused technology efforts:

- Hardware
- Field and particle interfaces
- Ecological and societal impacts

Brief discussions of each area, including summaries of the proposed technology efforts, are presented in the following paragraphs. Ground-based analyses and experiments comprise the bulk of the activity, but a Shuttle-based space test may be required to refine and corroborate the data obtained in ground tests.

Hardware Technology - Table 3 shows some of the technical areas deserving evaluation along with a summary of specific areas and rationales. It is presently estimated that a 4-yr program would be required to perform the key ground evaluation with a thruster intermediate in size between the present 30-cm (11.7-in) size and the sizes of interest of ~1 m for SPS. A flight test of a full-size thruster may be required to confirm lifetime and performance due to the expected limitations in vacuum-facility pumping capabilities in the 1986 time-frame. The power-processor technology program (primarily evaluation of high-power components) could be performed completely in ground tests.

6. Field and Particle Interfaces

The bulk of the field and particle interfaces will be adequately addressed in on-going programs. The characteristics and impacts of the low-energy plasma from SPS-size thrusters would, however, require focused evaluation. At present, adequate scaling laws applicable to the relevant thrusters' dimensions and operating conditions are not available nor are plans in existence to obtain them. As a special consideration, due to anticipated vacuum-facility limitations, the Shuttle flight test mentioned earlier would be required to refine and verify the models and experimental data obtained during the ground-based program.
<table>
<thead>
<tr>
<th>GENERIC</th>
<th>SPECIFIC</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thruster Lifetime</td>
<td>Ion optics and cathode lifetime versus thrust level</td>
<td>Thruster refurbishment presently assumed in system studies. Large EOTV-mission life-cycle-cost reductions possible if refurbishment requirements are eliminated/alleviated through increased life</td>
</tr>
<tr>
<td>Scaling Phenomena</td>
<td>Increased thrust per module</td>
<td>EOTV costs directly related to number of thrusters/PPU’s. Strong cost benefits accrue for large increases in thrust/module</td>
</tr>
<tr>
<td></td>
<td>- Thruster shape</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Increases thrust/area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Advanced plasma containment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Multiple cathodes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power processor high power component technology</td>
<td>Component powers much higher than currently demonstrated in space. Heat-removal technology required (such as heat pipes) to maintain or reduce power-processed specific mass</td>
</tr>
<tr>
<td>Reduced Cost/Mass Power Management and Control</td>
<td>Simplified power processor concepts</td>
<td>Power processor and associated thermal control systems are cost and mass drivers in proposed EOTV designs. Simplification will affect system reliability</td>
</tr>
<tr>
<td></td>
<td>- Direct drive</td>
<td></td>
</tr>
<tr>
<td>Thruster Extended Performance and Operating Envelope</td>
<td>Increased and variable thrust/power</td>
<td>Increased T/P will reduce trip times and reduce EOTV fleet-size requirements</td>
</tr>
<tr>
<td></td>
<td>- Variable specific impulse operating range</td>
<td>Variable specific impulse will allow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Use of primary propulsion systems for on-orbit propulsion</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Minimize power (energy storage) requirements during occultation phases of orbit raisings</td>
</tr>
<tr>
<td>Solar Array</td>
<td>Radiation-resistant solar arrays</td>
<td>EOTV power system environments much different than on-orbit</td>
</tr>
<tr>
<td></td>
<td>Radiation-recovery technology</td>
<td>Power degradation during orbit transfer strongly affects EOTV scenario</td>
</tr>
</tbody>
</table>
7. Ecological and Societal Impacts

The impact of the argon-ion beams on the upper geosphere is presently under study. The present situation is that large-scale uncertainties exist as to the exact interaction phenomena to be expected. Ground and space tests will probably both be required to fully understand and accommodate as necessary the operation of ion beams on the scale of SPS.

D. SPS Station-Keeping and Attitude Control

Station-keeping and attitude-control operations are performed at LEO during transfer from LEO to GEO and at GEO. These operations are required for the LEO base, for the EOTV and POTV during transfer from LEO to GEO and return, and for both the GEO base and the satellites maintained at GEO.

1. Baseline Definition

Based on the several workshop presentations and discussions with Boeing and Rockwell study personnel, information on the baseline systems for station-keeping and attitude control was obtained. Both the Boeing and Rockwell baseline systems are noted in Table 4 according to function. Differences and open issues are readily identified by this comparison.

2. Baseline Difference/Open Issues

The two contractors have decided upon varying attitude-control and station-keeping scenarios based on assumptions that greatly differ.

For several of the attitude-control system (ACS) functions and locations, Boeing has decided to use chemical (O₂/H₂) rather than electric propulsion. Their differences in Isp greatly affect the amount of propellant which must be transported, stored, etc. The rationale for Boeing's baseline is that they believe the high-velocity ions coming out of the electric thrusters may be detrimental to the personnel and materials located at the LEO and/or GEO bases. Rockwell, on the other hand, has decided to use high-performance electric thrusters using SPS satellite technology. Personnel and equipment protection would be achieved by using
Table 4  
Baseline Systems - Station-Keeping and Attitude Control

<table>
<thead>
<tr>
<th>FUNCTION</th>
<th>BOEING</th>
<th>ROCKWELL</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO Base</td>
<td>Chemical (LO₂/LH₂)</td>
<td>Electric (Ion)</td>
</tr>
<tr>
<td></td>
<td>Isp 400 sec</td>
<td>Isp 13,000 sec</td>
</tr>
<tr>
<td>EOTV</td>
<td>Electric (Ion)</td>
<td>Electric</td>
</tr>
<tr>
<td></td>
<td>Isp 7,500 sec</td>
<td>Isp 8,300 sec</td>
</tr>
<tr>
<td></td>
<td>and chemical</td>
<td>and batteries</td>
</tr>
<tr>
<td>POTV</td>
<td>Chemical</td>
<td>Chemical</td>
</tr>
<tr>
<td>GEO Base</td>
<td>Chemical</td>
<td>Electric</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Isp 13,000 sec</td>
</tr>
<tr>
<td>Satellites</td>
<td>Electric</td>
<td>Electric</td>
</tr>
<tr>
<td></td>
<td>Isp 20,000 sec</td>
<td>Isp 13,000 sec</td>
</tr>
<tr>
<td></td>
<td>and chemical</td>
<td>and batteries</td>
</tr>
</tbody>
</table>
appropriate shielding and configurations to preclude ion impact. This "health" issue must be addressed in greater depth to decide whether this is a go or no-go decision.

Boeing has baselined the use of a backup chemical ACS system for both the EOTV and satellite. Rockwell relies on the use of an electric propulsion system for these functions. Rockwell utilizes energy-storage devices (batteries) to power the electric propulsion during these periods. They would possibly have to add more thrusters and batteries to cover the higher thrust periods. It seems clear that a much more detailed trade needs to be made relative to which of these baselines is more cost effective.

Both contractors have decided to resupply the satellite ACS propellants on a regular basis. However, Boeing's baseline is that this propellant will be stored at the GEO base and transferred to the satellite's tankage. Rockwell decided that it would be better to replace the empty tanks with new tanks that have been refilled after transport down to Earth. This differing philosophy probably has a great effect on the mass transport quantities and their costs. No clear definition of why these differing philosophies have been used is apparent. Therefore, a more detailed trade study should be undertaken which will highlight which of these approaches is more cost effective.

In addition to the above, several of the baseline decisions of both contractors seem to not have a good base in existing technology. These items are discussed below.

3. Technology Issues

Included here are items which must be evaluated and tested.

   a. Electric ion thrusters

   A new, large-diameter (~120 cm/46.8 in) thruster which must be developed exceeds the size of any fully qualified thruster to date. The largest previous
device has a diameter of 30 cm (11.7 in). This advanced technological undertaking becomes an item of considerable concern. Further compounding the situation is the probable need for two different thrusters (low Isp, high thrust and high Isp, lower thrust). A demonstration of this capability for long lifetime is definitely required.

A detailed study is also needed to assess the effect of thruster exhaust particles on the vehicle and any adjacent personnel. This latter information is needed to determine if electric propulsion can be used for control operations of the LEO and GEO bases.

b. Chemical thruster

While of lesser concern than the electrical-thruster questions, information is also required on pulsing oxygen/hydrogen thrusters. Performance (400 sec Isp pulsing) and life-testing are required to show SPS applicability.

E. Intra-Orbit Transport

The need to provide an intra-orbit transport capability is implicit in the construction and maintenance approach for SPS. It should be recognized, however, that a versatile vehicle is required to meet the varying on-orbit operations requirements independent of the construction site, i.e., LEO or GEO. First, there is the requirement for delivering payload from the HLLV depot to a LEO construction base located several kilometers away or to an EOTV for eventual delivery to a GEO construction facility. Second, there is a similar requirement in GEO for an intra-orbit transportation vehicle (IOTV) to off-load payload from the EOTV and deliver it to the GEO construction base. The characteristics of such a vehicle depend on the mass of payload being delivered and the number of payload modules which must be transferred to the construction site.

A small teleoperator IOTV will be required for local utilization and
a version was conceived by Rockwell. IOTV sizing assumed a minimum safe separation distance between the EOTV and SPS base of 10 km (6 mi) and a round-trip transfer time of 2 hr. This equates to a $\Delta V$ of 3 to 5 m/sec (9.8 to 16.4 ft/sec). A single advanced space engine is employed with an Isp of 473 sec.

In contrast, the Boeing design concept for an intra-orbit personnel/cargo tug shown in Figure 30 is a much bigger, manned vehicle which obviously has a much larger payload-carrying capability.

In either case the technology to build such a vehicle is well in hand at the present time. The only technological issues concern on-orbit refueling and engine life since it is expected that the IOTV will be reusable. On the first issue, General Dynamics has done considerable work in the area of on-orbit refueling; and it is suggested that such work continue. As for the second issue, engine-life requirements, although not defined at this time, are not thought to be critical. Definitive studies to determine whether these vehicles need to be manned or can be operated remotely (e.g., teleoperator operations) also remains open to further study. It is apparent that such vehicles, if manned, could profit if dexterous manipulator capability were added to the crew cabin. Payloads could thus be moved about with comparative ease from within the cabin, thus reducing the amount of extra-vehicular activity (EVA) required of the crew and increasing their productivity. The development of a flight station incorporating such dexterous manipulators is also strongly recommended. These same manipulators are needed for closed-cabin, cherry-picker operations on the construction base. Thus, such a program would serve a dual purpose.

Once SPSs are operational, a third requirement for satellite-maintenance sortie transportation also exists. The primary function of this class of IOTV is the resupply of SPS expendables, and any maintenance support equipment needed to
NOTE:
THIS IS A PRELIMINARY CONCEPT THAT HAS NOT BEEN OPTIMIZED

1000 LB THRUST ENGINE

LO₂ TANK

≈ 15600 KG LO₂

≈ 2600 KG LH₂

LH₂ TANK

≈ 9 m

ECLSS

2-MAN FLIGHT CONTROL MODULE

DOCKING PORT

Figure 30 Intra-Orbit Personnel/Cargo Tug Concept - Boeing
keep the SPS operational. The characteristics of such a vehicle are shown in Figure 31 as seen by Boeing. This vehicle is designed to deliver supplies to 10 satellites in GEO per sortie. Its size is the same as the POTV. Beyond any technological issues mentioned previously for the POTV propulsion system, no further issues are foreseen.

Based on IOTV requirements as they are presently understood, there does not appear to be any impediments in the development of any of the different types of IOTVs needed to support SPS construction or maintenance. It is strongly recommended, however, that the following technologies be pursued over the next three to five years for the benefit of SPS:

- Development of dexterous manipulators for IOTV and cherry-picker operations to maximize man's productivity while working in space
- Continued funding of cryogenic engine development to assure the safety, reliability, and life requirements for man-rated OTVs
- Funding for the development of fluid transfer systems, and broadened scope of such studies to include all critical fluids needed to resupply operational SPSs
- Teleoperator simulations should be undertaken to determine whether construction and repair operations can be done remotely or whether man is required in close proximity to the work site

The above issues should be addressed immediately with ground-based simulations and later with STS flight simulations. The issue of man's productivity in space hinges on the results of such studies and provides credibility to the SPS concept.
SUPPLY OTV MISSION

- SUPPLIES TO 10 SATELLITES/SORTIE

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Longitude Change (Deg)</th>
<th>Time (Days)</th>
<th>Payload (MT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base to 1st</td>
<td>5</td>
<td>5</td>
<td>2050</td>
</tr>
<tr>
<td>Between ea.</td>
<td>2</td>
<td>1</td>
<td>1850 (avg)</td>
</tr>
<tr>
<td>Return to Base</td>
<td>25</td>
<td>5</td>
<td>1720</td>
</tr>
</tbody>
</table>

- OTV PROP. REQMT = 77 MT
  (CAPACITY = 200 MT)

CREW OTV MISSION

- TRANSPORT MOBILE CREW MODULE to 20 SATELLITES IN 90 DAYS
- MODULE MASS = 287 MT
- OTV PROP REQMT = 32 MT

Figure 31 SPS Maintenance Sortie Transportation Vehicle
F. OTO Advanced Propulsion and Vehicle Concepts

The large impact that the OTO transfer vehicle has on the overall SPS requires the best possible choice be made of the propulsion devices for this mission. While the ion thruster selected in both the Boeing and Rockwell studies is certainly a viable candidate for this task, it is by no means the only available option. Furthermore, the reference ion engine (~120 cm/46.8 in diameter, 8,000 sec Isp) is not within the state-of-the-art and will require substantial technological development. The decision for the choice of this engine over other candidates is not assured. In the selection of a propulsion system for the OTOTV, the evaluation of the candidate systems has been inconsistent, with a disproportionate effort being placed on the argon-ion thruster. It is recommended that the evaluation of alternate systems be given a more substantial treatment to account for both near-term applications and long-term potential. The systems to be studied, and compared, need to include MPD thrusters; solid-, gaseous-, and plasma-core nuclear reactors; and the electromagnetic mass driver as well as the argon-ion thruster. Other advanced concepts, such as laser or microwave power transmission for electric propulsion, should also be considered as should dual-mode nuclear/electric and very advanced chemical systems, which may be less conceptually developed but offer considerable potential.

The recommended study should concentrate on the optimum way to accomplish the task of transferring material from LEO to GEO. Operating costs should be included; but for the first round, it may be desirable to discount the engineering and developmental costs. Environmental considerations should be given a high priority in this study to preclude encountering severe problems later on. It is recommended that a comprehensive but relatively short-term (perhaps 1 yr) study be made of the competing advanced propulsion concepts to determine which ones best...
fulfill the needs of the SPS. At the conclusion of this study, technological assessment and component development should begin on those which prove most promising. This decision should determine which system is most practical for the GBED, which requires high reliability but not necessarily lowest cost, and the system which would best provide low operating cost but may not be available in the time frame seen for the initial power stations.

The following paragraphs briefly describe the candidate advanced-propulsion systems. Each is described with the advantages it offers, disadvantages it may have, the current status of technology, and the required technological program.

1. MPD Thrusters
   a. Potential

   The MPD thruster offers a highly attractive alternative to the low-thrust devices for OTO transportation. The advantages that the MPD thruster offers include the following:

   - High-thrust density (10,000 N/m²) that allows one MPD thruster system to replace a large number of ion thruster systems while providing an equivalent thrust level
   - Potential of reducing LEO-to-GEO transfer times down to several weeks as compared to ion thruster transfer times which are on the order of several months
   - Capability for steady state or pulsed operation that permits close impulse bit control for attitude control and station-keeping functions
   - Simpler system that offers potentially lower costs
   - Capability of operation over a wide range of propellants that permits selection of a working fluid that can provide low costs and minimal
interactions with the environment.

b. Status

The MPD thruster is in a development phase while concurrently being supported by a strong research base. The physics of this type of thruster have been researched extensively over a sizable period of time with a high level of confidence being generated in the results and with no technological barriers identified. The data base for this thruster is therefore extensive and continuously expanding. Under an on-going technological development program receiving support from both NASA and the Air Force, thruster research apparatus has provided inferred steady-state performance data in the neighborhood of 5 mW, which represents a power of interest for SPS applications and does not require an extrapolation to a desired operating power level. Performance goals of 50 per cent at 3,750 sec with argon has been established for the thruster. Recent results (40 per cent at 1,500 sec) from the research effort suggest these goals may be conservative and that performance somewhat in excess of these goals may be expected.

Major areas that are currently being addressed in the existing development program include direct measurements of thruster performance and erosion rates. The performance measurements will be undertaken in the near future. Specially designed fiberglass facilities, which provide minimum interaction between the exhaust plume and the vacuum tank walls, have been installed in a new electric propulsion laboratory at Princeton. A thruster and thrust stand have been designed, fabricated, and checked out. Installation and check out of the test set-up within the vacuum tank will occur within two months. After a shakedown phase, verification of the thruster performance data will commence. This thrust stand will also represent a powerful tool for the evaluation of changes in thruster geometry.

Tests are also underway to establish erosion-measuring techniques. Erosion
rates of operating thrusters will begin to accumulate as pulsed thruster operation at a high repetition rate can be established. Although possible in space, steady state operation in a laboratory is precluded by the high propellant throughput and low environmental pressures required. Efforts are underway, both at Princeton and JPL, to provide high repetition-rate thruster operation. A test facility to provide a high repetition rate has been designed and is expected to be in place at JPL in about one year. Erosion-rate indications will begin to accumulate at that time.

The thruster system is presently in a study phase with some experimental experience with inductive and capacitive energy storage for pulsed operation. A completely steady-state thruster system required for the SPS application has not been studied.

c. Needs

The needs represented here below require an augmentation of the present baseline MPD development program:

- System studies for SPS applications
- Development of MPD thrust system components
- Flight experiment demonstrating steady-state 5-mW operation
- Thruster interactions study for multiple thruster operation
- Augmentation of the thruster development effort for thruster optimization and lifetime demonstration tests
- System demonstration tests

2. Nuclear Electric OTV

A solid-core, nuclear-electric OTV concept is shown in Figure 32. This advanced concept has shown economical transport performance in previous studies and should continue to be studied as the SPS concepts evolve.
interactions with the environment.

b. Status

The MPD thruster is in a development phase while concurrently being supported by a strong research base. The physics of this type of thruster have been researched extensively over a sizable period of time with a high level of confidence being generated in the results and with no technological barriers identified. The database for this thruster is therefore extensive and continuously expanding. Under an on-going technological development program receiving support from both NASA and the Air Force, thruster research apparatus has provided inferred steady-state performance data in the neighborhood of 5 mW, which represents a power of interest for SPS applications and does not require an extrapolation to a desired operating power level. Performance goals of 50 per cent at 3,750 sec with argon has been established for the thruster. Recent results (40 per cent at 1,500 sec) from the research effort suggest these goals may be conservative and that performance somewhat in excess of these goals may be expected.

Major areas that are currently being addressed in the existing development program include direct measurements of thruster performance and erosion rates. The performance measurements will be undertaken in the near future. Specially designed fiberglass facilities, which provide minimum interaction between the exhaust plume and the vacuum tank walls, have been installed in a new electric propulsion laboratory at Princeton. A thruster and thrust stand have been designed, fabricated, and checked out. Installation and check out of the test set-up within the vacuum tank will occur within two months. After a shakedown phase, verification of the thruster performance data will commence. This thrust stand will also represent a powerful tool for the evaluation of changes in thruster geometry.

Tests are also underway to establish erosion-measuring techniques. Erosion
rates of operating thrusters will begin to accumulate as pulsed thruster operation at a high repetition rate can be established. Although possible in space, steady state operation in a laboratory is precluded by the high propellant throughput and low environmental pressures required. Efforts are underway, both at Princeton and JPL, to provide high repetition-rate thruster operation. A test facility to provide a high repetition rate has been designed and is expected to be in place at JPL in about one year. Erosion-rate indications will begin to accumulate at that time.

The thruster system is presently in a study phase with some experimental experience with inductive and capacitive energy storage for pulsed operation. A completely steady-state thruster system required for the SPS application has not been studied.

c. Needs

The needs represented here below require an augmentation of the present baseline MPD development program:

- System studies for SPS applications
- Development of MPD thrust system components
- Flight experiment demonstrating steady-state 5-mW operation
- Thruster interactions study for multiple thruster operation
- Augmentation of the thruster development effort for thruster optimization and lifetime demonstration tests
- System demonstration tests

2. Nuclear Electric OTV

A solid-core, nuclear-electric OTV concept is shown in Figure 32. This advanced concept has shown economical transport performance in previous studies and should continue to be studied as the SPS concepts evolve.
interactions with the environment.

b. Status

The MPD thruster is in a development phase while concurrently being supported by a strong research base. The physics of this type of thruster have been researched extensively over a sizable period of time with a high level of confidence being generated in the results and with no technological barriers identified. The data base for this thruster is therefore extensive and continuously expanding. Under an on-going technological development program receiving support from both NASA and the Air Force, thruster research apparatus has provided inferred steady-state performance data in the neighborhood of 5 mW, which represents a power of interest for SPS applications and does not require an extrapolation to a desired operating power level. Performance goals of 50 per cent at 3,750 sec with argon has been established for the thruster. Recent results (40 per cent at 1,500 sec) from the research effort suggest these goals may be conservative and that performance somewhat in excess of these goals may be expected.

Major areas that are currently being addressed in the existing development program include direct measurements of thruster performance and erosion rates. The performance measurements will be undertaken in the near future. Specially designed fiberglass facilities, which provide minimum interaction between the exhaust plume and the vacuum tank walls, have been installed in a new electric propulsion laboratory at Princeton. A thruster and thrust stand have been designed, fabricated, and checked out. Installation and check out of the test set-up within the vacuum tank will occur within two months. After a shakedown phase, verification of the thruster performance data will commence. This thrust stand will also represent a powerful tool for the evaluation of changes in thruster geometry.

Tests are also underway to establish erosion-measuring techniques. Erosion
rates of operating thrusters will begin to accumulate as pulsed thruster operation at a high repetition rate can be established. Although possible in space, steady state operation in a laboratory is precluded by the high propellant throughput and low environmental pressures required. Efforts are underway, both at Princeton and JPL, to provide high repetition-rate thruster operation. A test facility to provide a high repetition rate has been designed and is expected to be in place at JPL in about one year. Erosion-rate indications will begin to accumulate at that time.

The thruster system is presently in a study phase with some experimental experience with inductive and capacitive energy storage for pulsed operation. A completely steady-state thruster system required for the SPS application has not been studied.

c. Needs

The needs represented here below require an augmentation of the present baseline MPD development program:

- System studies for SPS applications
- Development of MPD thrust system components
- Flight experiment demonstrating steady-state 5-mW operation
- Thruster interactions study for multiple thruster operation
- Augmentation of the thruster development effort for thruster optimization and lifetime demonstration tests
- System demonstration tests

2. Nuclear Electric OTV

A solid-core, nuclear-electric OTV concept is shown in Figure 32. This advanced concept has shown economical transport performance in previous studies and should continue to be studied as the SPS concepts evolve.
Figure 32 Nuclear Electric OTV - Boeing
3. Gas-Core Reactor OTV

A nuclear-reactor heat source was considered as an alternative to the solar array to power the OTVs. The gas-core reactor was studied as the concept most adaptable to this mission and is presented in Figure 33.

The specific impulse of a nuclear propulsion system is intermediate between that of chemical systems and electrical propulsion systems as indicated below:

- $i_{\text{D}_2/\text{LH}_2} \approx 470$ sec
- Nuclear rocket $\approx 2,000$ sec
- Electric rocket propulsion $\approx 6$ to $8,000$ sec

Mass in orbit, hence cost, can be expected to be less with higher Isp.

Neutron and X-ray radiation shielding is required for reactor usage in proximity to personnel. This consideration would seriously limit the flexibility with which such a vehicle could be used. Shielding is heavy and shielding design is a difficult problem. After-heat disposal during reactor shut-down is also an important consideration. Unshielded reactors, on the other hand, would require remote handling so that malfunction repair and maintenance in space could be expected to be very difficult; however, it warrants further consideration.

The basic concept of the gas-core reactor relies on the use of thermal radiant energy transfer from a high temperature ($\sim 80,000^\circ$K) radiating fissioning uranium plasma to a submicron tungsten particle-seeded hydrogen propellant stream. The plasma is vortex-confined by a cool nonabsorbing buffer gas. In one of the several gas-core reactor concepts which have been conceived, the fuel and buffer gas flows are separated from the propellant stream in the core by a transparent wall which allows containment of the fuel within a closed-loop circuit.
Nuclear Gas Core Reactor OTV Mass Summary

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Propellants</th>
<th>Specific Impulse</th>
<th>Thrust</th>
<th>Engine Mass</th>
<th>Pressures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium - 233 dioxide</td>
<td>LH₂</td>
<td>2080 to 2425 s</td>
<td>445 to 1780 kN</td>
<td>42,000 to 91,000 kg</td>
<td>271 kN/m² (operating)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>384 kN/m² (maximum)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Stage Element</th>
<th>Mass, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structures and Mechanisms</td>
<td>18,780</td>
</tr>
<tr>
<td>Main Propulsion System</td>
<td>56,800</td>
</tr>
<tr>
<td>Auxiliary Propulsion</td>
<td>600</td>
</tr>
<tr>
<td>Avionics</td>
<td>260</td>
</tr>
<tr>
<td>Electric Power</td>
<td>480</td>
</tr>
<tr>
<td>Thermal Control</td>
<td>1,220</td>
</tr>
<tr>
<td>Growth Allowance (15%)</td>
<td>11,730</td>
</tr>
<tr>
<td>Dry Mass</td>
<td>89,920</td>
</tr>
<tr>
<td>Auxiliary Propellants and Fluids</td>
<td>2,000</td>
</tr>
<tr>
<td>Total Inert Mass</td>
<td>91,920</td>
</tr>
<tr>
<td>Mainstage Propellants LM₂</td>
<td>124,290</td>
</tr>
<tr>
<td>OTV Total Mass</td>
<td>216,210</td>
</tr>
</tbody>
</table>

Figure 33 Nuclear Gas Core Reactor OTV — Rockwell
The fuel would be processed for subsequent reinjection into the core region. Propellant exit temperatures in the range of 4,000° K to 6,700° K are predicted for the previous range of fuel-radiating temperatures. Corresponding specific impulse in the range of 1,000 sec to 1,900 sec and thrust-to-weight ratios of 0.3 to 1.3 have been estimated for engine powers of 600 mW to 4,600 mW. (Engine mass without propellant is 39,000 kg or 85,800 lbm.)

The gas-core reactor engine offers the combination of high thrust and moderate specific impulse with the result that rapid LEO-to-GEO trips can be made. Thus, perhaps as few as one vehicle would be required, consequently reducing mass in LEO. However, it must be realized that crew shielding (shallow shielding) must be incorporated that, depending on the safety considerations, will add to the engine basic weight. An assessment must also be made of potential upper atmospheric pollution.

The technology development for the gas-core reactor would probably be longer than electric propulsion devices, but the high thrust, high specific impulse combination may make the gas-core reactor a promising candidate for use in applications beyond the initial deployments.

Although the gas-core reactor requires advanced development of several disciplines, numerous "proof-of-principles" experiments have been conducted over the past 15 years. For instance, a seeded flowing gas stream (simulating the propellant) has been heated by radiation from a dense plasma to temperatures exceeding 4,000° K. A radiating plasma (equivalent black-body temperature of 6,000° K) consisting of argon and UF₆ has been successfully contained within a container of cooled fused silica without causing coating of the walls and transmitting over 90 per cent of the source radiation through the walls. A system was developed
that permitted separation of the uranium from the argon and demonstrated that recirculation of the UF₆ was indeed feasible.

While these experiments have been on a small scale relative to that required for the nuclear light bulb engine, they do demonstrate that much of the technological "know-how" necessary has been developed.

4. Mass Drivers

The mass driver reaction engine (MDRE) shown in Figure 34 and other electromagnetic accelerators such as the rail gun provide promising alternatives to electric propulsion for LEO to GEO cargo-transfer missions. The MDRE is capable of accelerating its reaction mass to 1,000 G to 10,000 G and has a high efficiency of 70 per cent to 96 per cent, which permits extremely high performance. Thrust is produced by using electromagnetic forces to accelerate a reaction mass to high exhaust velocities (10 km/sec to 30 km/sec [6.2 mi/sec to 18.5 mi/sec]). In the mass driver, reaction mass is carried in a superconducting bucket which is accelerated to the desired exhaust velocity. This reaction mass is then released and expelled from the mass driver while the empty bucket is decelerated and returned for refilling with a new reaction mass. The mass driver is a linear synchronous motor and is based on the well-proven technology of electric motors. The superconducting bucket is magnetically supported by the guide strips lining the mass driver coils and therefore has no physical contact (i.e., no friction or wear).

The MDRE has the unique feature of being able to use any material for a reaction mass and thus eliminates the need for specialized propellants. Because of this fact the reaction mass is not ionized and will be in a retrograde escape orbit, thereby eliminating the possibility of harmful effects to the ionosphere. For safety reasons, liquid oxygen or other similar material can be used as a reaction mass, rather than a solid pelletized reaction mass, to eliminate a
Figure 34 Mass Driver Reaction Engine Concept
potential hazard to other orbiting vehicles. The MDRE also has the feature of variable Isp which is easily chosen by the value of acceleration and length of the MDRE. Since the MDRE operates in the 1,000 sec to 3,000 sec Isp range with a higher thrust than that of the ion engine, shorter trip times ( ~90 days) are possible with little sacrifice in payload delivered per mission as compared to the 180- to 210-day missions for argon engines. This makes it possible to reduce the fleet size by a factor of 2 to 3 over the ion engine EOTV and reduces initial lift into LEO.

5. Other Concepts

In addition to the specific propulsion alternatives that have been discussed, there is one other propulsion system/vehicle concept that may merit serious attention. This transportation concept uses a chemical or electric propulsion system and a remote power supply with energy transmitted to the OTV by microwaves or lasers. In the SPS scenario, where the cargo OTV makes many trips between LEO and GEO, the removal of the power supply from the OTV and subsequent decrease in its mass may significantly decrease the transportation trip time. The transmission of the power by microwaves or lasers would surely be made feasible by the large development put into the SPS power transmission and conversion systems. A remote power supply for an electric propulsion OTV would eliminate the anticipated problem of degradation of the onboard exposed solar array during long transfer spirals through the Van Allen belts.
IV. OTHER MAJOR CONSIDERATIONS

A. Professional and Industrial Capabilities

The universities and technical institutes need to contribute to an SPS program in three important ways. First, they can identify areas of fundamental science and engineering which underlie the SPS in general and specific. Second, they can assist by performing research on topics of basic and applied science needed to undergird the technical and more applied tasks of industry and government. Third, they alone can provide the requisite flow of educated young people who will necessarily step into leadership roles of the program in the critical next decades.

For any of these to occur in a healthy and productive fashion requires deliberate attention from cognizant federal agencies and other interested parties. Without their close attention, financial support, technical liaison, and mutual concern, any academic effort will be sterile and the entire program will suffer. This history of past collaborations between the government agencies and the academic community bears out these generalized assertions. In those fields, especially in aerospace and associated engineering and scientific disciplines, where the pattern of sponsored research in universities has been established in the past and is generally representative of the industrial and governmental interest in an area, the reservoir of basic knowledge and the flow of creative personnel have been sustained, and the overall enterprise has been the more efficient. Where such academic support patterns have been inadequate or poorly composed, the field as a whole has tended to stumble, stagnate and overrun its supply of basic data and creative people. The specific mechanisms for stimulating the academic sector are well tried and would be equally effective in context of the SPS. They are as follows:

IV-1
- A substantial support of basic research in specific areas appropriate to the SPS program to the university prerogatives and to the interests and capabilities of the faculty and students

- A careful selection of major grants to allow the most qualified institutions to establish centers of excellence in particular fields by acquiring suitable capital, research facilities, and then developing incisive academic programs in those fields

- A program of undergraduate scholarship, graduate fellowships and assistantships to encourage the best engineering and science students to undertake studies in these fields

- Involvement of productive and articulate faculty in program planning and assessment processes by membership on advisory groups and private consultation arrangements

With the above elements functional, an ambiance of relevance and excitement develops in the academic community which seems to invigorate the professional sector and enhances enthusiasm for the program.

The aerospace industrial complex today possesses the fundamental skills, knowledge, and many of the facilities needed to accomplish the SPS program. These capabilities include conceptual design; systems engineering; experimental, development and qualification testing and manufacturing; as well as ground and flight checkout and operations.

Only a fraction of this total capability is currently directed to advanced activities of the space program. While Shuttle and some spacecraft programs are related to the SPS program, broad research and technology, and direct SPS tasks are insufficiently funded to maintain a satisfactory industrial
base during the coming decade. This base, then, will not be available when
needed. This is especially true of SPS space transportation in the areas of
advanced vehicle technology, propulsion, and operation in space. Unless
specifically provided for, capabilities in these and other areas will be
dissipated before SPS funding rises above the threshold level.

Industry needs full insight into the SPS program in order to relate its
requirements to business projections. They must be able to identify the SPS-
unique requirements for special skills and will need government support for
technological work and special facilities as well as access to government
facilities. Industry access to SPS studies, program assessment activities
and policy issues can go a long way toward preparing the aerospace sector
for a program of the magnitude of SPS, so it can plan activities to
match its expertise. Reviews of on-going programs that relate current cap-
abilities to future SPS should also be made. Finally, an informed and involved
industry can provide positive support to the SPS program through meeting with the
decision makers and through support of congressional hearings.

Professional societies offer a capability that should be utilized in
support of the SPS program. They should have access to study findings and
recommendations, should be invited to participate in program assessments, and
should be encouraged to promote symposia. Additionally, they should write
position papers and inform members of Congress.

In conclusion, the capabilities of the university and industrial
communities are needed to support and participate in the SPS program. They have
a large stake in defining, justifying, supporting and performing their roles
in the ultimate success of such a vast undertaking. Support of these vital
capabilities is necessary so their participation will be available in support
of a national commitment to the SPS program.

B. Cost and Decision-Making

The viability of the SPS concept must be assessed on the ability to deliver competitive electrical power at the utility bus bar compared to other options. An estimated cost of approximately $92 billion (1979) was derived from cost-estimating relationships and includes all research, technology and development and production of the first 5-GWe SPS. As shown in Figure 35a, transportation represents ~45 per cent of the R,T&D costs and ~25 per cent of the initial 5 GWe SPS, shown on Figure 35b. Of the transportation costs approximately half is for the HLLV. The recurring transportation, as shown in Figure 35c, is dominated by ESLEO transport which represents ~60 to 70 per cent of the costs and the recurring costs from LEO to GEO is ~ 20 per cent. The uncertainty in ESLEO transportation costs is significantly less than from LEO to GEO. Therefore, reduction in cost-risks and technology enhancement must be addressed to critical areas of the latter. In the former, low-cost operations are the key to providing competitive SPS energy for HLLV and later SSTO vehicles.

Because the final SPS must be cost-competitive with other energy systems, reduction of cost and cost uncertainty must be an objective of much of the R, T&D work. SPS space transportation has already been identified as a major cost element so that reduction of transport cost uncertainty deserves a substantial share of next-phase resources. Costs and decision-making conclusions include the following:

- ESLEO - Vehicle cost uncertainty can be reduced by specific R,T&D. Operational costs uncertainty can best be reduced by STS operations experience
Figure 35 SPS Space Transportation Costs
- LEO Operations - Man-hours are a significant cost driver; R,T&D and STS operations are needed to improve estimates of man-hours for SPS transport.

- LEO to GEO (Electric Transfer Vehicle Assumed) - Long life of photovoltaic arrays in trapped radiation environment is needed; ground-based R,T&D can significantly reduce the associated cost uncertainty. Ion-thruster development should include in-space testing; otherwise, major cost uncertainties will remain.

- GEO Operations - Personnel transfer assumes using chemical rockets and GEO activity entails major cost uncertainties. Also, extra costs are needed for safety provisions; R,T&D is necessary but not sufficient to remove these uncertainties.

At this early stage in a major program such as SPS, arguments based on comparing cost estimates for different technical approaches cannot yield valid decisions. The only way to get valid decisions based on cost-related choices is to perform continuous studies and analyses. Carefully selected research and technology work will assist in selection and in reducing cost uncertainties.

Cost and decision items that require R,T&D to reduce cost uncertainty are given below:

- ESLEO
  - Composite structure
  - Reusable cryogenic insulation
  - Reusable thermal protection systems
  - Long-life engines (many starts, few man-hours of maintenance between flights)
  - Self-test technology to reduce checkout man-hours (on ground and in orbit)
Facility/vehicle design integration, including pre-launch cargo processing and design for maintenance

- LEO TO GEO

Solar photovoltaic system degradation and annealing
Ion thrust design and qualification
Large, low-density structures
Electric power processors
Automated rendezvous and docking of large, flexible items
On-orbit servicing
Man-rating, risk assessment, safety hazard protection, rescue
Guidance and attitude control (interaction with large flexible structures)

Reasons for priority selection of the above list from the longer lists presented to the workshop are as follows:

- Propulsion efficiency (hence, mass of inert components and of propellant brought up from Earth) of the LEO-to-GEO vehicles has impact on other transport elements. Thus, the size and the cost uncertainties of all vehicles are magnified, and substantial efforts to reduce these uncertainties are justified

- Heavy lift (and, to a lesser degree, personnel transport) from ESLEO for SPS will involve vehicles of unprecedented size and number of flights. It is much too early to select a vehicle from among the practical possibilities; a design reference is useful for study but both options must be vigorously pursued. Composite structures, instead of metal tanks, are but one example of new technologies whose cost impact could be very favorable but is today unknown
- Personnel and operational costs in all phases are a major cost element with uncertainties reducible to some extent by study, analysis and simulation, but substantial cost uncertainties will remain that can only be reduced by flight experience. STS operations might well be considered as a source of data for the next phase of SPS.

- Safety criteria for personnel and redundancy of space vehicles for mass transport have not been explicitly addressed in technical planning. While percentage reserves appear to have been applied to individual designs for vehicles and in the number of vehicles hypothesized for total fleets, explicit treatment of accidents has not been undertaken. The next phase of SPS must assess the risks which can be accepted and determine the technical requirements and costs to provide STS redundancy (including design requirements for individual vehicles and extra vehicles) to reduce unacceptable risks.

- The present plan addresses hardware technology at the component and subsystem level to reduce cost and uncertainty. Transport operations, their requirements and costs for ground, LEO, GEO and intra-orbital activities are less well known and do not appear to be addressed other than in terms of the most elementary construction and manipulation capabilities. This especially applies to emergencies and recovery therefrom. While the next phase program probably cannot undertake significant efforts in this area, it should conduct studies to provide detailed estimates of these requirements to define future plans and programs for a technology verification phase.
There are other significant issues that will remain open despite analysis. One of these is the effect of all engine exhausts on the atmosphere, ionosphere, and plasma around the Earth. Because these environmental effects have a public interest element as well as a technical/cost element, extra and early attention to them is needed. The technological readiness date is an important factor in the selection of technologies to be pursued and the specific form of the R,T&D program. The rationale for the selection of specific dates appears not to be fully appreciated nor is the effect of varying the date understood.

The basic concept of technological readiness needs clarification. Can it be defined in terms of the range of uncertainty and the form of the uncertainty of both performance and cost? If this can be achieved, the user of the technology can than make the decision as to when the technology is ready. For SPS, in distinction to certain other space efforts, this question may prove crucial.

Since the operational system envisions construction of two 5-GWe satellites per year for a 30 yr-time span and eventual maintenance of 60 SPS satellites at GSO, ground and space transportation operations represent major cost and manpower uncertainties. HLLV must be turned around in 4 to 5 days. Short launch pad operations are necessary.

Airline-type operations using on-board failure prediction and autonomous operational sequencing will be required. In addition, airline cargo-type processing must be achieved, and computer-based cargo manifesting is essential to maximize payload mass per flight.

At LEO, base maintenance and repair will be required for the EOTV. Logistics and depot maintenance must be addressed to minimize manpower.
If transportation system operations and maintenance can be streamlined to levels similar to other mature transportation systems, significant cost reductions might be achieved. This would require a design that is structured for ease of maintenance and one not requiring refurbishment after each flight.

Finally, it is necessary to develop and utilize overall program evaluation and formulation tools that do not explicitly consider performance and cost uncertainties. It is also necessary to establish the value of the R&D projects and program in terms of the information to be obtained in the form of performance and cost uncertainty reductions in each program phase. In other words, the R,T&D program for SPS should be considered as one aimed at the sequential resolution of uncertainty through R,T&D. This is elaborated in Appendix A. It is strongly urged that these tools be developed and utilized in the continuing formulation of the R,T&D program of the SPS.

Cost is defined as the summation of price times quantity where the summation is across all components and encompasses labor, material, and capital. It should be noted that even if all these quantities were known precisely, the cost would still be uncertain by a possibly large factor because of price uncertainties (the cost-effectiveness ratios yield values of price but require significant assessments and do not reflect changes in the "world" relative to the "historic" world). Many of the prices may be correlated and thus averaging of higher and lower outcomes may not result. Because of performance uncertainties, the quantities (ranging from number of solar cells to number of flights) required will be uncertain. The net result is that the SPS cost (and its transportation component) will also be uncertain. In fact, the cost must be considered as being a random variable with a large standard deviation. At present, it is not realistic
to state a cost for the SPS. The only thing that can be stated with a high level of confidence is that the SPS will not be built unless it is economically competitive. This implies that there must be a high probability that the present value of the SPS will be equal to or less than the present value of the cost of other alternatives.

Concluded are the following:

- Since cost is a random variable with a long standard deviation, a single specific value of cost should not be used for decision-making

- It is inappropriate at this time to consider a decision to build (or not to build) an SPS

- It is appropriate to consider the next phase in a multi-phase program. The decision should only be to commit (or not to commit) to the next phase

- An important element of each phase is its impact on the probability of commercialization

- The SPS program should be considered aimed at the sequential resolution of uncertainty through R&D

- It is too early to base major SPS transportation decisions on the comparative costs of identified technical options. Cost uncertainties must be reduced by transport system R,T&D

- In addition to present transportation approaches, some very advanced technological options should be given a reasonable amount of attention since, if successful, they could result in a major improvement of SPS cost-effectiveness. Examples are SSTO vehicles and MPD thrusters
Personnel costs in all phases will be significant, and current operational cost uncertainty is not reducible by analysis; simulation and actual flight experience are needed to support SPS design decisions and cost estimates.

C. SPS Transportation System Funding and Timing

A GBED program has been defined for the period of 1981-1986. It incorporates the major technological areas and focuses the efforts required to resolve key issues that would affect a decision to proceed with an SPS technology-verification phase; to support societal and other nontechnical assessments; to define preferred system concepts; and to define plans for a post-GBED phase. This program is to provide a logical stepping stone toward the initial visibility needed for an evolutionary phased program definition in support of SPS program needs. A more detailed analysis of the GBED items for the transportation area shows, however, that assumptions have been made which tend to prematurely close out technical program options and constrain technological requirements. These assumptions are responsible for curtailing the level of funding effort by a factor of between 2 and 5 below that deemed productive for some areas. For example, the GBED reliance on other NASA programs to provide timely technological answers is probably misplaced; and current configuration assumptions force an underestimate of augmentation required. The GBED program for transportation alone needs a funding of $100 million for the 5-yr period of 1981-1986.

Figure 36 shows the present SPS scenario in terms of annual mass that must be lifted into LEO versus calendar years to 2040. Increases of five and ten per cent over the STS baseline capability are also indicated so that the scenario is shown to be rather unrealistically loaded in the 1990s unless a
Figure 36 NASA Space Transportation Technology Planning Scenario
(Assume Shuttle STS Baseline: 30 Tons Per Flight, 50 Flights Per Year)
major national commitment were to be made by the mid-1980s. This appears to be highly unlikely and should not be the sole or primary basis for overall planning.

Figure 37 shows the present NASA space transportation planning for SPS in terms of primary reference vehicles, and it is even more clearly shown that the technical readiness for SPS can surely not be realized while even the moderate (10 per cent) growth would be very ambitious. This would indicate that substantial revision in SPS timing should be contemplated.

D. Atmospheric Effects of the SPS

Since the atmosphere from the ground to GEO will be subject to rocket exhaust, it is expected that all regions will be perturbed by its effluents to some extent. The main reason for concern arises from both the size of the vehicles (their effluent-emission rate) and their launch frequency. In the troposphere, the ground clouds formed during launch of the HLLV, and to a lesser extent, the SSTO could give rise to some local weather modifications and effects on the quality of the air. Weather modifications can result from two sources. First, injection of the local atmosphere and possible changes in local circulation and numbers of clouds. Second, the injection of cloud condensation and ice nuclei can at a microscale affect the physical processes of clouds, a process that could ultimately influence cloud formation, precipitation, and possibly haze or fog formation. These effects arise from the entrainment of surface debris and dust, after-burning of exhaust products in the ambient air, and injection of fuel impurities. Use of fuels such as RP may lead to concentration of sulfur dioxide and other pollutants that would lead to local air-pollution problems. After-burning of even clean fuels
Figure 37 NASA Space Transportation Planning - Reference Vehicles
may result in levels of oxides of nitrogen that could lead to air-pollution problems, especially if the Environmental Protection Agency sets a fairly low NO\textsubscript{x} standard. Emissions of sulfur and nitrogen compounds could also contribute to acid rain, but the levels are not expected to be significant.

Higher in the atmosphere, no significant stratospheric impacts from the use of CH\textsubscript{4} or H\textsubscript{2} fuels are anticipated, since the exhaust products are indistinguishable from ambient constituents present in substantially higher concentrations. However, at greater heights, the atmosphere becomes increasingly rarified and consequently more susceptible to large-scale perturbations. By the same token, our understanding of such perturbations, as well as the state of the upper atmosphere, becomes less clear at very high altitudes. Scientists are currently identifying what effects could occur but are limited in their ability to predict what will occur when the SPS is a reality. Effects that could arise in the mesosphere include chemical composition and dynamic changes brought about by the addition of water vapor especially above 70 km to 80 km (42 mi to 48 mi). This water vapor could also contribute to the formation of ice-crystal clouds. The rate and location of water vapor injections will also influence ionization levels in all regions of the ionosphere from the D-region through the F-region. Injections of rocket exhaust directly in the F-region will produce dramatic reductions in local plasma density and therefore influence radio-wave propagation and, perhaps, other physical phenomena. Avoiding injections will mitigate processes (not fully understood at present) which will remove at least some of the exhaust products injected both above and below into the F-region. Of greatest concern are the long-term, chronic effects in the ionosphere of once or twice daily injections of water and hydrogen molecules over 30 or more years.
Above the F-region, the principal exhaust products will be argon (AR⁺) ions from EOTV flights and H₂O and H₂ from POTV flights. Effects may arise both from the next accumulation of H atoms and the energy associated with these injections combined with that of HLLV and PLV circularization and de-orbit burns. This addition of thermal energy and mass may lead to changes in temperature and density that could influence satellite drag and the stability of the Van Allen radiation belts. Interactions of these exhaust products with ambient neutrals and plasma will give rise to background levels of airglow which may interfere with remote sensing. Also, the thermal or radiation transfer properties of the thermosphere may be altered by the addition of large amounts of water vapor.

Finally, the injection of AR⁺ ion beams, containing both mass and energy large in magnitude compared with that naturally present in the plasma and the magnetosphere, may significantly alter both the composition and structure of this most rarified region of the satellite environment. In addition to possible alternations of the radiation doses received by vehicles in the radiation belts, such injections may alter the intensity and frequency of high-energy particle precipitation events at mid-to-high latitudes. Electromagnetic wave propagation could be influenced by plasma instabilities triggered by the AR⁺ ion injections. Finally, some consideration has been given to the influence that SPS injections in the magnetosphere may have on the solar-weather effect. A related effect would be changes that may result from AR⁺ injections on the manner in which the magnetosphere responds to changes in the solar wind and magnetic storms. Large ionospheric auroral currents associated with such storms have been observed to cause current surges and trips of circuit breakers in long-
line telephone systems and power transmission lines in northern latitudes. Alteration of the latitude at which these events occur could make their impacts on populated areas more significant.

While present knowledge does not permit a definitive statement regarding mitigating strategies, some suggestions deserve future attention. These include the use of alternative ions such as hydrogen or the use of neutrals instead of ions. Trajectory shaping, thrust scheduling, and selection of type of propellant on the basis of altitude should also be considered.

Data are needed on the concentrations and fluctuations of upper-atmospheric constituents and on perturbations caused by rocket effluents. Definitive data are needed on effects of AR+ and chemical injections above 200 km (120 mi). The GBED program should include opportunity to design experiments that could combine technology testing with atmospheric effects studies. Unless some experimental data are obtained in GBED, it will be difficult to substantially reduce uncertainties especially regarding effects above 500 km (300 mi). It is recommended that small-scale space experiments be conducted during the GBED program to stimulate the refinement of theoretical modeling technique and planning of larger-scale, more sophisticated experiments. In addition, GBED time-frame experiments will provide a basis for development and refinement of both ground-based and airborne diagnostic instrumentation.
V. CONCLUSIONS AND RECOMMENDATIONS

The primary conclusion is that the SPS space transportation studies so far conducted are well done and give confidence that with further systems analyses and substantial R,T&D existing technological concepts could provide a basis for the SPS, although timing and costs are at present highly uncertain. Advanced space transportation concepts that appear to offer greatly improved operations and reduced costs should receive emphasis in the next phase of SPS.

While it is too soon to commit to the development of specific vehicles (except a low-thrust OTV), additional analyses, and R&T (including ground and space testing) can reduce uncertainties within the decade of the 1980s. Whereas the timing of the present SPS program is clearly unrealistic with respect to space transportation, time is available to plan a proper program and establish a firm foundation. SPS should be considered basically as a global energy source of great potential that may contribute to meeting the Earth's future power needs.

The ESLEO transport requirement of SPS is a great challenge in scale and character of operations. However, an evolutionary series of heavy-lifet and personnel-launch vehicles with chemical rocket propulsion can be targeted realistically to move heavy masses into LEO for $30(1979)/kg by the year 2000. More advanced propulsion technology and vehicles may make $15(1979)/kg a goal in the foreseeable future.

Although LEO to GEO (including intra-orbit transport) with electric orbital transport vehicles appears to be promising for massive cargoes, this requirement will probably need a variety of vehicles including chemical rocket stages and much further analysis and technology attention, especially
REFERENCES

As a consequence of the manner in which this workshop report was generated, it has not been possible to identify references throughout the text. The listing of references below is offered as the best indication of the source of material of the report.


Wales, W., SPS Transportation System - Orbit to Orbit Transfer (EOTV) NASA MSFC, December 19, 1979.


APPENDIX A

SPS Research, Development and Demonstration (R,D&D)* Program Evaluation and Formulation

It is assumed that the objective of the present SPS program is the sequential resolution of uncertainty through research and development. The existence of performance and cost uncertainties leads to risk associated with continued SPS-related investments. The risk can be viewed in terms of the likelihood that energy from the SPS will cost more than the energy from other technologies. It is assumed that this objective will have to be accomplished within budgetary constraints and that all desired projects cannot be undertaken simultaneously. It is therefore necessary to be in a position continuously to evaluate projects and select the mix of R,D&D projects that maximizes benefits from limited resources.

It is important to observe that an R,D&D project yields a tangible product of economic value only upon complete development of a technology and only upon commercialization of it. In general, only the commercialization phase of every R,D&D results in direct benefits to society. There are, however, indirect benefits of energy R,D&D such as price shifts on nonrenewable resources brought about by expectations deriving from the R,D&D activities. The earlier phases of the R,D&D can be used in the decision-making process to continue the project, to change it, or to terminate it. The economic value of the earlier phases of the R,D&D process is thus the value of the information which

*Research, development and demonstration (R,D&D) used in this appendix is the approximate equivalent of research, technology and development (R,T&D) used in the text.
they produce. It is this value which one should compare to the cost of performing an R,D&D subproject when making the decision to fund it, and not to the economic value which is obtained by commercialization of the technology that might ultimately be developed as a result of the R,D&D project.*

The information becomes valuable when it is used in a decision-making process by increasing the probability of choosing the best alternative. For example, consider the decision to wager on the outcome of flipping a coin. Most would agree that a bet of $1 to 10 cents that the coin will land heads is not a good wager to enter (an expected-value decision-maker clearly would not make this wager). But it would obviously be a good wager if it could somehow be known in advance that the coin would land on heads.** In this case, the value of the information that the coin would land heads is 10 cents, the amount to be gained from its use. On the other hand, the value of the information that the coin would land tails is zero because, since the bet is on heads, the decision to not enter the wager is unchanged by this information. Before knowledge of the outcome of the flip is obtained, one can only know that there is a 50-50 chance that the coin will land on heads. Thus, before obtaining this information one can only say that there

*Although the value of information produced by an R,D&D subproject is a function of the economic value obtained by commercialization, they are significantly different quantities.

**This example is, of course, somewhat artificial since no one would wager against a sure thing; and since, if the outcome of the flip were really known in advance of the flip, the flip would be superfluous.
is a 50 per cent chance that the information will be worth 10 cents and a 50 per cent chance that it will be worth nothing; hence, the information has an expected value of 5 cents (0.5 x 10 cents + 0.5 x 0 cents). An expected-value decision-maker should be willing to pay up to 5 cents to obtain this information prior to entering the wager.

It is not easy to see how one could obtain knowledge of the outcome of a flip of a coin in advance. Nonetheless, it does seem intuitive that even imperfect information could have some value. For example, suppose the coin were selected at random from a bucket of coins, some of which were fair coins and some of which were weighted to land heads a high fraction of the time, perhaps 95 per cent. It would clearly be of value to know which type of coin was chosen and this could be determined easily by "test flipping" the coin.

Energy R,D&D is a similar process. Each R,D&D phase is a process of "buying" information on the ultimate outcome of the overall project or program. If this information makes clear the fact that the technology cannot be developed to a point of successful commercialization, the project can be terminated, thus preventing the expenditure of additional funds. If, on the other hand, the project is continued, it will be with the confidence gained from having eliminated some of the uncertainty that existed at the start.

A major difference between flipping the coin and energy R,D&D lies in the fact that the latter involves the purchase of information from a sequence of R,D&D projects that has, in the past, caused analytical complications which have prevented proper analysis of more practical problems. Recently developed techniques overcome these complications.*
The problem can be stated as the evaluation of the decision to initiate or continue an energy R,D&D project, or to commit to the next subproject, recognizing and accounting for the following:

- Nearly all R,D&D projects are multiphasic efforts. They consist of a sequential set of subprojects, each of which is funded independently based upon the results of previous subprojects (and, perhaps, upon a set of external variables, such as prices and availability of competing technologies)

- The outcome of an energy R,D&D project (or subproject) cannot be known before completing the project. If it could, there would obviously be no need to do the project.** All that can be known in advance is the range of possible outcomes and the relative likelihood that any particular outcome will occur, compared to any other outcome

*See "A Energy RD&D Project/Program Evaluation Methodology," ECON, Inc. Report No. 79-221-1, April 15, 1979, prepared under DoE Contract No. ER-78-C 05-5863. This section has been abstracted from this report.

** It is sometimes thought that R,D&D is a process of buying technology improvements. It is not. The technology improvements are available options prior to any R,D&D effort. What the R,D&D effort does is to provide the information necessary better to discriminate between the available options. The technology improvement which appears to result from an R,D&D effort actually results from the decision process following the R,D&D effort, in which the better available options are chosen for further consideration. For example, consider a battery test which determines performance as a function of a number of design parameters. Prior to the test, all design options are available alternatives but, since performance cannot be predicted as a function of design option, the better alternatives cannot be discriminated from the worse alternatives. The test provides the information necessary to make the choice between design options, but it is the choice of design option (the decision) that results in a good battery design, not the information gained by the test. Recognition of the role of the decision process in the evolution of a technology through an R,D&D project is key to this methodology of evaluation.
The economic output of each R,D&D phase is a sequential resolution of the uncertainty that exists at the start. Such an output is information upon which one may choose a future course of action from the set of alternative courses; for example, to continue, to terminate, or to continue in a modified form.

The result of an R,D&D project, if successful, is a commercial technology which, if implemented, yields economic benefit.

This statement of the problem is focused on an evaluation of the next increment of an energy R,D&D project as it is only the increment for which a commitment will be made. Since, in general, the economic output of the next increment (or subproject) of the R,D&D project will be information, the problem may be equivalently stated: Evaluate the information to be obtained in the next subproject in an energy R,D&D project. It is implicit that the next subproject is deemed economically desirable if the value of the information which it provides exceeds its cost. Other methodologies which do not explicitly address the net value of the information produced by the next increment of the project will systematically underestimate the value of pursuing the technology. This is true because they do not account for all the alternate courses of action available to the project manager.

To accomplish the above requires that both cost and performance be considered as uncertainty variables described by ranges of uncertainty and the form of the uncertainty. These estimates must be made and without the specific projects. In order to utilize these uncertainty assessments it is necessary to develop the following:
• An engineering system model that interrelates that technical performance of the pertinent subsystems and results in the determination of quantities

• A cost model that forecasts prices based upon specified economic parameters and as per the engineering system model

• A benefit model that uses market parameters and the cost (from the cost model) to obtain benefits

It is only through the use of this technique that R,D&D programs can be formulated that quantitatively consider uncertainty and risk reduction and the value of information. It is strongly urged that these techniques be developed and utilized in the continuing formulation of the R,D&D program of the SPS.
APPENDIX B
LIST OF WORKSHOP PARTICIPANTS

Carl A. Aukerman
NASA/Lewis Research Ctr.
Cleveland, OH 44135
216-433-4000

Larry B. Bassham
Aerojet Liquid Rocket Co.
P.O. Box 13222
Sacramento, CA 95813
916-355-2496

Rudi Beichel
Aerojet Liquid Rocket Co.
3244 Shasta Way
Sacramento, CA 94821
916-483-4556

M. W. Bell
Rockwell International
12214 Lakewood Blvd.
Downey, CA 90241
213-922-3241

Roland P. Bergeron
Rockwell International
12214 Lakewood Blvd.
Downey, CA 90241
213-594-3805

Ronald Boyland
Grumman Aerospace Corp.
Mail Stop A09-25
Bethpage, NY 11714
516-575-2594

George Bremer
North American Rockwell
Mail Stop AA56, Dept. 562
6633 Canoga Avenue
Canoga Park, CA 91304
213-884-2434

James D. Burke
Jet Propulsion Laboratory
180-703F
4800 Oak Grove Drive
Pasadena, CA 91103
213-354-6363

George V. Butler
McDonnell Douglas
5301 Bolsa Avenue
Huntingdon Beach, CA 92647
714-896-3600

David C. Byers
NASA Lewis Research Ctr.
Cleveland, OH 44135
216-433-4000

David B. Cagle
University of Alabama in Huntsville
Huntsville, AL 35899
205-895-6257

David L. Christensen
University of Alabama in Huntsville
Huntsville, AL 35899
205-895-6257

C. C. Christman
Lockheed Missiles and Space Co.
Dept. 61-65, Bldg. 104
P.O. Box 504
Sunnyvale, CA 94086
408-742-8646

Earle Crum
NASA Johnson Space Center
EW4
Houston, TX 77058
713-483-3083

J.P.R. Cuffe
Pratt and Whitney
Mail Stop B52
P.O. Box 2691
West Palm Beach, FL 33402
305-840-3378

Eldon E. Davis
Boeing Aerospace Corp.
Mail Stop 8F74
P.O. Box 3999
Seattle, WA 98124
206-773-8150

Gerald Driggers
L-5 Society
Rt. 1, Box 533
Cropwell, AL 35054
205-525-5767

Richard Earhart
Battelle Columbus Laboratories
505 King Avenue
Columbus, OH 43201
614-424-5068
Hans Paul  
2208 DeRussey Road, S.E.  
Huntsville, AL 35801  
205-534-7640

Eugene V. Pawlik  
Jet Propulsion Laboratory  
4800 Oak Grove Drive  
Pasadena, CA 91103  
213-354-3455

Robert W. Riebling  
National Aeronautics and Space Administration  
RST-5  
Washington, D.C. 20546  
202-755-3278

Richard Rodgers  
United Technologies Corp.  
Silver Lane  
East Hartford, CT 06108  
203-727-7227

Kenneth E. Rossman  
University of Alabama in Huntsville  
Huntsville, AL 35899  
205-232-3251

Donald Rote  
Argonne National Laboratories  
EES-12  
9700 South Cass Avenue  
Argonne, IL 60439  
312-972-3786

Robert Salkeld  
Systems Development Corp.  
266 Blood's Ridge Road  
Bear Valley, CA 95223  
213-829-7511

F. Carl Schwenk  
National Aeronautics and Space Administration  
Washington, D.C. 20546  
202-755-2450

William R. Snow  
Department of Physics  
Princeton University  
Princeton, NJ 08540  
609-452-4398

Joe W. Streetman  
General Dynamics  
6113 Portobello Ct.  
San Diego, CA 92124  
714-277-8900

Ernst Stuhlinger  
3106 Rowe Drive  
Huntsville, AL 35801  
205-534-9828

Myron R. Uman  
National Academy of Sciences  
2101 Constitution Avenue, N.W.  
Washington, D.C. 20418  
202-389-6897

Anthony R. Valentino  
Argonne National Laboratories  
EES-12  
9700 South Cass Avenue  
Argonne, IL 60439  
312-972-8060

Francis L. Williams  
Martin Marietta Corp.  
P.O. Box 29304  
New Orleans, LA 70189  
504-255-3738

Wayne Wilson  
Boeing Aerospace Corp.  
12040 Avondale Place  
Redmond, WA 98052  
206-885-2257

Gordon Woodcock  
Boeing Aerospace Corp.  
MS8R-72  
P.O. Box 3999  
Seattle, WA 98124  
206-773-7894

B-3