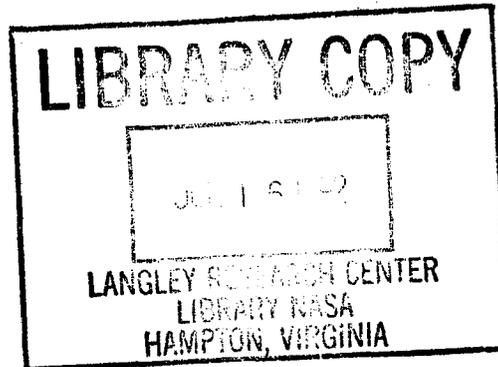


**A RAND NOTE**

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**Space and Surface Power for the  
Space Exploration Initiative:  
Results from Project Outreach**

**C. Shipbaugh, K. Solomon,  
D. Gonzales, M. Juncosa**



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MINS: / ELECTRIC GENERATORS/ ENERGY STORAGE/ POWER TRANSMISSION/ THERMAL PROTECTION

ABA: Author

ABS: The analysis and evaluations of the Space and Surface Power panel, one of eight panels created by RAND to screen and analyze submissions to the Space Exploration Initiative (SEI) Outreach Program, is documented. In addition to managing and evaluating the responses, or submissions, to this public outreach program, RAND conducted its own analysis and evaluation relevant to SEI mission concepts, systems, and technologies. The Power panel screened and analyzed submissions for which a substantial portion of

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the concepts involved power generation sources, transmission, distribution, thermal management, and handling of power (including conditioning, conversion, packaging, and enhancements in system components). A background discussion of the areas the Power panel covered and the issues the reviewers considered pertinent to the analysis of power submissions are presented. An overview of each of the highest-ranked submissions and then a discussion of these submissions is presented. The results of the analysis is presented.

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**A RAND NOTE**

**N-3280-AF/NASA**

**Space and Surface Power for the  
Space Exploration Initiative:  
Results from Project Outreach**

**C. Shipbaugh, K. Solomon,  
D. Gonzales, M. Juncosa  
with T. Bauer, R. Salter**

**Prepared for the  
United States Air Force  
National Aeronautics and Space Administration**

**RAND**

*N93-18848 #*



## PREFACE

This Note describes the findings of the Space and Surface Power panel, one of eight project panels established by RAND to evaluate submissions to the Space Exploration Initiative (SEI) Outreach Program, also called Project Outreach. Project Outreach is a NASA-sponsored program to elicit innovative ideas, concepts and technologies for space exploration. The project was sponsored by Project AIR FORCE and by RAND's Domestic Research Division, with technical oversight provided by the Assistant Secretary of the Air Force (Space).

The findings of the other RAND panels are reported in the publications listed below.

*Space Transportation Systems, Launch Systems, and Propulsion for the Space Exploration Initiative: Results from Project Outreach*, by T. Garber, J. Hiland, D. Orletsky, B. Augenstein, and M. Miller, N-3283-AF/NASA, 1991.

*Automation and Robotics for the Space Exploration Initiative: Results from Project Outreach*, by D. Gonzales, D. Criswell, and E. Heer, N-3284-AF/NASA, 1991.

*Human Support Issues and Systems for the Space Exploration Initiative: Results from Project Outreach*, by J. Aroesty, R. Zimmerman, and J. Logan, N-3287-AF/NASA, 1991.



## SUMMARY

### BACKGROUND

President Bush has called for a Space Exploration Initiative (SEI) to establish a permanent base on the Moon and to send humans to Mars. An initial step toward achieving these goals was taken when NASA and the National Space Council established Project Outreach to identify innovative approaches to the many technical challenges posed by the SEI. Individuals from academia, nonprofit corporations, for-profit companies, and the general public were asked to submit their own ideas and proposals (hereinafter termed *submissions*) on how to best satisfy SEI mission goals. RAND participated in Project Outreach by screening and reviewing these submissions for NASA and the Project Outreach Synthesis Group. All submissions received by RAND were screened, sorted into categories, and ranked within each category using a common ranking system. The highest-ranking submissions in each category were then analyzed by separate panels of experts.

A principal objective of the Space and Surface Power panel was to screen and evaluate all submissions in an unbiased manner. Each submission was scored on a scale of one to five for each of five attributes: safety, utility, feasibility, innovation, and cost. Submission scores for each attribute were weighted, added, and normalized to form a single scalar measure to rank all submissions. The submission ranking system is described in more detail in App. A.

### CLASSIFICATION OF SPACE AND SURFACE POWER SYSTEMS

In this Note, *space power systems* are defined as systems that generate, store, or deliver power for use in spacecraft or related systems. *Surface power systems* are defined as systems for use on a planetary surface other than Earth. Included in the surface power category are stationary Earth-based systems that transmit energy to spacecraft or receiving stations on nearby planets by means of light or microwaves.

The submissions screened by the Space and Surface Power panel proposed systems that can be classified into at least one of five technical areas:

- Power generation
- Power transmission
- Energy storage
- Thermal management
- Handling

Most submissions fell into the power generation area, which was further divided into five subareas:

- Solar power
- Nuclear power
- Fuel cells
- Batteries
- "Other"

The "other" category covered various unusual power sources, including unusual chemical reactions, planetary wind, nuclear pulse, and antimatter concepts. Although submissions in this subarea were more innovative as a rule, they were often evaluated as being less feasible to implement than other proposals because their development involved significant engineering uncertainties.

The power transmission area included power beaming by laser or microwave transmitters as well as power transmission using superconducting cables and fiberoptics. The energy storage area included concepts for new or improved batteries and fuel cells and the use of in-situ materials. Thermal management included submissions on heat transfer and rejection. The power handling area included a variety of topics, such as power conditioning, power conversion, the improvement of specific components, packaging, and control. Naturally, there was some overlap of technical areas. Fuel cells, for instance, can both store energy and act as a regenerative energy source.

#### **HIGHEST-RANKED SUBMISSIONS**

The Space and Surface Power panel screened 167 submissions and selected the 22 highest-ranked ones for further analysis. Table S.1 lists these 22 submissions in descending order of rank by title and Project Outreach identification number. These submissions fall into all five of the power system areas and all five of the power generation subareas. Eight of the 22 included technical backup information in addition to a one- or two-page submission summary. Backup papers were used in our detailed analysis of the highest-ranked submissions but were not considered during the screening process.

While several submissions proposed concepts similar to those found in the NASA 90-Day Study (NASA, 1989), others proposed the development of power systems not included in the NASA study. Some submissions also offered potential cost-saving concepts through

improvements of perhaps as much as a factor of two or three in the use of photovoltaic or thermionic devices, thermal radiators, and fuel cells.

**Table S.1**  
**Highest-Ranked Space and Surface Power Submissions**

Rank in Descending Order	Project ID Number	Title
1	100950	Cascade Thermionics for Space Solar Power
2	101403	High-Utilization Platinum Electrocatalysis for High-Efficiency Regenerative Fuel Cells
3	101257	Project SELENE
4	101237	Low Temperature Enhanced Electrical Storage for PV Space and Surface Lunar/Mars Power Systems
5	100772	Gas Generators for Emergency Use
6	101404	Mechanical Cell Bypass Device for Nickel-Hydrogen Batteries
7	100673	Enhanced Phase-Change Processes Using Ultrasonic Vibrations for Space Power Systems
8	101243	Surface Power Beaming for Utility Power Distribution on the Lunar/Mars Surface
9	100949	Nuclear Power for Space-Based Systems
10	100610	High-Capacity Heat Pipe Radiator
11	101221	Modular SP-100 Reactor Dynamic Power System for Lunar and Mars Surface Power
12	101266	Solar Pumped Laser Concept for Power Beaming
13	101524	Development of Optical Waveguide Solar Power System for Exploration of the Moon
14	101240	Dynamic Isotope Power System for Dedicated Emergency Power for Habitat
15	101410	Advanced Ceramic Fabric Heat Pipes
16	100216	Regenerative Solid Polymer Fuel Cells
17	100951	Fiberoptically Coupled Integrated Structure Solar Array
18	100213	In-Core Thermionic Power Systems
19	101407	Improved Performance of Nickel-Hydrogen Batteries Using Controlled Variations of Gas Pressure
20	101406	Self-Contained Forced Gas Flow in Nickel-Hydrogen Batteries
21	101222	Integrated Lunar Power Center and Simulator
22	100948	Development of In-Situ Energy Storage

In analyzing the highest-ranked submissions, we found numbers 4, 7, 8, 10, 11, 14, 18, and 22 to be especially interesting and recommended that the Synthesis Group give them special consideration. The other submissions either lacked the technical detail needed to evaluate the proposed concepts or proved to have drawbacks not found in the initial screening. The submissions that appeared to offer the best overall potential dealt with nuclear power sources, power beaming, the development of in-situ resources (including the use of solar dynamic power), and thermal management. The concept of power beaming was not included in the SEI 90-Day Study and appears to merit further consideration.

## **NOTEWORTHY CONCEPTS FROM LOWER-RANKED SUBMISSIONS**

We found that there were interesting and potentially useful system concepts to be drawn from some submissions that were not among the highest ranked. Such concepts were found in a number of submissions proposing propulsion systems that might also provide power to a number of spacecraft systems. These submissions also provided examples of how some concepts also applied to other panels, in this case the Space Transportation Systems, Launch Systems, and Propulsion panel. One such submission proposed the development of a gaseous-core nuclear reactor for spacecraft propulsion. Such a system might be able to provide a very high specific impulse and thus lead to short trip times for voyages to Mars. However, the engineering feasibility of this family of systems is very risky, in contrast to that of solid-core thermal propulsion concepts, which can build on results from the 1955–1973 ROVER/NERVA programs. The open-cycle gas-core propulsion concept is technologically more risky than a closed-cycle system because of potential containment problems, but the former may offer a higher level of performance.

Nuclear pulse propulsion concepts, such as Orion or Daedalus, could also potentially offer high performance. The Orion design developed by General Atomics would use small nuclear explosives and have reasonably low technological risk, but would have many other disadvantages, such as potentially severe usage constraints based on the Nuclear Test Ban Treaty. More speculative proposals, such as inertial confinement fusion concepts (e.g., the British Interplanetary Society's Daedalus design, or the Lawrence Livermore National Laboratory Vehicle for Interplanetary Space Transport Applications (VISTA) design, could eliminate treaty-related objections, but these concepts involve a high degree of technological risk and would probably suffer from extremely long development schedules unless major breakthroughs are made in current nuclear fusion research programs.

## **ADDITIONAL NOTEWORTHY CONCEPTS**

A number of additional concepts not suggested in the submissions are worthy of consideration by the Synthesis Group and NASA. Rechargeable high-energy density batteries may offer an energy storage capacity of about 200 W-hr/kg. Capacitors may be advanced to storing tens of W-hr/kg with rapid discharge for power conditioning. High-speed flywheels could potentially offer a form of compact energy storage. And superconducting storage rings made from high-temperature superconducting cuprates could also provide a new class of efficient and long-lived energy storage devices. High-temperature superconductivity research has shown dramatic progress, and further development is warranted.

Finally, multimegawatt, magnetohydrodynamic power systems may offer mass savings in comparison with conventional generators. However, they are considered to have a high degree of technological risk. Such systems would require large amounts of feed material and thus would have a limited lifetime in the absence of an abundant in-situ fuel source.

## **SPACE AND SURFACE POWER ISSUES RAISED DURING PROJECT OUTREACH**

A number of space and surface power issues became apparent during Project Outreach and were considered in detail in the analysis process by the panel members. Specific solutions or recommended approaches to these issues were not found; however, a number of observations were made in the course of framing these issues. These issues, briefly discussed below, must be addressed before a detailed SEI mission architecture can be transformed from paper studies into large-scale procurement programs.

### **Environmental Implications of SEI Power Systems**

A number of possible SEI space power systems will have to be tested on Earth to some degree before they can be tested further and deployed in space. In particular, nuclear systems must be ground tested in an environmentally safe manner and in accordance with congressionally approved regulations. Also, just as is done in current NASA programs, launch reliability must be taken into account in the design of future SEI space power systems, particularly in the design of space-qualified nuclear reactors, to reduce the level of environmental risk to a publicly agreed upon and reasonable level.

Submission #101257 suggests that high-powered Earth-based lasers be used to beam power to spacecraft overhead or receiving systems on the Moon. If such a system were feasible, it would pose a serious risk to aircraft, birds, and other airborne objects that could come into contact with the beam. Regulations would have to be developed for such systems, and access to surrounding airspace and land would have to be restricted for safety reasons during periods of power beaming. The Anti-Ballistic Missile Treaty may introduce complications as well.

### **Use of In-Situ Materials**

Two top ranked submissions (#100949 and #101221) propose that Lunar or Martian regolith be used as shielding for nuclear surface power systems. This idea is attractive since reactor shielding can significantly increase the mass and volume of a reactor system. The use of in-situ materials could significantly reduce reactor system launch costs. However, the cost and time required for reactor site preparation may increase substantially if the Lunar or Martian surface must be extensively manipulated to provide adequate shielding. Thus, there

appears to be a trade-off between the time and cost involved in reactor site preparation and the cost of transporting a fully shielded reactor from Earth.

### **Nuclear vs. Nonnuclear Power**

Nuclear systems offer a number of performance advantages over other power generation systems, but they are accompanied by unique safety and policy issues that could severely constrain their use in the SEI. If advanced high-performance solar power systems are deployed on the Moon, they may provide specific power levels about equal to those provided by a nuclear reactor such as the SP-100. However, to continuously produce power, Lunar solar power sources must be supplemented because of the two-week Lunar night. Solar arrays would thus have the additional job of charging heavy batteries or fuel cells during the Lunar day to provide power at night.

Solar power is an even less attractive option for Mars missions. The solar constant decreases by a factor of two during a voyage from the Earth to the Mars solar orbit. Thus, to generate the same power on Mars as it would on Earth or the Moon, a solar power array would have to have twice the area. Although the Martian night is not as long as the Lunar night, batteries or fuel cells would still be needed. Solar arrays could also degrade in an unprotected Martian environment because of the abrasive effects caused by Martian sandstorms.

A nuclear power system would not suffer from these solar power limitations and could generate the same power levels on either the Moon or Mars. And if a dynamic power conversion system is integrated with a nuclear space power system, very high specific power levels could be achieved. In addition, as proposed in submission #100949, a dual-use nuclear system could be developed to provide both spacecraft prime power and propulsion. If such a system were appropriately designed, it could be landed on the surface of Mars and could provide power to a Martian base.

It appears that nuclear power systems could offer important advantages over other systems, especially for Mars missions. However, the policy issues now looming over the use of nuclear space power must be resolved before such systems can be developed and deployed for the SEI. Foremost among these issues is official determination of a minimum safe Earth orbit altitude beyond which space nuclear power systems would be permitted to operate. SEI nuclear space power systems should also be developed in an unclassified program and designed with a sufficient margin of safety to satisfy informed public scrutiny.

### **Startup vs. Evolutionary Power Needs**

Strong weight must be given to the initial phases of any mission on the Lunar or Martian surface when mass, specific mass, and ease of system startup are all important considerations. An Earth-based power-beaming system may be used to provide power to the first robots or other systems to arrive on the Moon, but this would not be the case for a Mars mission. Perhaps the best systems for initial surface operations are passive solar-powered systems, such as those suggested in submissions #100950 and #101257. However, larger power sources would be required for more elaborate and energy-intensive operations on a remote planetary surface, in which case solar dynamic or nuclear power systems would be needed. Surface power system requirements should conform with the scale and intensity of operations planned for a surface base. For example, as the number of heavy-construction robots or human habitats grows at a surface base, so should the capabilities of the surface power system.

### **Manned vs. Unmanned System Requirements**

Important concerns in designing manned and unmanned spacecraft are the reliability, safety, and power level requirements for associated space power systems. Reliability and safety may be traded off for unmanned missions, to the extent that these elements are not vital to the support of manned missions. For example, nuclear reactors on board unmanned spacecraft may not require the amount of shielding needed for a manned system.

In contrast, human life support systems may introduce new power requirements. Life support systems requiring high power levels may be needed for manned Mars missions if magnetic shields are used to protect the human crew from high-energy solar and galactic background radiation. If such an active shield were sufficiently large (on the order of 1 m) and could support a 10-tesla field, it could shield the human crew from most solar radiation events. However, such a shield would require that large amounts of energy be initially delivered from the spacecraft's power system to the shield magnets. This power requirement alone could drive the power system design for a man-rated Mars transfer vehicle.

### **Development of New Power Transmission Methods**

Power can be distributed by means of laser or other electromagnetic beam generating systems. However, current state-of-the-art systems would be relatively inefficient because of the small antenna size used and the  $1/R^2$  loss suffered in the far-field region between antennas. In addition, power beaming through the Earth's atmosphere suffers from complications due to atmospheric turbulence. In spite of these difficulties, progress has been made in producing high-power laser systems, high-power wide-aperture optics, efficient solid-

state microwave and millimeter-wave transmitters, and in the field of adaptive optics. As suggested in a number of submissions, power could be beamed from Earth to spacecraft, from Lunar power station to exploration rovers, and (according to the most ambitious submission, #100107) from large-scale Lunar power stations to a globally distributed power reception infrastructure on Earth.

While it may be prudent for NASA to make only limited use of power-beaming systems in the SEI program, their use should still be considered. And by funding research and development of power-beaming systems, NASA can provide the groundwork for future engineering advances and potential commercial spin-offs. In the future, power beaming may perhaps be harnessed to build a new power system that will make use of the Moon's resources and thus not contribute to global warming or any other of the Earth's environmental problems.

## ACKNOWLEDGMENTS

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## ACRONYMS AND ABBREVIATIONS

$^3\text{He}$	helium-3
A	ampere
AC	alternating current
AIAA	American Institute of Aeronautics and Astronautics
AMTEC	alkali-metal thermoelectric converter
AU	astronomical unit
C	Centigrade
cm	centimeter
$\text{CO}_2$	carbon dioxide
CW	continuous wave
deg	degree
DIP	dynamic isotope power
eV	electron-Volt
EVA	extravehicular activity
F	Fahrenheit
FFRDC	federally funded research and development center
ft	feet
g	gram
GaAs	Gallium Arsenide
GeV	gigaelectronvolt
GV	gigavolt
GW	gigawatt
GWe	gigawatt-electric
$\text{H}_2\text{-O}_2$	hydrogen-oxygen
$\text{H}_2\text{O}$	water
hr	hour
HTS	high-temperature superconductor
ICF	inertial confinement fusion
IMLEO	initial mass in low Earth orbit
IOC	initial operating capability
IR	infrared
$I_{\text{sp}}$	specific impulse

J	joule
JPL	Jet Propulsion Laboratory
K	kelvin
kg	kilogram
kHz	kilohertz
kN	kilonewton
kT	kiloton
kW	kilowatt
kWe	kilowatt-electric
L-1	Lagrange point-1
LEO	low Earth orbit
LH <sub>2</sub>	liquid hydrogen
LiH	lithium hydride
LOX	liquid oxygen
m	meter
mA	milli-amp
mg	milligram
MHD	magnetohydrodynamic
mm	millimeter
MMW	millimeter wave
MW	megawatt
MWe	megawatt-electric
NaK	sodium potassium
NEP	nuclear electric propulsion
NERVA	Nuclear Energy for Rocket Vehicle Applications
O <sup>3</sup>	ozone
PEM	proton exchange membrane
psi	pound per square inch
Pt	platinum
PV	photovoltaic
RFC	regenerative fuel cell
RTG	radioisotope thermal generator
SDI	Strategic Defense Initiative
sec	second
SEI	Space Exploration Initiative

SELENE	Segmented Efficient Laser Emission for Nonnuclear Electricity
SEU	single event upset
SNAP-10A	Systems for Nuclear Auxiliary Power
SPFC	solid polymer fuel cell
SSF	space station freedom
TT	technical translation
V	volt
v	velocity
W	watt
W-hr/kg	watt-hour/kilogram
$\Delta V$	changes in velocity



## 1. INTRODUCTION

*Abs.*

This Note documents the analyses and evaluations of the Space and Surface Power panel (hereinafter called simply the Power panel), one of eight panels created by RAND to screen and analyze submissions to the Space Exploration Initiative (SEI) Outreach Program. In addition to managing and evaluating the responses, or submissions, to this public outreach program, RAND conducted its own analysis and evaluation relevant to SEI mission concepts, systems, and technologies. The screening and analysis of Project Outreach submissions were conducted on an accelerated schedule between July and October 1990, and involved staff and consultants throughout RAND's departments and research divisions.

The eight panels created to screen and analyze the submissions encompassed *the following:*

- ① Space and Surface Power ;
- ② Space Transportation Systems, Launch Systems, and Propulsion ;
- ③ Structures, Materials, Mechanical Systems, and Extraterrestrial Resource Utilization ;
- ④ Automation and Robotics ;
- ⑤ Communications ;
- ⑥ Human Support ;
- ⑦ Information Systems ; *and*
- ⑧ Architectures/Missions .

*End*

This Introduction describes the background of the SEI, the overall methodology used in submission handling, the analysis procedures, and some general results and observations.

### BACKGROUND

President Bush has called for a Space Exploration Initiative that includes establishing a permanent base on the Moon and sending a manned mission to Mars. The national space policy goals developed by the National Space Council and approved by President Bush on November 2, 1989, were the following:

- Strengthen the security of the United States.
- Obtain scientific, technological, and economic benefits.
- Encourage private sector investment.
- Promote international cooperative activities.
- Maintain freedom of space for all activities.
- Expand human presence and activity beyond Earth orbit into the solar system.

To support these goals, Vice President Quayle, Chairman of the National Space Council, asked NASA to take the lead in identifying new and innovative approaches that will be required to travel to the Moon and Mars, and to live and work productively on both. In response to the President's announcement, NASA conducted a 90-day study (commonly referred to as "the 90-Day Study") that presented a variety of strategies for accomplishing the objectives. It also solicited new ideas and concepts for space exploration through the SEI Outreach Program, which consists of three principal efforts:

1. Direct solicitation of ideas from academia, nonprofit organizations, for-profit firms, and the general public.
2. Review of federally sponsored research.
3. A study by the American Institute of Aeronautics and Astronautics (AIAA).

The results of the three efforts listed above will be presented to a Synthesis Group chaired by Thomas P. Stafford, Lieutenant General (ret.), USAF. The recommendations of the Synthesis Group will, in turn, be reviewed by NASA. From this process, a number of alternative mission paths will emerge, from which NASA may select several for detailed study over the next few years. In addition, the process is expected to yield innovative technologies and system concepts for possible development.

#### **GENERAL OBSERVATIONS ON THE SUBMISSIONS**

Our first observation was that the submissions did not contain any new scientific laws or principles, or fundamentally new technologies. For example, some submissions suggested applications of high-temperature superconductivity, which five years ago could have been considered a new technology. However, superconductivity was first discovered in the early 1900s, and the possibility of high-temperature superconductors was discussed soon afterward, so it should be understood that "new" scientific discoveries are a matter of perspective.

The submissions did contain, however, a number of old ideas that have new implications in the context of the SEI. For example, several submissions included the concept of a spacecraft hovering at a libration point, a concept that has been proven by NASA's International Sun-Earth Explorer-3 satellite, which was put into orbit around the sun-Earth libration point, L-1, in 1978. Libration concepts take on considerable new meaning in the context of potential use as transportation nodes for a Mars mission.

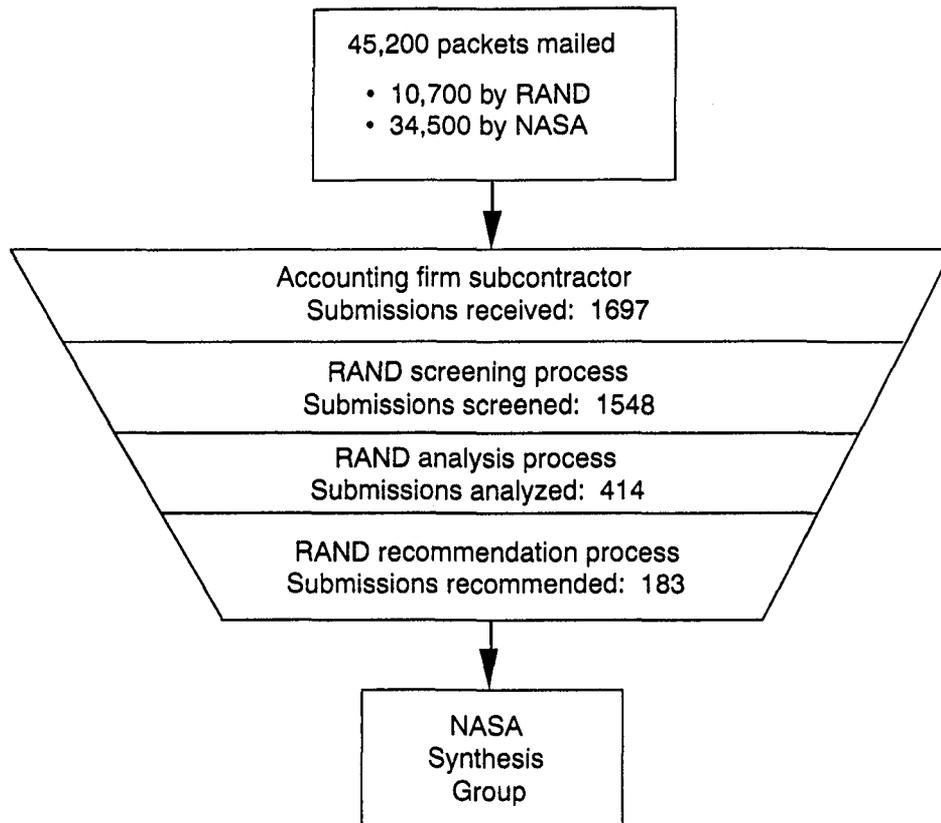
The submissions also contained ideas that had not been heretofore supported by the submitter's organization, which may have been an industrial firm, university, or NASA itself. This is a natural consequence of the priority planning process and resource allocation decisions of each individual organization. Thus, many of the submitted ideas were not completely new, but simply have not received much support.

Lastly, we observed that the submissions were sufficiently diverse to support a wide range of SEI mission concepts and architectures.

#### **THE SUBMISSION PROCESS**

Figure 1.1 presents a flow diagram of the Outreach evaluation process. RAND mailed out 10,783 submission packets in addition to the 34,500 that were mailed out by NASA. A total of 1697 submissions were received and were initially processed by a subcontractor firm, KPMG Peat Marwick. Of the 1697 submissions received, 1548 were judged by Peat Marwick to contain sufficient information for screening by RAND. The screening process selected approximately 215 submissions for more formal analysis. The output of that analysis process was the set of priority submissions and recommendations reported in this and several companion Notes.

For further discussion of the sources of submissions and their management by RAND, please see App. A.



**Fig. 1.1—RAND's Outreach Process**

## **THE SCREENING PROCESS**

The screening process objectives were to

- Assure relative insensitivity to the quantity of submissions.
- Select submissions to be analyzed at length.
- Have each submission reviewed by at least two technical experts working independently.
- Examine robustness by providing more than one ranking method.
- Maintain analytic rigor.

The first objective of the screening process was to assure a good capability to deal with the quantity of submissions, whatever their numbers. Therefore, we established a submission-processing "production line" that was insensitive to the quantity of submissions.

The next task of the screening process was to decide which submissions would be analyzed. We decided that the range and depth of our analysis would have to be a function of

(1) the resources available, (2) the perceived quality of submissions across panels, and (3) the relative importance of topics to the overall SEI program.

In the screening process, each submission was reviewed by at least two technical experts working independently. The screening process was robust because more than one ranking method was employed. A related goal was to maintain analytic rigor by maintaining a tracking systems that enabled later analysis of our methodology.

In the screening process, a group of attributes was used to evaluate each submission. The panels chose to score their various submissions using the same five principal attributes:

- Utility
- Feasibility
- Safety
- Innovativeness
- Relative cost

Each panel tailored its own criteria for scoring an attribute according to the panel's specific needs. For example, *safety* meant a very different thing to the Space Transportation Systems, Launch Systems, and Propulsion panel than it did to the Communications panel.

Attributes were independently scored by two or more reviewers on a scale of one to five, with five being the best. Written justification for the scoring was input into the text field in the database. We used a widely accepted Macintosh relational database, Fourth Dimension by ACIUS, Inc., for storing and using the various information components of each submission.

For each submission, pertinent background information was logged into the database, including the unique ID number of the submission, the reviewer, the date, the name of the panel performing the review, and the title or subject of the review. To remove any bias from the process, the panels did not have information concerning the submitter's name or organization. Reviews of the submissions were entered in a text field. Each reviewer was required to briefly explain the reasons for scoring a submission as he or she did.

If any attribute score varied by more than one among different reviews of the same submission, the submission was reviewed again, this time with the panel chairman participating with each of the original reviewers. However, there was no pressure to reach consensus.

A complete discussion of the quantitative means by which panels used their attribute criteria to rank and evaluate submissions is provided in App. A. The specific criteria used by the Power panel in assigning attribute scores are also discussed in App. A.

## **THE ANALYSIS PROCESS**

The object of the analysis process was to select the submissions to be recommended for further consideration by the Synthesis Group. Where possible, we analyzed the submissions quantitatively within the context of the important performance tradeoffs in their respective technical areas.

Each panel prepared a working draft reporting on the results of its analysis in its area of technical responsibility. Each working draft was organized into technical discussions of the important technical subareas identified by that panel. Where possible, important performance tradeoffs in each subarea were examined quantitatively.

Submissions that arrived with no backup paper, i.e., no detailed substantiating information or documentation, were analyzed in the context of the technical discussions of the appropriate subareas, thus providing necessary background. The majority of submissions did not, in fact, include backup papers, making an extended analytical discussion almost mandatory in most cases.

## **SCOPE OF THE POWER PANEL**

The Power panel screened and analyzed submissions for which a substantial portion of the concept(s) involved power generation sources, transmission, distribution, thermal management, or handling of power (including conditioning, conversion, packaging, and enhancements in system components).

The 167 submissions received by the Power panel included a number of submissions whose concepts overlapped into the areas of other panels and were, in some cases, reviewed by several panels. Transportation concepts frequently depended on the viability of some power concept. In particular, the Space Transportation Systems, Launch Systems, and Propulsion panel received a number of submissions that addressed nuclear propulsion. Also, a few submissions dealing with architectural, mission, human support, and "other-oriented" issues introduced concepts that depended on the availability of power sources. Submissions that proposed emergency devices were also an example of this overlap. For cases in which two panels reviewed a submission, each panel reached its own ranking of the submission based on its own criteria.

The average weighted scalar score was used to choose a highest-ranked sample of submissions for further analysis. In addition, four other sampling methods were used for comparison.<sup>1</sup> These other modifying methods were dominated by the attribute combinations

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<sup>1</sup>See App. A for a detailed explanation of these ranking methods.

of feasibility-safety, safety-feasibility, safety-utility, and utility-safety. In each case, the first attribute dominated the ranking order.

The 22 highest-ranked submissions were selected using the primary ranking method (average weighted scalar scoring method). A total of 41 submissions were chosen to be among the top 22 by one or more of the ranking methods. Twenty-nine appeared among the top submissions in two or more methods. This strong, though not perfect, correlation implies that the screening process was robust and consistent.

## **STRUCTURE OF THE NOTE**

Section 2 presents a background discussion of the areas the Power panel covered and the issues the reviewers considered pertinent to the analysis of power submissions. These areas and issues do not follow directly from the submissions; they were formulated by the panel to provide an analysis framework that would encompass all the submissions evaluated.

Section 3 presents an overview of each of the highest-ranked submissions and then a discussion of issues related to these submissions. The overview provides a descriptive listing of the top submissions; the ensuing discussion analyzes the submissions in terms of the main issues they either address or generate.

Section 4 offers the basic results of our analysis. It includes general findings on issues and comparisons of power areas, and it specifically highlights submissions found to be outstanding with regard to the general findings.

The appendices provide details on a number of topics and submissions. Appendix A presents the specific criteria used by the Power panel reviewers to evaluate the submissions and the relative weighting of the criteria. Appendix B lists all Power panel submissions by title and ID number. Appendices C through J present analyses of the top submissions that were accompanied by a technical backup (i.e., submissions that included several pages of background describing the technology involved). Appendices K through O discuss concepts that were raised in submissions not ranked among the top group but that are nevertheless important and interesting. Finally, Apps. L, M, and N discuss fusion reactors, antimatter energy sources, and gas core nuclear reactors, respectively.

## 2. TECHNICAL AREAS AND ISSUES

In this section, we first discuss the general technical areas into which power systems were classified for study. We then examine the broad issues that we considered relevant to the study.

### TECHNICAL AREAS

The Power panel was concerned with the following five technical areas, each of which has a number of subareas, as shown in Fig. 2.1:

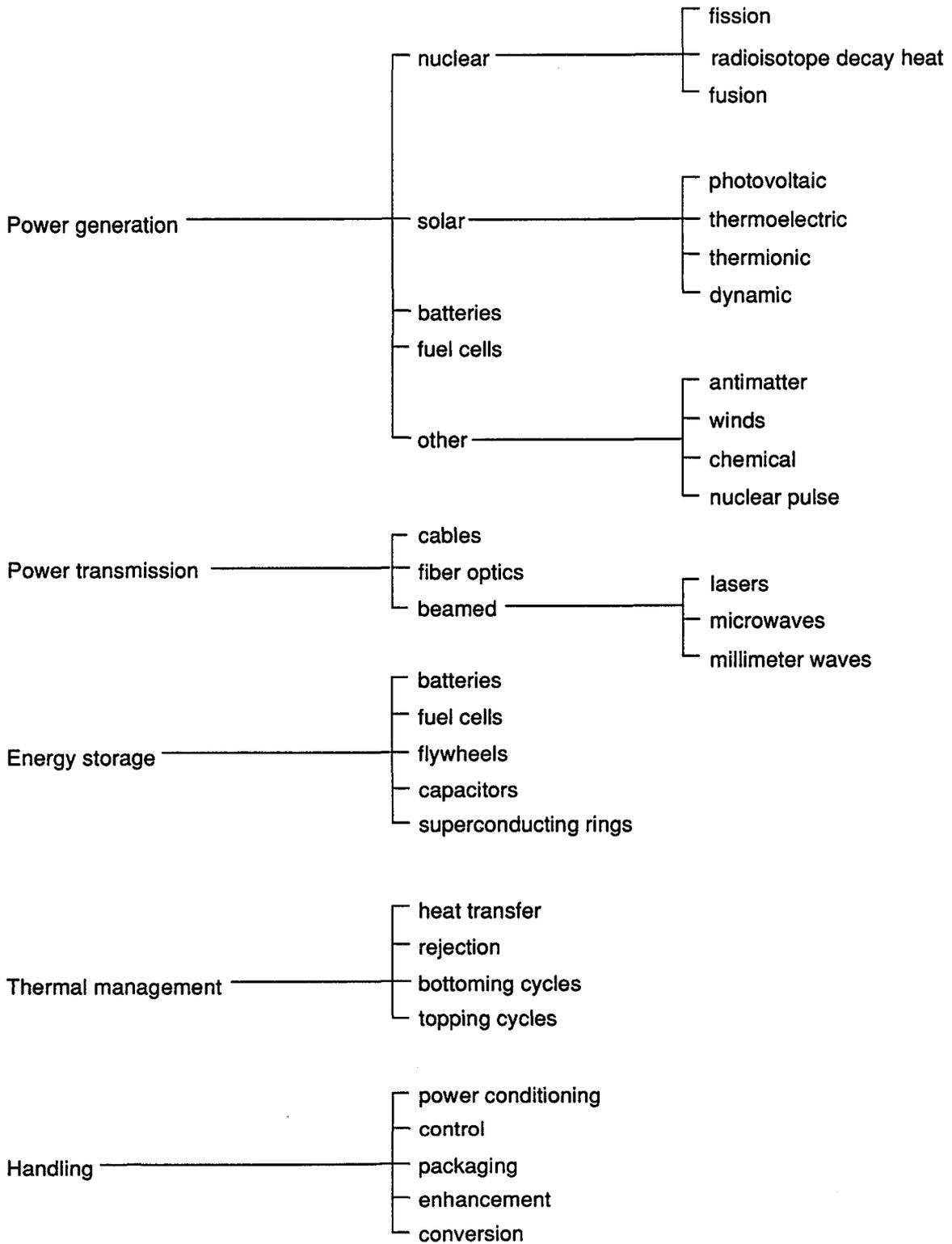
- Power generation
- Power transmission
- Energy storage
- Thermal management
- Handling

We next offer a general explanation of what these areas cover and of some of the potentially applicable technologies within each of them.

### Power Generation

Power generation, the area concerned with the source of energy for the system, had a number of subareas—nuclear, solar, batteries, fuel cells, and a loosely defined category of “other” concepts. (Some variants of the first four subareas are baselines in the NASA 90-Day Study—see NASA, 1989). When a submitted concept fit the subject area of two panels, (e.g., a transportation idea that emphasizes the utility of a particular source of power, such as controlled thermonuclear devices or nuclear explosives to drive an interplanetary vehicle), that concept became a subject for both panels.

Nuclear power generation can be derived from fission reactors, the decay of radioisotopes, or, possibly, nuclear fusion. Solar power generation includes photovoltaic, thermoelectric, thermionic, and dynamic concepts. Batteries can provide power for limited applications or backup systems. Fuel cells can be used to supply power and, in a regenerative system, would be used in tandem with another power generation concept. Some other sources of power that might be considered include various chemical reactions (liquid hydrogen/oxygen, solid propellant gas generator, etc.), magnetohydrodynamic generator,



**Fig. 2.1—Surface and Space Power Areas**

alkali-metal thermoelectric converters (AMTEC), planetary winds, antimatter, and nuclear pulses.

Average and peak power levels, mass, and specific power are some important measures of performance for power generation systems. Many other factors must be considered in evaluating these systems including safety, risk of development (e.g., what is the expected time schedule and probability of achieving development milestones within the time frame of the SEI), availability of fuels, lifetime, reliability, and cost.

### **Power Transmission**

The area of transmission was used for any concept for transporting power. Submissions in this area could introduce concepts significantly different from baseline concepts and thus deserving of attention for their innovation and potential utility. Within a structure or on a planet's surface, it is possible to transmit power (1) over a network of cables (possibly cooled or superconducting), (2) in the form of light in fiber-optic cables, and (3) through space by means of lasers, or by microwave or millimeter-wave (MMW) devices. Beamed power is the only one of these three forms of transmission suitable for long distances through space from point to point, unlike the former two possibilities, and might be practical on the Moon. Losses, power densities, and distance of transmission are important measures of performance for these systems.

### **Energy Storage**

The energy storage area concerned any concept for retaining energy for later use. Some of these concepts also fell into the area of power generation, but many were distinct. Rechargeable batteries can be used as a storage system to supply such needs as might occur during eclipse or the Lunar night. Regenerative fuel cells similarly function as storage devices. Flywheels, capacitors, and superconducting rings are other concepts for power storage, as distinct from power generation. Storage capacity, deliverable rate of discharge, and lifetime with respect to depth of discharge are important measures of performance for these systems.

### **Thermal Management**

Thermal management was the area that covered thermal storage concepts and heat transfer and rejection. This area overlaps that of energy storage for in-situ thermal storage. As applied here, we are concerned not with storage of heat for later use as a power source but with storage as a means of handling system heat. Heat pipe and radiator mass and volume requirements are important for space systems. In-situ thermal storage concepts might be

relevant for Lunar surface missions. It is important to compare Brayton, Rankine, and Stirling thermodynamic cycles for dynamic systems. Thermoelectric and thermionic cycles require careful consideration of topping and bottoming cycles. Measurements of efficiency and radiator mass per unit of power generated are important measures of performance for these systems.

### **Handling**

The area of handling included power conditioning, control, packaging, and the enhancement of specific components or power conversion devices. Steady-state requirements must allow for night, eclipse, and emergency conditions. Packaging defines the ease of adding additional units, melding components into a hybrid system, and initial power delivery, as well as the potential for evolution of initial or early power systems. The environment maintained for systems affects efficiency via such variables as radiation and temperature, and also is a factor in reliability because of such risks as those posed by micrometeoroids or debris. Mass and volume are important measures of performance (and in general are important to the other power system areas), as are any benefits from improving power efficiency or extending power availability to remote sites.

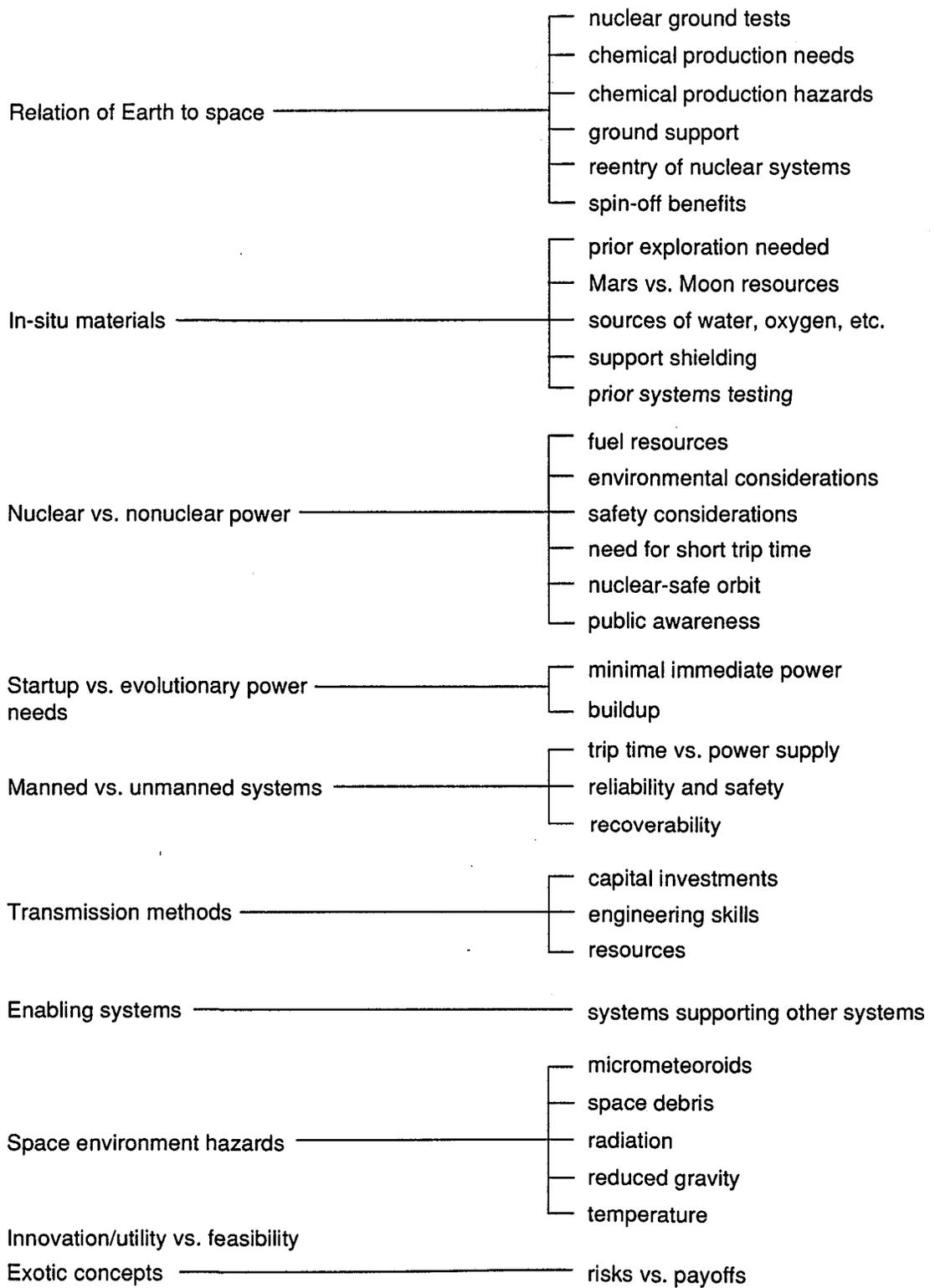
### **TECHNICAL ISSUES**

Figure 2.2 lists the ten issues relevant to the Power panel. These issues overlap in some cases, but we believe this set illustrates the breadth of concerns to address when examining space power systems. Each issue generates a number of topics to consider.

### **Space Power and Earth Support**

Generating power for space raises a number of technical issues for both development tests and the infrastructure maintained on the Earth's surface. First, the use of Earth facilities limits the space power that can be supplied. Earth support for space power involves ground testing, manufacturing, and, in cases that entail sustained use of space power sources, further Earth support operations. There is thus the question of how such Earth-based operations affect the cost, time and safety involved in making space power systems available. Continued reliability of ground facilities will affect some space power operations. A related question is how space power affects the Earth in terms of such issues as safety and spin-offs.

The production of toxic chemicals or materials with special properties may impose demands on industries. Toxic chemicals (e.g., PU-238 for radioisotope sources) or materials with special properties, (e.g., GaAs for solar arrays), including space-qualified photovoltaic



**Fig. 2.2—Issues Relevant to Power Concepts**

materials, may be available in only limited supplies. Another supply problem is that some power concepts may require massive, expensive initial mass in low Earth orbit (IMLEO).

There may be subtle concerns associated with supplying a space operation from ground facilities. Laser siting needs some redundancy of sites for power beaming/receiving to reduce the likelihood of downtime. This requirement might increase the cost of a power beaming concept.

The need to conduct ground tests of nuclear propulsion systems impinges on the issue of whether to pursue nuclear or nonnuclear systems. For instance, the time schedule for developing a nuclear system depends on when ground station testing can be done, which in turn is affected by concerns about the safety of nuclear testing on Earth. Nuclear ground tests must be environmentally as well as technologically acceptable.

The reentry of nuclear systems or impacts on launch are additional environmental issues affecting the Earth. These issues are addressed by using nuclear-safe orbits,<sup>1</sup> reactors designed to resist criticality upon core compaction, and reactors and radioisotope sources that remain intact during crashes or any other accidents.

The development of space power concepts may give rise to spin-offs beneficial to Earth systems, such as electric transportation.

### **In-Situ Materials**

Proposals for in-situ use of materials found on the Lunar surface or Mars present both possibilities and concerns. Some possibilities for using these materials as structural material, shielding, or storage media were proposed by some submissions. One issue is the trade-off between the utility of such concepts and the large amount of on-site activity needed to configure large masses or structures. There is also the question of how much prior exploration is needed, and the related consideration of how the Moon and Mars differ in resources. Where will water or oxygen-liberating compounds be found? What resources are valuable, and how might we find and learn how to exploit them?

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<sup>1</sup>Altitudes above at least 700 km are necessary, depending on the ballistic coefficient of the satellite and the solar effects on the upper atmosphere. The actual number could vary from about 1000 to about 2000 km. It is a subject of debate and may never be clearly resolved. Halo orbits around the sun-Earth system (e.g., L-1) could offer considerable advantage for storage stability.

Proving the technology on Earth requires some simulation of extraterrestrial operations. Demonstrating viable mining technology, such as extracting suitable quantities of Al or O<sub>2</sub> given the power supplies that will be available, is an example.

If fusion can be realized, the Moon offers a prospect for an advanced fuel. <sup>3</sup>He might be mined from the Lunar surface and used in aneutronic fusion reactors without producing the same quantities of radioactive materials found in deuterium-tritium fusion. However, sustained controlled thermonuclear reactions have not been demonstrated with deuterium-tritium, which is relatively easy to achieve in comparison with burning <sup>3</sup>He, so the technology risk for this application is high. There is also the issue of competition by burning deuterium which is relatively plentiful and extracted with little difficulty from water on Earth. The drawback to deuterium fusion is that it liberates neutrons and tritium. Although <sup>3</sup>He is rare and difficult to extract, there are sources on Earth. The issues concerning <sup>3</sup>He are, how expensive is it to produce, where is it available for practical purposes, can it be ignited, and does the large relative reduction of neutrons justify the drawbacks?

#### **Nuclear vs. Nonnuclear Power**

The issue of whether to use nuclear or nonnuclear power is central in planning for space operations and must be resolved. Nuclear power is of high utility, but safety considerations must be given the highest importance. There is thus a trade-off limit on risk and benefit that must be understood by all parties to space exploration, including the public.

As the risks and benefits are evaluated, the public and policy makers must be informed about nuclear safety practices in a credible fashion if unfounded emotional concerns are to be resolved and decisions made based on sound technical understanding. It will likely be necessary to demonstrate very large benefits.

There should be different considerations for continuously active radioisotope sources and U-235 fueled fission reactors. Obviously, the launch of a U-235 reactor that contains no fission products should not be considered a high-risk operation. There may be potentially hazardous materials such as beryllium present, but these would not exceed the conventional risks posed by other launch features.

Radioisotopes are a source for concern, and every effort must be made to ensure the intact recovery of a source in the event of a launch accident. Intact recovery should, in principle, be considered plausible. In the case of reentry, there are two choices: intact recovery or burn up.

Given the feasibility of storage in nuclear-safe orbits, re-entry should only be a concern for the lower range of low Earth orbit (LEO). However, this lower range is the easiest to reach, the safest from a space environment perspective, and for many applications the best region for orbits (e.g., imaging satellites that require resolution).

One risk trade-off issue is nuclear safety vs. the benefit of short trip time or, in the case of nuclear electric propulsion (NEP) cargo, the benefit of decoupling manned vehicles from unmanned supply trips. To some degree there are nonnuclear alternatives to shorter trip times, although there are practical limits driven by the specific energy differences of nuclear and nonnuclear sources.

In addition to the risk to people, the risk to materials needs to be considered. Composites could be weakened by neutron effects, and this weakening could affect, say, the heat transfer systems.

#### **Startup vs. Evolutionary Power Needs**

Some concepts consider high-utility approaches to power but do not consider the fact that personnel who are on the Moon or a planetary surface performing extensive setup activities will need to have handy a small but adequate power source. A source need not be evolutionary for a one-time mission, but a more permanent presence calls for systems that can be extended or supplanted. The passive nature of photo cells makes photovoltaic arrays an attractive initial power source.

#### **Manned System Needs vs. Unmanned System Needs**

The issue of an appropriate power system for manned vs. unmanned missions affects different areas, e.g., launch cost and initial operating capability (IOC). Reliability and safety may be traded off for unmanned missions, to the extent that these elements are not vital as support for manned missions. For instance, the need for shielding differs for nuclear unmanned vs. manned missions.

There are also power needs for life support systems. A potentially demanding system would be a magnetic shield to protect humans against background cosmic radiation. Such a shield would require a large energy investment to establish the magnetic field (and some need to cool the magnets, if they are superconducting). Active magnetic shielding was analyzed in detail by the Life Support panel; a brief discussion is given below.

We can derive a crude estimate of the amount of power needed for a shield against a large spectrum of cosmic rays. By equating the force associated with the radial acceleration of a charged particle in a magnetic field with the Lorentz force exerted by the field, the radius of curvature,  $r$  (meters), or the trajectory of the particle in the field,  $B$  (teslas), can be described as a function of the particle's momentum,  $p$  (gigaelectronvolts/c), and charge,  $Q$  (expressed in multiples of electron charge):<sup>2</sup>

$$0.3 Br = p/Q$$

For protons incident at a few GeV/c or less, a field of 10 teslas over a region on the scale of a meter is a sufficient shield to deflect the incident particles. Thus, in principle it should be possible to build a magnetic field to shield against solar cosmic rays (which in large flares can be potentially lethal) and a significant fraction of the charged portion of the galactic cosmic radiation background. This field does not shield against neutral radiation or charged particles with a high momentum (i.e., protons with momentum greater than 10 GeV/c). To the extent that background neutral radiation must be shielded against, the bulk of the shielding might be placed within the magnetic field to minimize secondary production. Production of neutral pions (which decay into gamma rays) and high-energy photon secondaries can pose a threat to electronic equipment in power systems by producing electrons via further electromagnetic showers.

From a power perspective, the bottom line is the energy,  $E$ , needed to provide a specified level of protection.  $E$  is a product of the volume,  $\Delta V$ , of the field region and the magnetic field energy density:

$$E = (B^2/2 \mu_0) \Delta V$$

where  $\mu_0$  is the magnetic permeability of free space. In practice, an integration must be performed over the field region. At 10 teslas, a field region of a few hundred cubic meters would require  $10^{10}$  J. This is a huge energy requirement but not an impossibility. Note that the general dependence of volume on  $r^3$  means that the energy tends to be minimized (for a given threshold of protection) by increasing  $B$  rather than  $r$ . Superconductors can eliminate the resistive losses, and the cooling system becomes the power driver. The current density is

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<sup>2</sup>The general motion is that of a helix along the field lines, so more generally the pitch would be included. What concerns us is the circular dimension needed to deflect a particle out of the field region; i.e., the width of the field region should exceed the Larmor diameter,  $2r$ .

another driver. A safety issue is the consequence of a quench in which superconductivity is lost and explosive heating of the material is a danger to surrounding structures.

### Transmission Methods

Once a power source is selected, the power distribution or transmission paths must be evaluated. Power can be distributed by electrical cables (perhaps cooled or even superconducting), laser or microwave beams, conduit pipes for liquid hydrogen and liquid oxygen (LH<sub>2</sub>/LOX), or even fiber optics.

Methods dependent on conduits or cables require some investment in laying down these networks and, just as critically, a fair amount of extravehicular activity (EVA) to inspect, repair, and upgrade them. Some techniques may integrate pipes, lines, or cables into structures or planetary and Lunar surfaces in such a way as to render maintenance impossible. The lack of air on the moon, which makes spacesuits and complicated EVA necessary, is an advantage for power beaming because there is no medium to cause thermal blooming, refraction, scattering, etc.

Power beaming is cited as a way of alleviating the problems of deploying and maintaining transmission media (and the materials properties limitations of such media), but power beaming has its own problems: divergence vs. range, aiming and tracking difficulties, atmospheric effects (if power is beamed from or to the Earth's surface), collection efficiency (which might be a function of divergence for vehicles, whose spot size increases as the vessel recedes from the transmitter), safety (e.g., if aiming at a rover), size of aperture and related optics problems, and choice of wavelength (which figures into both atmospheric-band absorption effects and the diffraction-limited divergence of a beam).

The distinction between near- and far-field power beaming must be considered with regard to applications. In the near-field, the Rayleigh range describes a distance, **R**, over which the beam rays remain parallel for a laser (or for which the beam "is not formed" for a microwave antenna) and that is a function of the beam diameter, **D**, and wavelength,  $\lambda$ :

$$R \sim D^2/\lambda$$

For a wavelength of a few microns (short-wavelength infrared [IR]), an aperture 10 cm in diameter would result in a Rayleigh range of several kilometers. The diffraction-limited spread angle,  $\theta$ , of the beam beyond this region is approximately

$$\theta \sim \lambda/D$$

and depends on the geometry of the aperture. The aperture diameter is given by the last element in the optical system that handles the beam. It is advantageous to have large apertures close to the source. In general, the diffraction limit is of greater importance than near-field considerations in determining the smallest achievable spot size for an optical system.

### **Enabling Systems**

Some concepts require an enabling system. Regenerative fuel cells require an external power source to perform electrolysis. Initial power may be needed to start pumps in some dynamic systems. Storage systems must sometimes be considered in the context of their power generation source.

### **Space Environment Hazards**

The degree of space environment hazards is an issue. The effect of kinetic impacts (debris, meteoroids) in LEO is a consideration for orbital power supplies and for mirrors in particular. Long-term micrometeoroid impacts on such components as photovoltaic arrays may be an issue for Mars vehicles or Lunar surface operations. The radiation effects of the Van Allen belts are of concern for higher orbits in LEO. Also of interest are the electrical effects of solar flares on a Moon or Mars vehicle. The reduced-gravity environment might impose some pump requirements, and certain types of batteries may be restricted to surface use. Temperature variations mean that certain requirements, such as the need to heat solid polymer fuel cells, must be examined. The effect of ultraviolet radiation on materials is a potential problem for components (e.g., radiator components) whose large surface areas may be subjected to prolonged exposure. Also, the deleterious effect of atomic oxygen on materials should be considered for the upper atmosphere.

One special hazard requiring consideration is the effect of background galactic cosmic rays. The Human Support panel is quite interested in the effects of such rays on the crew, but their effects on equipment are also a matter of concern. One particular concern could be whether single-event upsets (SEUs) in electronic equipment will prove troublesome to a large, long-term presence and will require remedy in special cases. Another special concern is the very highest energy region of the cosmic ray spectrum. A class of events, Centauro, has been claimed to attain energies of as much as  $10^{20}$  eV.<sup>3</sup> To put that figure in

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<sup>3</sup>Centauro events get their name from the observation that on the order of a hundred secondary particles can be produced in the primary interaction between the Centauro particle and a target atomic nucleus. It is not entirely clear what types of particles initiate the events. They are thought to be coming from such specific astronomical objects as binary X-ray sources, which means they must be neutral in such cases because galactic magnetic fields would otherwise bend their trajectories and make

perspective, the highest-energy particle accelerators on Earth are only on the order of  $10^{12}$  eV. In principle it is possible for Centauro events to contain enough energy to boil many drops of water (by the energy from a single subatomic particle!), were the energy confined locally. In fact, a spread-out shower of high-energy secondaries is expected if a Centauro particle interacts with a nucleus in a vehicle, habitat, or shield. Such a shower could be potentially hazardous, perhaps to equipment, but the chief interest in Centauro studies is scientific curiosity. Showers containing up to  $10^{11}$  particles averaging about 1 GeV each have been observed near sea level, dispersed over many square kilometers. Particles giving rise to such Centauro events are thought to be extremely rare and to have a flux of perhaps one per square kilometer every few decades. However, there are large uncertainties in the flux.<sup>4</sup> Experiments with the Fly's Eye detector in Utah are being conducted to investigate this interesting phenomenon.<sup>5</sup>

### **Innovation/Utility vs. Feasibility**

The concepts for space power and propulsion sources involve both near- and far-term technologies. The problem of deciding between concepts that are highly innovative and promise great utility and concepts with strong feasibility but high development risk thus arises. The selection process is biased against risky, unproven concepts. Some concepts may promise an extremely high payoff but have only a marginal chance of being developed in an engineering sense in the next 20 years. The use of gaseous core fission reactors for a Mars vehicle is an example of a system that has low demonstrated feasibility but would have high utility if it could be demonstrated.

### **Exotic Concepts**

More difficult to reconcile innovative but risky concepts that are basically sound is the problem of how to regard concepts that obey the laws of physics and offer extremely high payoffs but have no certain engineering route at present. Included in this category would be nuclear fusion and antimatter applications. In the latter case, one significant question is whether inertial confinement fusion can leverage off antimatter. Some of these exotic

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their origins indiscernible. Gamma rays have been offered as candidates, but some high-energy physicists dispute this explanation. Very few Centauro events have been observed.

<sup>4</sup>It is necessary to collect a sufficient sample of any shower of particles produced, subsequent to the primary Centauro-nucleus interaction, to allow reconstruction of the incident Centauro particle's energy and direction. With a large enough sample of observed events, the uncertainties in both the energy spectrum and the flux of Centauro events might be reasonably resolved.

<sup>5</sup>As an example, a scientific study to explore the nature of high-energy showers has been proposed by E. C. Loh, et al. (1990).

concepts seem to warrant an aggressive research program; others may have an extensive history but still remain unproven.

### 3. DISCUSSION OF SUBMISSIONS

This section begins by briefly discussing the top 22 submissions—i.e., the set, of submissions that received a scalar average of 4.0 or greater (see Table 3.1). This overview is intended to provide a descriptive listing of the highest-ranked submissions.

Following the overview is a discussion of the submissions in terms of the issues raised by the framework discussion of Sec. 2. Submissions that included technical backups (i.e., for which there was more technical information) are further analyzed in individual appendices.

Only 14 percent of the full set of 167 submissions arrived with a technical backup paper. However, 36 percent of the top 22 submissions handled by the Power panel contained a backup. This higher percentage for the top 22 is not a product of the screening process, since the screening was performed without examining the backups. An in-depth analysis of each of the eight top submissions that had backups is given in Apps. C through J.

A few submissions that did not receive high scalar rankings were judged interesting based on innovation and utility. The concepts embodied in these submissions are discussed in Apps. L through O.

#### HIGHEST SCALAR-RANKED SUBMISSIONS

The 22 submissions selected for analysis by the Power panel reflect all five of the main power areas. The greatest emphasis was, however, on power generation, a reflection of the overall trend for all of the power submissions. Of the 22, five proposed nuclear fission or radioisotope concepts, three emphasized solar power, three advocated battery improvements, two proposed fuel cell improvements, three dealt with power beaming, one advocated the emergency use of chemical generators, one proposed in-situ storage, three addressed thermal management, and one emphasized the handling of components. The least represented area was "handling," which included discussions of power conditioning, control, packaging (system configuration), and enhancement to specific components or power conversion devices (such as turboalternators).

**Table 3.1**  
**Top 22 Submissions by Ranking**

Submission ID	Avg Scalar	Title Subject
100950	4.55	Cascade Thermionics for Space Solar Power
101403	4.45	High-Utilization Platinum Electrocatalysis for High Efficiency
101257	4.40	Project SELENE
101237	4.35	Low Temperature Enhanced Electrical Storage for PV Space and Surface Lunar/Mars Power Systems
100772	4.32	Gas Generators for Emergency Use
101404	4.31	Mechanical Cell Bypass Device for Nickel-Hydrogen Batteries
100673	4.25	Enhanced Phase-Change Processes Using Ultrasonic Vibrations for Space Power Systems
101243	4.23	Surface Power Beaming for Utility Power Distribution on the Lunar/Mars Surface
100949	4.23	Nuclear Power for Space-Based Systems
100610	4.22	High-Capacity Heat Pipe Radiator
101221	4.20	Modular SP-100 Reactor Dynamic Power System for Lunar and Mars Surface Power
101266	4.18	Solar Pumped Laser Concept for Power Beaming
101524	4.16	Development of Optical Waveguide Solar Power System for Exploration of the Moon
101240	4.16	Dynamic Isotope Power System for Dedicated Emergency Power for Habitat
101410	4.15	Advanced Ceramic Fabric Heat Pipes
100216	4.13	Regenerative Solid Polymer Fuel Cells
100951	4.10	Fiberoptically Coupled Integrated Structure Solar Array
100213	4.06	In-Core Thermionic Power Systems
101407	4.05	Improved Performance of Nickel-Hydrogen Batteries Using Controlled Variation of Gas Pressure
101406	4.01	Self-Contained Forced Gas Flow in Nickel-Hydrogen Batteries
101222	4.01	Integrated Lunar Power Center and Simulator
100948	4.00	Development of In-Situ Energy Storage

Within this limited set of selections, one would not expect all subareas to be represented, and this is the case. Some subareas do not appear to be as viable as others; e.g., wind power on Mars is relatively unattractive, as discussed in some detail in App. K. Further, the submission pool may not have been large enough for us to have the best possible representative submissions in all subareas, so there may be viable concepts that do not appear in the top-ranked selections.

**Cascade Thermionics for Space Solar Power (#100950)**

Submission #100950 primarily addressed the concept of generating solar power by stacking three thermionic conversion devices in a topping/bottoming cycle configuration with a peak temperature of 2600K and a sink temperature of as low as 500K, to increase the efficiency of cells from 15 percent to a predicted 51 percent. This is an interesting concept, but more so for surface power than for space power because in space one expects to reject

heat at a temperature that is about 75 percent of the source temperature in order to optimize efficiency and the size of the heat-rejection system. There might be surface applications in space missions in which larger radiators are possible, and there may be possible spin-offs for Earth-based systems.

The technologies this submission wants to draw upon are (1) close-spaced (SAVTEC) thermionic converters, (2) converters with "transparent" collectors, (3) cesium-barium converters, and (4) oxygenated converters. SAVTEC has been patented, and the other technologies are currently being investigated under experimental programs or are under consideration for experimentation.

### **High-Utilization Platinum Electrocatalysis for High-Efficiency Regenerative Fuel Cells (#101403)**

Submission #101403 proposes to enhance proton exchange membrane (PEM) fuel cells via a technique for increasing the accessible catalytic surface, which puts this submission within the areas of power generation, power storage, and, to some degree, handling. The technique reduces the size of platinum particles and provides a surface to support them, enhancing surface catalysis, saving on the mass (and cost) of platinum required, and improving efficiency. The submission proposes reducing the cost of platinum by a factor of 20 and the PEM stack volume and weight by a factor of 10, and estimates a 20 percent increase in efficiency. The submission (without backup) feasibility data claims (1) 0.5 mg Pt/cm<sup>2</sup> used compared to 4 mg Pt/cm<sup>2</sup> stated for state of the art, (2) 500 mA/cm<sup>2</sup> achievable compared to 50 mA/cm<sup>2</sup> state of the art, and (3) operation at 0.96 V compared to 0.8 V for state of the art.

One problem with fuel cells has been oxygen overvoltage, and a remedy has been to use chlorine for high efficiency. If the concept offered in this proposal is viable, it is a worthwhile alternative.

### **Project SELENE (#101257)**

The Project SELENE (Segmented Efficient Laser Emission for Nonnuclear Electricity) submission proposes the delivery of 3 MWe power to a 75 m<sup>2</sup> photovoltaic (PV) receiver on the Lunar surface from an Earth-based laser, with emphasis on developing the associated optics. This submission thus falls into the areas of power generation, transmission (beam), and handling. The emphasis in this submission is on the development of adaptive optics for transmission through the Earth's atmosphere. The submission claims that the approach will make feasible low-weight telescopes and beam expanders having apertures in excess of 15 m at optical wavelengths, which the submission notes to be in excess of anything yet developed. The submission also proposes that the laser be used for laser electric propulsion.

This idea is interesting but not new. As the submission points out, a lot of effort has been expended on large aperture optical systems, and it is not clear to what extent achievements from a crash program such as the one proposed can be expected.

**Low Temperature Enhanced Electrical Storage for Photovoltaic Space and Surface Lunar/Mars Power Systems (#101237)**

Submission #101237 proposes the improvement of electrical component performance, putting it in the area of handling. This submission proposes (1) the cooling (liquid nitrogen, LN<sub>2</sub>) of materials to enhance electrical performance, and (2) a study to determine the effects on performance of such materials as pure aluminum (impurities can reduce both electrical and thermal conductivity). The submission offers as examples a 20 to 25 percent increase in capacity gained by cooling the storage capacitors, an increase in efficiency from 35 percent to 50 percent for an alternating current (AC) rotary alternator by using pure aluminum, and an efficiency increase to 70 percent with cooling.

This proposal is interesting for the very simplicity of its concept. The study proposed might yield some areas of significant benefit. New developments in materials and the (established) benefits of component improvement by lowering temperature are a plus.

The trade-offs on efficiency improvements vs. the mass, volume, and cost of the cooling system must be demonstrated for a large number of specific components. However, in many cases this demonstration will be clear and routine (e.g., many resistors have well-established performance trends as temperature is lowered).

**Gas Generators for Emergency Use (#100772)**

The concept of using solid-propellant gas generators as emergency power or oxygen sources is proposed, and thus falls under the area of power generation and overlaps with human support considerations. This is an established concept and is not innovative, but is seen in many applications today. The utility and reliability of air bags in automobiles is one example of an emergency system relying on gas generation from a solid. The concept of breathable oxygen must contend with the need to filter any other products.

The submission proposes a general concept rather than elaborating on technical details.

**Mechanical Cell Bypass Device for Nickel-Hydrogen Batteries (#101404)**

Battery reliability improvement is proposed by submission #1014045, which falls under the areas of power generation, storage, and handling. This submission proposes implementation of a device that will reduce the failure probability of battery systems by

overriding impaired cells by "an improved electrical current bypass in the event of an open cell."

Although the concept is technically not dismissible, the proposal does not provide technical elaboration or backup and cannot be evaluated further. Nevertheless, this concept could be useful if it can be demonstrated.

#### **Enhanced Phase-Change Processes Using Ultrasonic Vibrations for Space Power Systems (#100673)**

Submission #100673 proposes improved high-capacity energy storage of phase-change materials. This submission, which falls under the area of thermal management, suggests that ultrasound be used to remove voids in materials experiencing phase changes, since problems associated with voids are aggravated by the space environment. Specifically, void formation is not predictable, and surface burnouts or large temperature gradients become issues.

This idea seems to be a good one to explore and has been used a great deal in other contexts. An example of an area in which phase-change material is useful is portable life-support systems for spacesuits (with a wax that melts when too hot and solidifies in shade).

The concept has potential if (1) there is a problem with bubble development in a phase-change medium and (2) there is weak gravity, unlike that found on Earth.

#### **Surface Power Beaming for Utility Power Distribution on the Lunar/Mars Surface (#101243)**

Submission #101243 advocates the use of laser or microwave power transmission. The concept is not novel and should work for some applications. It may be of interest in some special cases, such as for a Mars rover, but it does not seem to be a central technology. There is a risk for manned applications, since laser reflection may be great enough to cause problems on manned rovers. Microwave transmission to supply points could have low power densities but might have spillover risk.

#### **Nuclear Power for Space-Based Systems (#100949)**

The use of an ENABLER nuclear thermal rocket fission reactor as a dual source of transportation and prime power is proposed in submission #100949, which falls in the area of power generation. The closed Brayton cycle advocated for the power conversion unit uses turboalternators to provide the output from the gas-cooled reactor. The proposal also advocates the tunability of the system from a few kilowatts to megawatts-electric. A 1-MWe plant is estimated to have a mass of 10,700 kg, including a 1565-kg tungsten shield, a 740-kg

LiH shield, and a 2955-kg radiator with an efficiency of 19.6 percent. Radiation is estimated at 5 rem/year at 500 m.

The ENABLER produces several gigawatts-thermal. Experience with the NERVA programs gives some plausibility to solid core fission rockets, although the engineering development of dual systems is not as straightforward as developing the technology for propulsion only.

#### **High-Capacity Heat Pipe Radiator (#100610)**

Submission #100610, which addresses the use of thermal management to save launch mass and volume costs, is a very interesting concept with a potentially high payoff for power systems, given the space-mission demands on heat transfer and rejection. A coiled pipe that consists of layers of ceramic and metallic materials and that can be unfurled for deployment is proposed. The specific mass of the radiator is estimated at  $0.7 \text{ kg/m}^2$  (which would be an order of magnitude improvement), the room temperature heat rejection is 6 kg/kW, and the coiled diameter is reported as 30 cm for a 1- to 10-kW radiator.

This idea should probably be pursued, based on its technical soundness and utility.

#### **Modular SP-100 Reactor Dynamic Power System for Lunar and Mars Surface Power (#101221)**

Submission #101221 primarily addresses power generation and proposes the use of an SP-100 system with a dynamic rather than a thermoelectric conversion device to raise the power level to 600 to 800 kWe. Brayton or Stirling engines with an efficiency in the range of 20 to 30 percent are proposed for development. This approach will require some development, but since the SP-100 program is firmly established, there appears to be strong motivation to pursue it. The dynamic system gives a large advantage in efficiency over the thermoelectric (baseline 100 kWe). A Brayton cycle might be better at higher power levels, and a simpler Stirling cycle might be better at lower levels.

The submission proposes a modular approach when higher power needs are encountered.

#### **Solar Pumped Laser Concept for Power Beaming (#101266)**

Submission #101266, which primarily addresses transmission, suggests that a 100- by 10-m PV receiver with a 10 percent laser efficiency could provide a 100-MW laser output (if attainable; solar pumping might be more inefficient). The general idea has been around for some time and has serious technical problems in pointing and in overall energy efficiencies. It is not clear that this concept would contribute to the SEI, although success in transmitting

more modest power levels through the atmosphere could have benefits for optical communication systems. Aiming will depend on the distance between transmitter and receiver and the associated apertures. Atmospheric transmission needs to be studied and established.

**Development of Optical Waveguide Solar Power System for Exploration of the Moon (#101524)**

Submission #101524 proposes the distribution of concentrated solar radiation to a protected location by fiber optics. This form of transmission could offer some protection against the degradation found from beginning-of-life to end-of-life (which can be as high as 30 percent for PV systems in LEO). A concentration factor of 1000 to 10,000 is proposed. If this concept is plausible on a large scale, some activity will be required to deploy the cable network. Trade studies will have to address the length of routes, whether they are to be buried, and the number of distinct cables.

**Dynamic Isotope Power System for Dedicated Emergency Power for Habitat (#101240)**

Submission #101240 proposes the combination of 2.5 kWe Brayton cycle dynamic isotope power (DIP) modules to provide for a habitat in the event of a disabled central power supply. This concept, which is not new, is much like one of the 90-day Study baseline concepts and could be important as a way to provide an auxiliary power supply. For this specific proposal, one issue is selection of the power level. The module size should be scalable over the range of a few kilowatts according to the amount of plutonium per unit; perceived mission needs should be the driver.

At a mass of 2000 kg, the specific power is not outstanding. Turbine reliability is a question. A Stirling cycle might be more reliable and a reasonable choice for the low power levels.

**Advanced Ceramic Fabric Heat Pipes (#101410)**

Submission #101410, which falls under thermal management, addresses the use of fabric composites to decrease the mass of a heat rejection system by 50 to 90 percent over present systems. High-strength ceramic fabrics are bonded with thin metallic foils, with the outer ceramic functioning as a load-bearing composite and the inner liner as a permeability and pressure boundary for the working fluid. The operational capability is cited as 20 to 1800 K.

### **Regenerative Solid Polymer Fuel Cells (#100216)**

Submission #100216 proposes to make a solid polymer fuel cell (SPFC) (H<sub>2</sub>-O<sub>2</sub>) regenerative and have it serve not only as a storage and power source during the dark portion of an orbit but also as an electrolyzer during the sunlit portion. This concept is an extension of baseline ideas. The development of a polymer fuel cell that might operate at temperatures of 50 to 80° Celsius rather than several hundred degrees Celsius is proposed (the low mobility of ions in solid polymers has generally required higher temperatures for operation). The temperature environment must be maintained. The concept's spin-off value for electric vehicles and utilities is also advocated in the proposal.

### **Fiberoptically Coupled Integrated Structure Solar Array (#100951)**

Submission #100951 falls into the area of handling. It proposes that structures be designed to protect photocells from the space environment. Studies to determine the effect of integration on structural integrity, the amount of fiberoptic cable required, aiming at the sun, collectors, and response to radiation environments would be needed. The proposal cites protection of the photocells from micrometeoroids as an advantage and claims (without backup) that the integrated structure would provide power with less than 2 percent degradation over spacecraft lifetime.

### **In-Core Thermionic Power Systems (#100213)**

Submission #100213 proposes the use of in-pile conversion cells in a nuclear reactor to extract high specific power at a high temperature. The emitter temperature is high (1800 K) for efficiency, and the reactor temperature must be higher. The 1800 K temperature is presented as demonstrated technology, and the 2200 to 2400 K is presented as an advanced technology requirement. The thermionic cells are the size of "D" flashlight batteries and produce 100 to 200 w each. Heat rejection occurs at the collector at 1000 K by a coolant loop from converter to radiator.

This in-pile concept is an approach to avoiding heat transfer problems. The submission states that an advantage of this concept is the ability to use modular thermionic cells to vary the power level. The proposal suggests that a core melt is not a problem up to a few megawatts, and that the risk of "core compaction" is small.

This concept is an attractive option and should receive a thorough technical review. Neutronics and high-temperature materials may be issues.

### **Improved Performance of Nickel-Hydrogen Batteries Using Controlled Variation of Gas Pressure (#101407)**

Submissions #101404, #101406, and #101407 all propose handling improvements in the performance and reliability of batteries. If specific technical concepts are validated, such improvements would be of some interest. The extent of the performance improvement cannot be estimated, however, because of the conceptual rather than technically detailed nature of these submissions.

Submission #101407 proposes that thermal management be improved by making hydrogen pressure adjustments to lengthen the total number of cycles. This concept and #101406 are plausible, but neither provides technical elaboration.

### **Self-Contained Forced Gas Flow in Nickel-Hydrogen Batteries (#101406)**

Submission #101406 is similar to #101407. It proposes improved battery efficiency leading to greater specific power. It indicates that internal moving parts are not needed, but external parts support convection and hydrogen transport to chemical-reaction sites. It proposes cells that would be smaller in volume than those for conventional nickel-hydrogen batteries, with a resultant cost savings.

### **Integrated Lunar Power Center and Simulator (#101222)**

Submission #101222 advocates an integrated project to study nuclear power, radioisotope production, and utilization of waste heat and in-situ resources. The submission is conceptual in nature rather than a detailed technical elaboration. The use of waste heat for farming and processing Lunar materials is suggested, although without detailed proposals. While it is not clear to what extent waste heat can be used for processing, its value to agriculture may be of interest.

### **Development of In-Situ Energy Storage (#100948)**

Submission #100948 addresses thermal management. It proposes the use of in-situ thermal energy storage in conjunction with an advanced solar dynamic generator. The specific mass quoted, 100 kg/kw, appears to be quite low. If validated, this concept would be attractive if a nonnuclear power source were chosen. The development of in-situ material is promising but of less obvious immediate practicality, since it requires some investment in setup activity.

## **ANALYSES OF SUBMISSIONS BY ISSUES**

We now discuss the submissions in terms of the issues delineated in Sec. 2.

### **Space Power and Earth Support**

Ground testing of nuclear systems must be done in an environmentally safe manner, and launches of radioisotope units must take into consideration launch reliability. Much of the technology required for submission #100949 was developed under the NERVA project. Some engineering development does, however, remain, which raises the issue of ground testing of nuclear systems. Submission #101240 requires large quantities of  $^{238}\text{Pu}$ , which raises problems. Production of this isotope is costly, and an accident at launch would focus attention on safety issues.

Submission #101257 requires the development of an Earth-based infrastructure of laser and associated optics at several sites. Sites would have to be chosen based on atmospheric conditions (climate, cloud cover, and altitude) in order to minimize transmission interference. Laser transmission would have to be done without endangering safety. For this reason, as well as concern about beam degradation via atmospheric effects, the slant angle should not be too great.

### **In-Situ Materials**

In-situ use of materials was treated by several of the top submissions. Submission #101948 raises the issue of what is a reasonable amount of initial EVA to invest to increase a surface habitat's capabilities with quantities of material that cannot feasibly be sent from Earth.

Submissions such as #100949 and #101221 lead to speculation about the use of the Lunar or Mars surface for radiation shielding. The geography is different, but craters or soil in either case are possibilities. There is an added complication to submission #100949—since the nuclear reactor is a dual-use reactor already activated from providing propulsion for the trip to Mars, shielding for its on-site use must be in place.

Submission #101222 is a rather ambitious proposal that suggests designing reactor systems whose waste products (heat, radiation) are exploited for such purposes as processing materials. The feasibility of such an approach is in question for a Moon mission.

### **Nuclear vs. Nonnuclear Power**

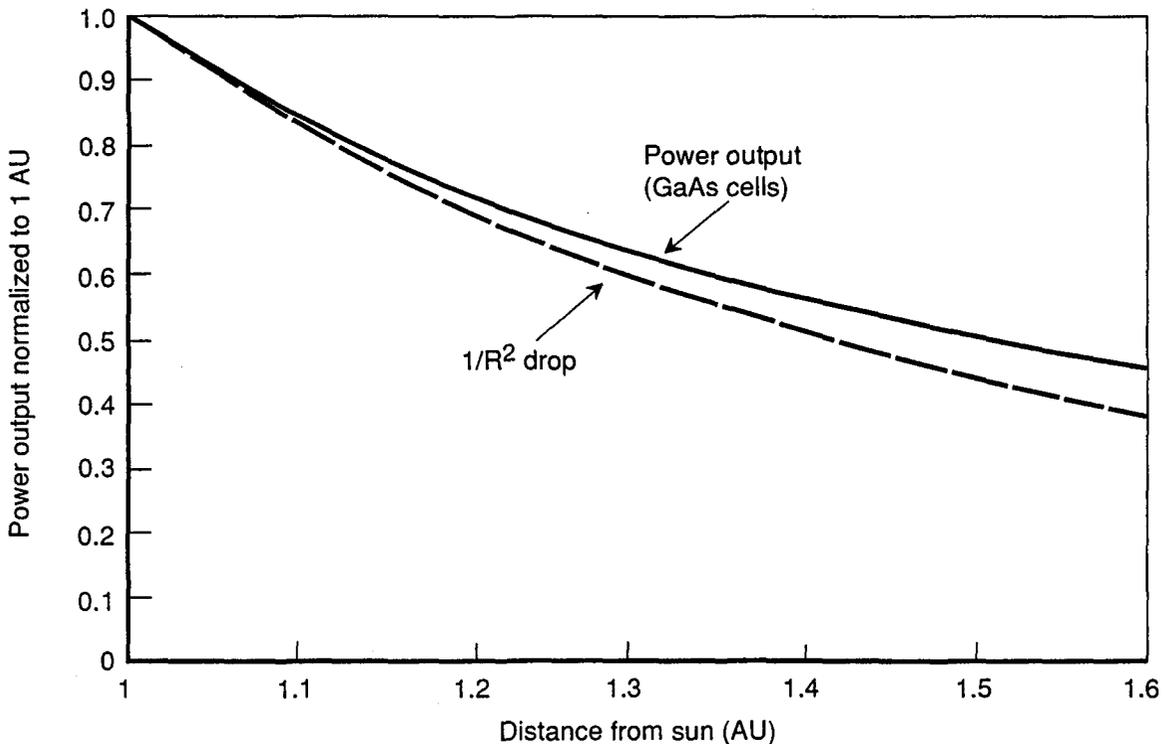
Nuclear systems offer a number of performance advantages over many other systems, but they involve unique safety and policy issues. Submission #101221 is closer to a baseline concept; although not high on innovation, it is high on utility and is illustrative of the high potential for nuclear systems. The mass of an SP-100 system is expected to be on the order of 3000 kg, depending on the shielding and power level. The specific power goes up as the power level increases. Of course, when modularity is invoked to go to higher power levels,

the scaling up may not quite reap the full extent of the power-to-mass benefits expected for large nuclear systems. Modularity has the advantage of reduced development costs and gives the potential for a family of different sizes, but it gives up the efficiency advantages of dynamic systems that offer much better power-to-weight ratios as the power level is increased. Modules offer some redundancy but could have common fail modes if there is a design problem under some operating condition.

There may be distinctions between the relative value of nuclear and nonnuclear (e.g., solar) systems on Mars or the Moon.

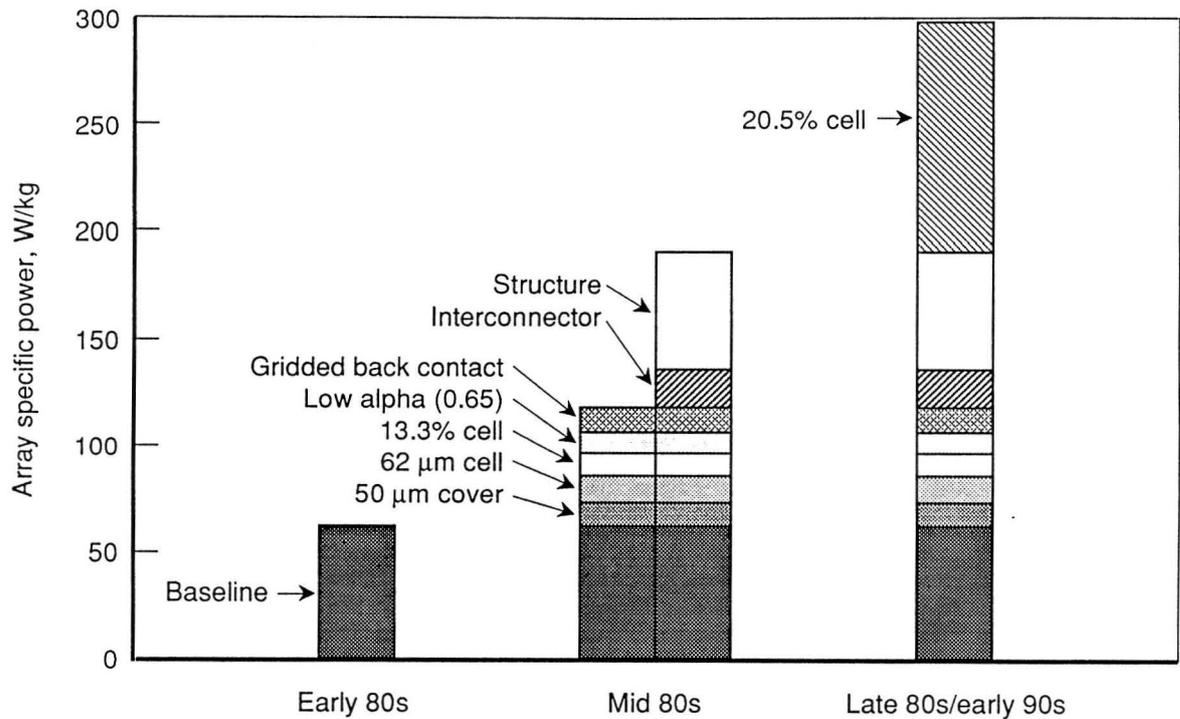
Figure 3.1 shows the solar power loss as a function of distance while traveling from the Earth to Mars. While a solar electric power unit may have an advantage over a nuclear electric power unit in that the latter cannot operate below the safe operational altitude above the Earth, a solar unit on a space vehicle would exhibit a marked decline from initial power during the Mars trip (i.e., a reduction by a factor of two).

In contrast, Figure 3.2 shows a time line for the improvement of solar array power. Improvement over the situation prevailing in the early 1980s by a factor of more than four might result, exceeding the performance of the SP-100 unless it adopts a dynamic conversion unit.



SOURCE: JPL (1989).

Fig. 3.1—Solar Photovoltaic Array Power Versus Distance from Sun



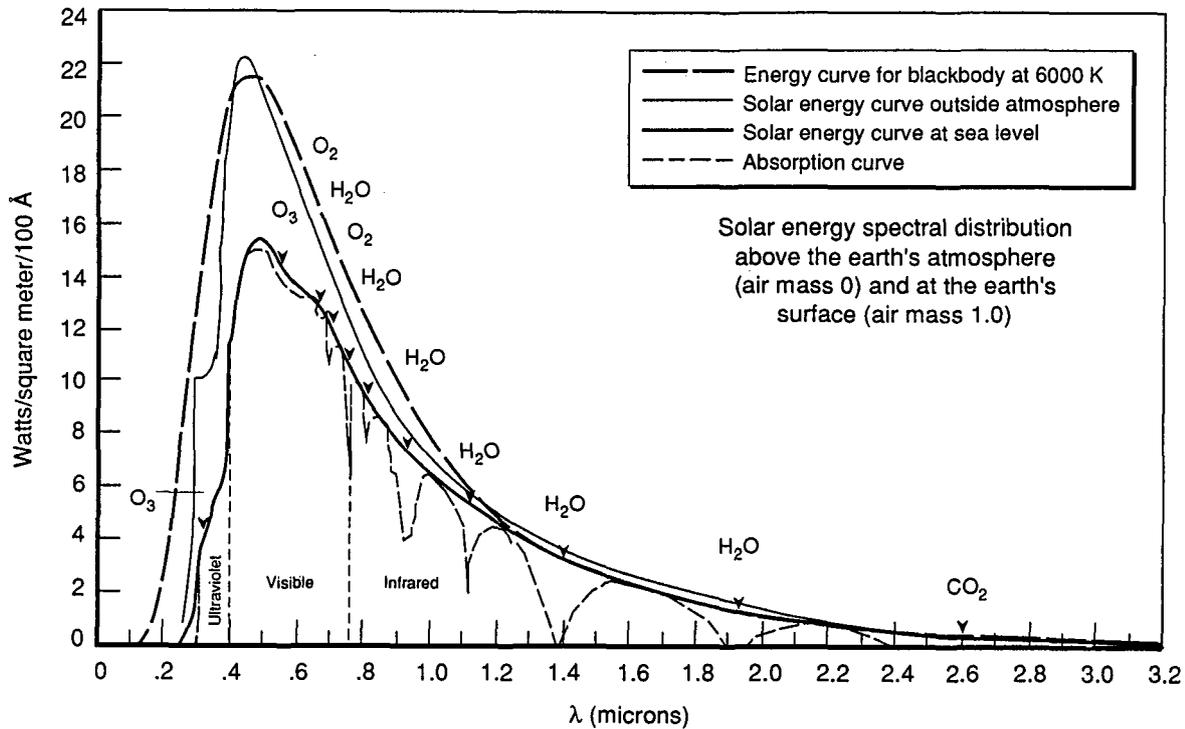
SOURCE: Brinker and Flood (1988).

**Fig. 3.2—High-Performance Solar Array Research and Technology**

Certain ideas about capturing solar radiation in other bands of the spectrum require a knowledge of the radiation intensity at those bands. They assume the overall intensity is spread out over the entire spectrum; however, the intensities in the low (ultraviolet) and upper (IR) ranges are substantially below those of the central (visible) range. Some submissions that proposed accessing such bands did not pass the utility criteria for inclusion in the top selections, although the point that the IR band broadly contains significant potential power is well taken.

For some applications (e.g., those of submissions **#101257** and **#101266**), the radiation arriving at the Earth's surface rather than the top of the atmosphere is important. In such cases, the atmosphere selectively absorbs radiation (because of the O<sub>2</sub>, O<sub>3</sub>, CO<sub>2</sub> and H<sub>2</sub>O in the air), and thus the intensities at the Earth's surface can be substantially irregular relative to the standard blackbody radiation intensities. Figure 3.3 illustrates all three curves as a function of wavelength: blackbody radiation intensity, solar radiative intensity arriving at the top of the Earth's atmosphere, and intensity of radiation at the Earth's surface.

Submission **#101222** proposes the production of radioisotopes on the Lunar surface, but it is not clear what the payoff for the added complexity of radioisotope production would



SOURCE: Hynek (1951, p. 272).

Fig. 3.3—Solar Radiation Intensity as a Function of Wavelength

be in the near term. The processing of reactor materials to isolate radioisotopes is not an operation that a crew should be expected to perform in any situation other than the case of an already long established presence on the Lunar surface with room for the appropriate experts. This approach seems unsuitable for the SEI. Submission #100949 advocates the advantages of a dual nuclear system for transportation and prime power. Surface operation of a reactor that has been operated in-flight must consider using full shielding (if geometry has been used to take advantage of using a partial “shadow” shield during transport), and landing operations must consider backscatter.

#### Startup vs. Evolutionary Power Needs

Strong weight must be given to the initial phase of any mission, when mass, specific power, and ease of setup are all important considerations. Beaming proposals might provide power to the Moon, so that relatively little must be taken along, but such is not the case for a Mars mission. The easiest systems to begin with are passive systems, such as the solar converter of submission #100950 or the PV array of submission #101257, but on board power supplies might be sufficient for the time it would take to place a reactor system in operation.

### **Manned vs. Unmanned Mission Requirements**

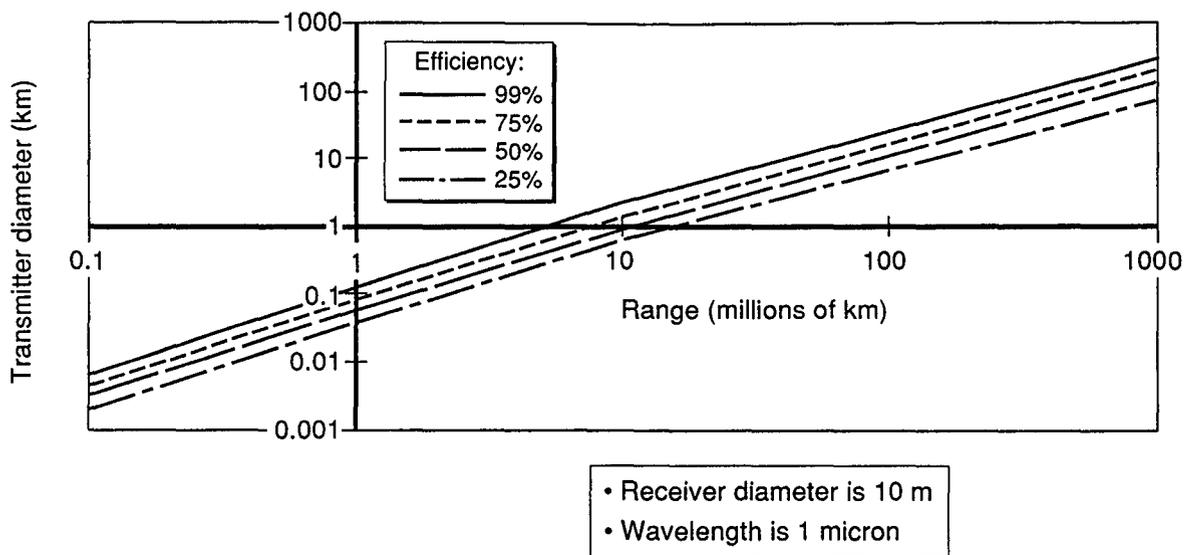
Manned missions have particular needs for power systems that do not need to be satisfied by remote exploration or cargo vessels. The utility of the emergency generator proposed by submission #100772 depends on the length of time the generator may be required in an emergency, which may render it inadequate in some cases. The proposed generator is good in terms of its potential for saving lives, but it suffers from being a one-shot emergency power source. Mass vs. power level and mass vs. duration of power are tradeoffs that need to be addressed for specific generators and missions. A shorter mission with a relatively small chance of an emergency might benefit more from the concept than a longer mission, such as a Mars trip.

### **Power Transmission Methods**

The issue of power distribution includes the interesting case of beaming (submissions #101257, #101243, and #101266). To keep the beam divergence small will require significant research and development in optical systems. Continuous aiming and delivery could be an issue. In some cases, thermal blooming and Raman scattering must be adapted. All of the beam and solar transmission submissions have divergence and  $1/R^2$  limitations, as well as those caused by atmospheric effects, aiming, and eclipsing.

Beamed power, eliminates on-site or in-vehicle power production problems and considerations, but it creates new problems and considerations. Figure 3.4 shows the relationship between transmitter diameter and range for various efficiencies—e.g., for an Earth-to-Mars range (about  $9 \times 10^7$  km), a transmitting antenna for 1 micron wavelengths with an efficiency of 75 percent at a 10-m receiving antenna (neglecting jitter losses) would have to be over 10 km in diameter.

Submission #101243 proposes surface power beaming. Compared to long-distance power beaming through space, this concept may have easily attainable applications, since the divergence loss is of much less magnitude and, for reasonably large apertures and short distances, the region is nearfield. The horizon on the Moon is shorter than the horizon on the Earth, which would suggest relays or high towers for surface beam broadcasting. Manned rovers are at some risk from power beaming, although the layers of gold that some spacesuits have had might offer some protection (heating would still occur, however). One advantage of short-distance broadcasting is that there is not the appreciable time delay of long-distance power beaming (such as from Earth to Moon). This lessened delay assists the problem of aiming.



SOURCE: Frisbee (1987).

**Fig. 3.4—Transmitter Diameter and Range for Different Efficiencies**

Submission #101257 relies on the development of adaptive optics. Even if the very large lasers and adaptive optics required could be developed, there is reason to doubt whether such a system could compete with a compact reactor system onsite. In any case, a demonstration by FY 1994, as suggested by the time schedule in the proposal, seems rather ambitious.

It is not clear that SELENE is cheaper than any other method. Thermal blooming remains to be worked out. The lasers might be mounted on a space station, but there are in-situ materials on the Moon, so this approach does not buy much. On Earth, the lasers have to be scattered around the world, contributing to cost.

Submission #101266 is based on the ambitious concept of a 100-MW laser, but it could have high utility for orbital transfer or Lunar surface power if the laser source can be realized. Given the relative difficulties of beaming power from Earth, this concept might make sense as an emergency technique to get power to a habitat with essentially no delay. For orbital transfers, the system might make sense for propulsion assistance.

Submissions #101524 and #100951 propose the use of fiber optics. These proposals attempt to enhance the performance of solar arrays by protecting the conversion devices from the environment or by creating high concentration factors.

### Enabling Systems

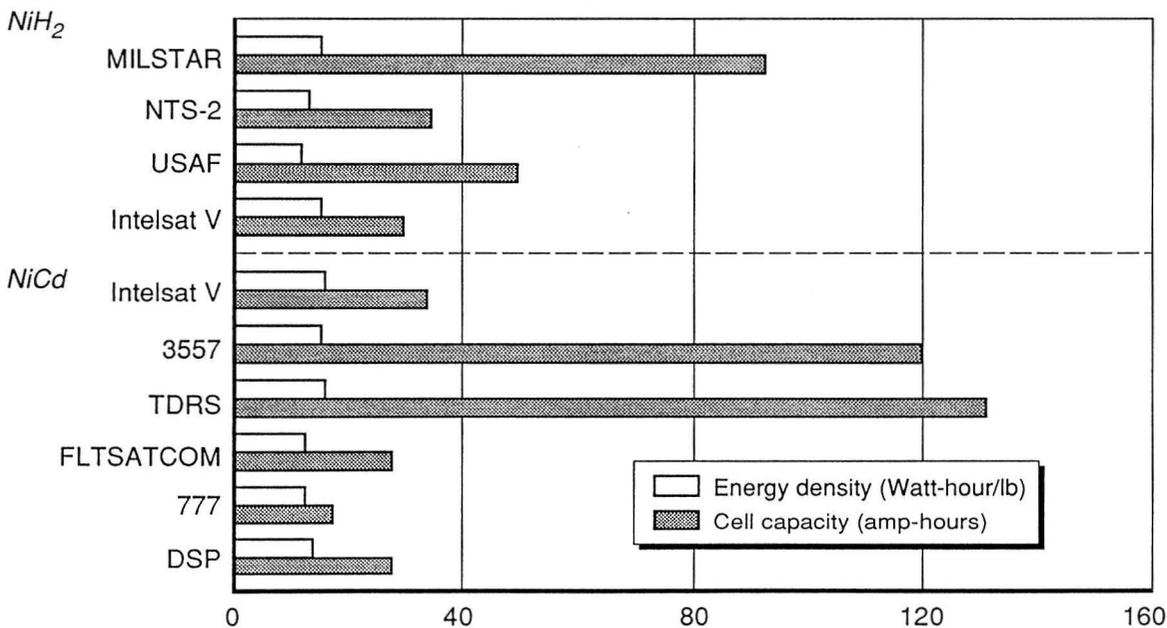
Some submissions proposed systems that enable or enhance major systems. Submission #101404, a proposal for improving battery reliability, is a qualitative-concept proposal and requires technical demonstration to establish the degree of utility that could be derived from enhancing Ni-H batteries. Submissions #101406 and #101407 are similar to submission #101404.

Figure 3.5 shows the energy characteristics of a number of batteries. Batteries are relatively heavy for any surface mission, as shown in Fig. 3.6. Battery weights vs. eclipse demands are shown in Fig. 3.7. The point to these figures is that battery improvements (submissions #101404, #101406, and #101407) are not of as much utility as improvements in several other types of space power sources. They may, however, have significant consequences for some Earth systems if validated.

Figure 3.8 shows the decay in lifetimes of acid fuel cells as a function of temperature and improvement in lifetimes over the years.

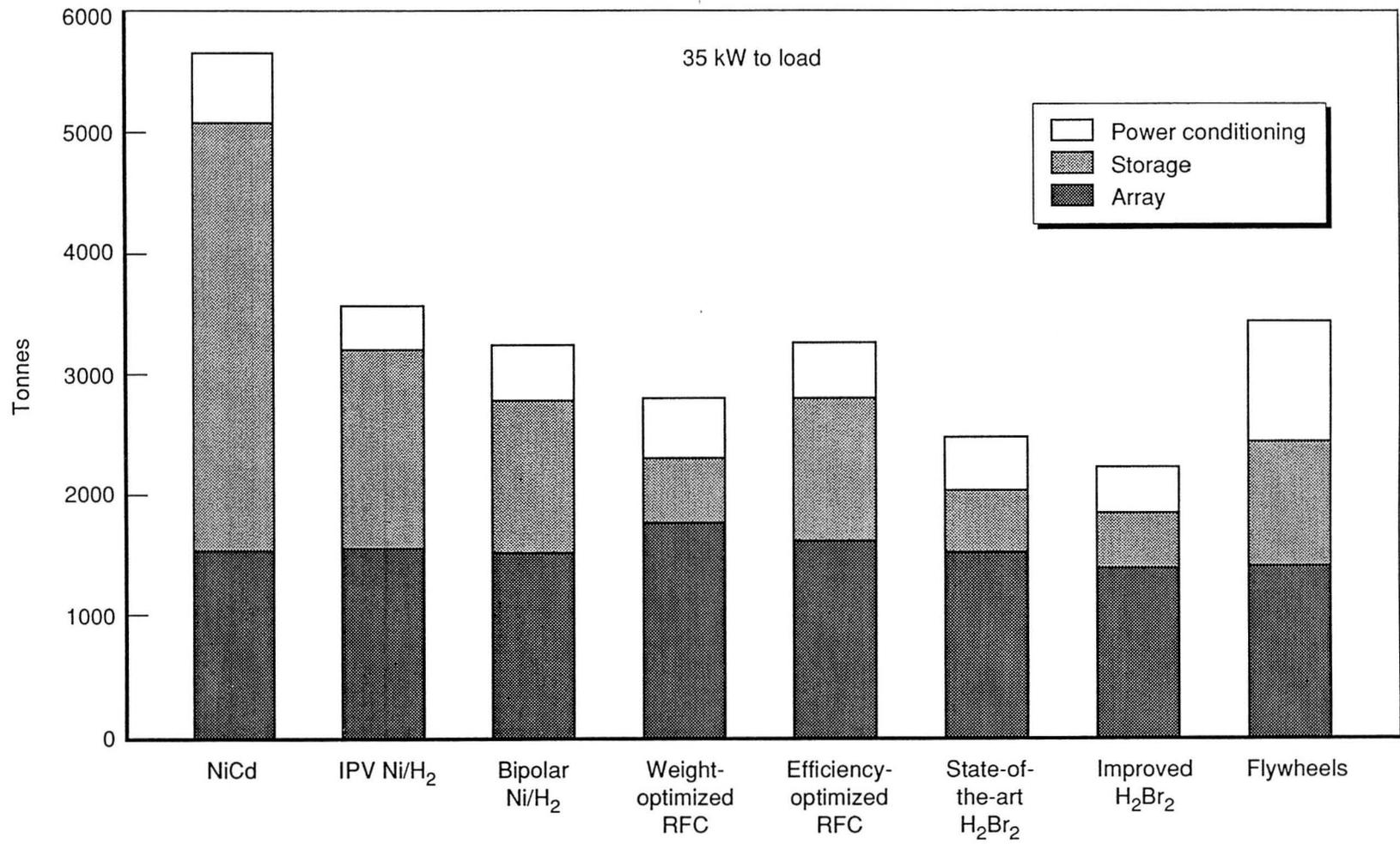
### Space Environment Hazards

The effect of the space environment on materials is highlighted by submission #100673, which attempts to minimize some of the problems associated with a weak



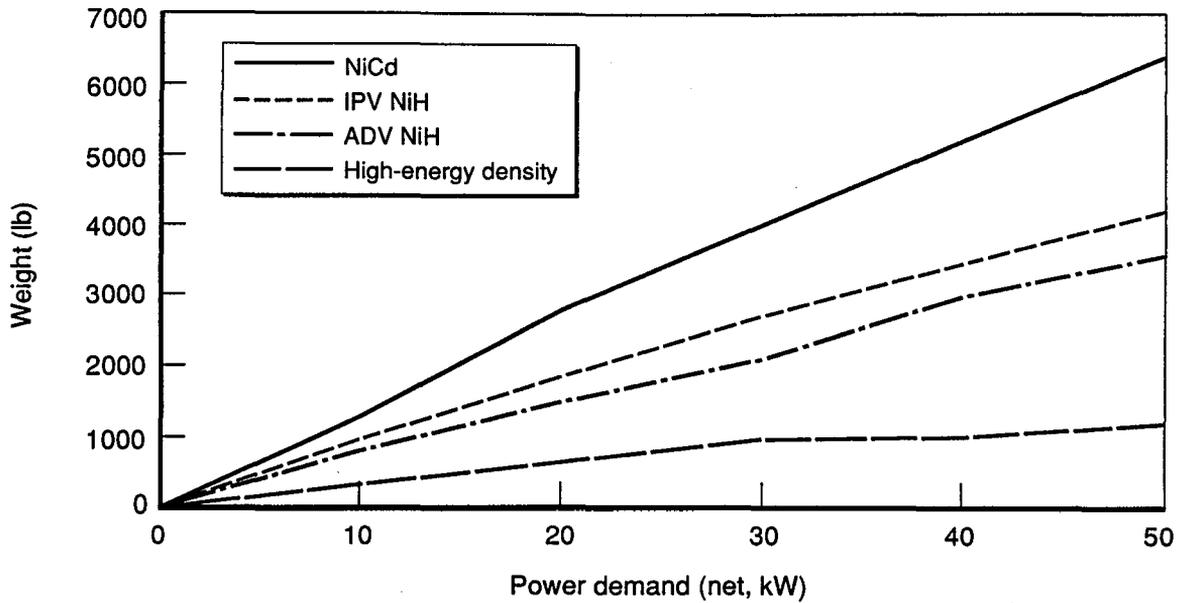
SOURCE: Lantafio (1989, p. 576).

Fig. 3.5—Battery Characteristics



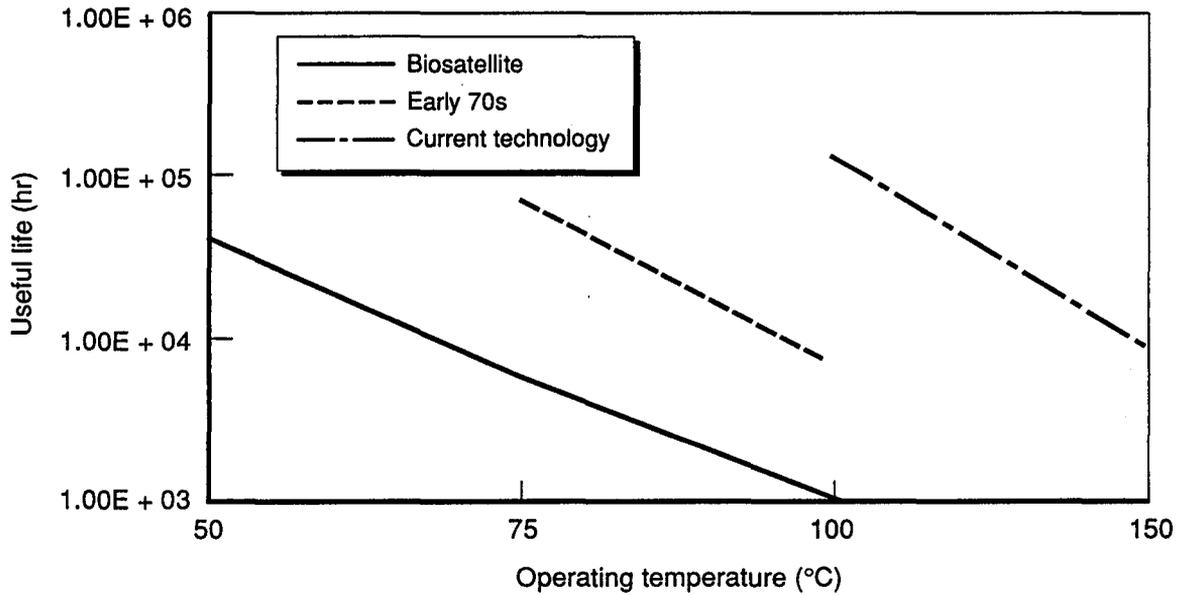
SOURCE: Thaller (n.d.).

**Fig. 3.6—Comparative Weights of Batteries**



SOURCE: Lantafio (1989, p. 573).

**Fig. 3.7—Total Battery Weight Versus Eclipse Power Demand**



SOURCE: NASA/Lewis Research Center (n.d.).

**Fig. 3.8—Acid Fuel Cell Decay Modeling**

gravitational field. Composite weakening by neutron effects is an issue that should be understood if heat pipes and radiators such as those suggested in submission #101410 are to be used in conjunction with nuclear reactor sources.

### **Exotic and Other Innovative High Utility Concepts**

The issue of how to handle exotic concepts and concepts that are highly innovative and have a potential for high utility but also have an accompanying feasibility risk can be illustrated by comparing the overall top-ranked submissions with the submissions ranked highest for innovation and, to a lesser extent, utility.

There were 16 of these latter submissions, as shown in Table 3.2. These were chosen by the innovation utility method in which innovation was required to be a 4 or higher. Nearly half of the innovation/utility selections were also top-ranked submissions.

There is a degree of risk inherent in innovation. The diverse area of power beaming is an illustration of the conflict between innovation and feasibility. There is a broad base of experience with laser and microwave devices, but to adapt these for long-distance power beaming, as proposed in submissions #101266 and #101251, can require innovation in associated optics.

Although nuclear fusion did not satisfy the overall weighting scheme, there were three fusion proposals (including a nuclear pulse concept—#100214) in the list of high innovation/utility submissions. The field-reversed configuration fusion reactor concept of submission #100197 is an example of innovative exploration in magnetic confinement in which the feasibility of confinement is a high risk.

An exotic concept can be found in three antimatter submissions. One very detailed submission, #200462, proposed a combination of methods, including antimatter, to create a fusion power source that could deliver specific impulses great enough, in theory, to reach Mars from Earth in less than 30 days. This concept is a prime example of an exotic case excellent in all regards except development risk and time schedule.

**Table 3.2**  
**Top Submissions in Terms of Innovation/Utility**

Submission ID	Title/Subject	Innov Avg	Utility Avg	Safety Avg	Feasibility Avg	Cost Avg
100951	Fiberoptically Coupled Integrated Structure Solar Array	5.0	4.7	5.0	3.0	2.7
101257	Project SELENE	4.7	5.0	4.0	4.0	4.5
200462	Antimatter Driven Fusion Propulsion System	4.5	5.0	2.5	2.0	1.0
100950	Cascade Thermionics for Space Solar Power		4.7	5.0	4.2	4.0
101237	Low Temperature Enhanced Electrical Storage for PV Space and Surface Lunar/Mars Power Systems		4.5	5.0	4.0	3.5
101266	Solar Pumped Laser Concept for Power Beaming	4.2	5.0	4.0	3.5	4.2
101231	Thermally Regenerative Alloy Cell for Electric Power Generation		3.7	3.7	3.0	2.7
100197	Space Electrical Power Using a D- <sup>3</sup> He Field Reversed Configuration Fusion Reactor		3.5	3.7	2.5	2.5
101259	Attenuation Method of Thermal Energy Storage for Space and Lunar Solar-Dynamic		3.2	4.5	1.5	3.2
100949	Nuclear Power for Space-Based Systems	4.0	5.0	3.7	4.5	3.5
101251	Power Beaming to Space and Exploration Facilities		4.5	3.7	3.5	3.2
100676	Matter/Antimatter Propulsion			2.5	2.0	1.2
101402	Pegasus II: A Multimegawatt NEP System		4.3	3.6	3.6	3.6
100610	High-Capacity Heat Pipe Radiator		4.0	4.7	4.0	4.2
100214	Fusion (Thermonuclear) Propulsion			2.2	2.5	2.7
100218	Liquid Sheet Radiator		3.5	4.7	3.2	3.2

#### 4. CONCLUSIONS

The Power panel evaluated a large sample of submissions covering all the main areas that concern power systems. A high level of correlation was found among disparate methods for ranking the submissions using the same five attributes (or measures of merit). The one notable exception was a small number of exotic cases that were high on utility and innovation but low on feasibility, not because of any inconsistency with physical laws, but rather because of their use of unproven engineering technologies. Many concepts presented in the submissions (e.g., solar and fuel cells) are very basic and hence noninnovative. However, they appear feasible. Costs are very difficult to estimate.

The highest-ranked submissions were analyzed to a detail appropriate for the amount of technical information presented. The majority (64 percent) of the top-ranked 22 submissions had no backup. In half of the cases, little specific analysis could be done because the submissions presented only general concepts with little or no technical elaboration. These submissions included #100216, #100410, #100772, #100951, #101222, #101243, #101404, #101406, #101407, and #101524. A number of submissions supplied a minimum of technical detail for what were essentially variations on established concepts. Submissions #101221, #101266, and #101240 were in this category.

Lack of preparation time may be only one reason for the lack of detail in some submissions. Proprietary information was not accepted, and some sources may have chosen to be extremely cautious in revealing concepts. Nevertheless, 36 percent of the highest ranked Power submissions did provide technical backups.

Some of the submissions that passed the initial screening were later evaluated less favorably for SEI applications. In some cases, the technology was found not to be best suited to SEI, but in many cases technical support for the concepts and demonstrations may have to be developed before suitability for SEI development can be established.

#### RECOMMENDATIONS FOR SYNTHESIS GROUP CONSIDERATION

##### Top Recommended Submissions

Eight submissions appeared to be essentially sound and worth having the Synthesis Group consider for use. The order in which these submissions are listed here is random and is not to be interpreted as a ranking of them. To determine the relative merits of these submissions, they would have to be considered in the context of particular mission and program options.

(1) Submission #101237 (**Low Temperature Enhanced Electrical Storage for PV Space and Surface Lunar/Mars Power Systems**) is noteworthy for its call for research on the rather simple technique of cooling to improve performance. The drawback is that while this concept has the potential for cost enhancement, it is not sufficiently innovative to represent a major revolution in performance.

(2) Submission #100673 (**Enhanced Phase-Change Processes Using Ultrasonic Vibrations for Space Power Systems**) is of interest for its potential for improving the cost effectiveness of phase-change storage systems.

(3) Submission #101243 (**Surface Power Beaming for Utility Power Distribution on the Lunar/Mars Surface**) is conceptual in nature and lacks carefully developed technical studies. However, as a proposal to investigate the use of beam transmission in the SEI, this submission highlights an area that can offer innovation and utility in many applications. Trade-off studies on power beaming in the context of particular mission program options might prove valuable. The mass savings brought about by remote power sources and the application of beaming to mobile or transportable receivers is one possible bonus area, and the ability to provide relatively high power quickly is another. Aiming and beam size at large distances are concerns, and the safety of manned vehicles is another concern to be included in any mission-specific study.

(4) Submission #100610 (**High Capacity Heat Pipe Radiator**) offers some savings and appears to be technically reasonable. This concept's greatest value would be for high-power nuclear propulsion systems, since radiator and heat rejection equipment is a large fraction of the power system mass in multimewatt systems.

(5) Submission #101221 (**Modular SP-100 Reactor Dynamic Power System for Lunar and Mars Surface Power**) does not go into extensive detail or offer any innovation. However, the case for developing dynamic conversion systems for the SP-100 appears to be quite reasonable. To take advantage of the economy of scale offered by nuclear reactors, it would be more desirable to use conversion technology (i.e., dynamic) rather than summing together a number of less efficient modules.

(6) Submission #101240 (**Dynamic Isotope Power System for Dedicated Emergency Power for Habitat**) credibly, although not innovatively, makes a case for dynamic conversion systems with radioisotope power sources for surface habitats.

(7) Submission #100213 (**In-Core Thermionic Power Systems**) makes a case for a passive conversion system on a nuclear reactor power source. This concept has appeal because of the relative simplicity and reliability of passive systems, as well as the somewhat better efficiency that might result from a thermionic rather than a thermoelectric system.

(8) Submission #100948 (**Development of In-Situ Energy Storage**) is not well developed, but it make a good point in calling for research on the potential use of in-situ material. Missions should exploit indigenous resources to the fullest extent possible, and that extent is determined through exploration and research. This submission proposes the use of a solar dynamic power generator in conjunction with energy storage in Lunar materials. Although the potential specific power is not as good as the case of nuclear dynamic power, solar dynamic is attractive, given the lack of atmosphere on the Moon.

In summary, the eight submissions that appear to offer the best overall potential deal with nuclear power source concepts, power beaming, the development of in-situ resources (including the use of solar dynamic power), and thermal management.

### **Top Recommended Submissions with Reservations**

Eight more submissions are recommended for the Synthesis Group's consideration, but with some reservations. These submissions are listed here randomly; they are not ranked by degree of concern.

(1) Submission #100950 (**Cascade Thermionics for Space Solar Power**) may be the right technology for surface power conversion, but not for space applications given the larger radiator sizes needed for lower-temperature heat rejection. Such a concept might be useful on the surface of Mars or the Moon.

(2) Submission #101257 (**Project SELENE**) is a potentially high-utility concept, but successful atmospheric transmission needs to be demonstrated. This seems like a big task, and what is needed now may be a demonstration of the adaptive optics rather than a directly supported SEI research program.

(3-5) Submissions #101404, #101406, and #101407 (**Mechanical Cell Bypass Device for Nickel Hydrogen Batteries, Self-Contained Forced Gas Flow, and Improved Performance of Nickel Hydrogen Batteries Using Controlled Variation of Gas Pressure**) could be collectively considered as one proposal to develop near-term devices to enhance battery performance. This concept is good in principle, but the detailed design concepts have been left out, and it is not possible to say how large of an improvement these devices would actually make if used by the SEI.

(6) Submission #100949 (**Nuclear Power for Space-Based Systems**) proposes a dual power/transportation system. The difficulty with this concept is that it is not clear whether an optimization of one system for both applications is a better route than two separate systems, each dedicated to one application (power or propulsion).

(7) Submission #101266 (**Solar Pumped Laser Concept for Power Beaming**) is interesting in that it seeks to eliminate the problem of atmospheric transmission. However, it is not clear how good the efficiency will actually be, and the cost effectiveness may be in question if there is no further demonstration.

(8) Submission #101222 (**Integrated Lunar Power Center and Simulator**) makes very general conceptual proposals to use waste heat from nuclear reactors, which is a good idea in principle. Specific uses must be demonstrated, however,—e.g., it is not clear that waste heat would be expeditious for mining. Another part of the proposal, to manufacture radioisotopes, is of little interest within SEI time frames given the difficulty involved.

The remaining six submissions in the top 22 did not have enough detail for in-depth analysis, although the concepts raised may be valid and in some cases are covered in more detail in other submissions.

### **Further Concepts**

This subsection describes some concepts that were not elaborated on by the submissions but are believed to be worthy of consideration.

High energy-density rechargeable batteries with energy densities approaching 100 to 200 W-hr/kg are good candidates for research and development for energy storage applications. Two candidates being investigated are sodium sulfur and lithium systems. A sodium sulfur battery system might provide instantaneous power densities of several hundred watts/kilogram with a life of several thousand cycles. The operating temperature is high—in excess of 300° C. Lithium-iron disulfide is a similar example. Current state-of-the-art systems are primary cells (based on irreversible reactions), such as lithium/calcium thionyl chloride, or mechanically rechargeable cells such as lithium/silver oxide. There are also other lithium variants, including the higher-risk lithium halogen systems.

Compact energy storage systems for spacecraft may include capacitors and flywheels. Capacitors may be developed to store in excess of 10 W-hr/kg. Discharge could be very rapid for a burst power need. Flywheels could also offer rugged energy storage devices. The choice of material affects failure modes, which in turn pose a safety concern. Composite materials might offer a few tens of watts-hour/kilogram capacity.

Magnetohydrodynamic power systems operate by the flow of a conducting fluid through a channel crossed by a magnetic field. The resulting Lorentz force causes opposing ion and electron drifts, charging electrodes to different potentials so electricity can be drawn away without the inefficiency of a heat cycle; this is the inverse of an ion engine. The need for a gas feed and exhaust system means that this approach is unsuitable for spacecraft but

might be of interest on a surface such as that of Mars if appropriate in-situ materials could be found.

High-temperature superconductors (HTSs) were mentioned in a number of submissions, but not elaborated on in enough detail for energy storage purposes. When first discovered, HTSs were unable to support large current densities and were therefore not thought to be useful for high-density energy storage. However, recent advances in Japan and the U.S. have dramatically increased HTS current-carrying capacities. If such HTS materials can be perfected, they could be used to store circulating electric currents. Such "super"-current storage batteries have been proposed as load levelers for electric power grids on earth. If the HTS ring that serves as the super-current storage battery is kept at or below the appropriate temperature, the super-current will circulate undergraded essentially forever if the device is large enough. There are some thermal losses at the boundary of the HTS, which depend on HTS skin depth thickness; also the effects of cosmic rays must be considered. If efficient and reasonably small HTS super-current batteries can be developed, they will prove especially useful for SEI space power applications.

#### **TECHNICAL AREAS AND ISSUES HIGHLIGHTED BY THE ANALYSIS**

A number of issues were highlighted during the evaluation process:

- Nuclear vs. non-nuclear power
- Power beaming
- Thermal management

We next discuss these issues and areas in more detail.

#### **Nuclear vs. Nonnuclear Power**

One of the most pressing issues was the question of whether to use nuclear or nonnuclear power sources. Although there is no single power source suitable for all missions, a strong case for a single source can be made in specific instances.

Nuclear power is of high utility, whether as a surface power system, space power system, or propulsion system. For surface power, nuclear reactors offer a large advantage in specific power over batteries, which have a very low specific power. For example, predictions for the SP-100 with Stirling conversion are slightly over 20 kg/kWe at the megawatt-electric level. Ten-megawatt dynamic reactors are expected to perform with a specific mass of about 5 kg/kWe. By taking advantage of the economy of scale of large nuclear reactor sources,

specific power performance can be achieved that other types of power sources cannot match. This approach is superior to the modular concept of supplying large power levels by adding together the power output of a number of smaller units. At high power levels, the radiator mass becomes a significant fraction of the total power system mass, and thus any improvement in radiator or heat rejection is of high value for nuclear space propulsion. On the other hand, the development of in-situ resources for surface applications of high-power systems should be of primary importance.

Fuel cells have restrictions on operating temperatures and life cycles and require another power source for the regenerative mode. Their prime use is as a backup to solar power sources. The Martian night is much shorter than the Lunar night, which means the energy storage requirements (and mass) are correspondingly reduced. A capacity of 200 W-Hr/kg for a regenerative fuel cell (RFC) would require a mass of about 60 tons to store enough energy to supply 1 MW through the Martian night. Current battery technology compares unfavorably with RFC, although nuclear systems offer mass savings over solar/RFC systems.

Solar power is a competitor with nuclear power for many applications; e.g., solar cells are preferable for low-power applications in low Earth orbit (LEO). The limits on solar photovoltaic power are (1) the solar constant near the Earth or Moon delivers about 1350 W/m<sup>2</sup>, (2) the efficiency of solar cells is generally limited to about 13 to 25 percent,<sup>1</sup> and (3) the need for space-qualified arrays of photocells. Solar dynamic systems must have adequate, large collectors.<sup>2</sup>

In the case of the space environment, the risks of radiation from a nuclear power source deserve a special comment. The generally accepted limit for risk to the population is only 0.5 rems per year, whereas for industrial workers it is 5 rems/year (or 3.5 rems per quarter, or 25 for a one-time case). The current space limit is 50 rems/year. With a reasonably shielded propulsion reactor, the crew is likely to risk an exposure from cosmic rays that is several times what they would receive from a nuclear power source.

A number of good submissions proposed nuclear power concepts. There are no technical reasons to categorically declare nuclear sources unsafe and nonviable. A U-238

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<sup>1</sup>However, point-contact silicon photocells can yield an efficiency of 28.5 percent, and a stacked GaAs-GaSb cell can yield 35 percent. There may be potential for development of space-based photocell performance somewhat beyond what has been the case.

<sup>2</sup>LUZ Corporation has constructed a set of solar concentrators with 275-MW capacity in the Mojave desert. A parabolic mirror configuration is used to heat oil, which in turn generates steam and drives a turbine. For reference, a planned 80-MW plant will involve 852 100-m-long collectors. This should be watched for Earth-based potential, and indications for SEI lunar surface applications—a few 100-kWe units are conceivable in an early application.

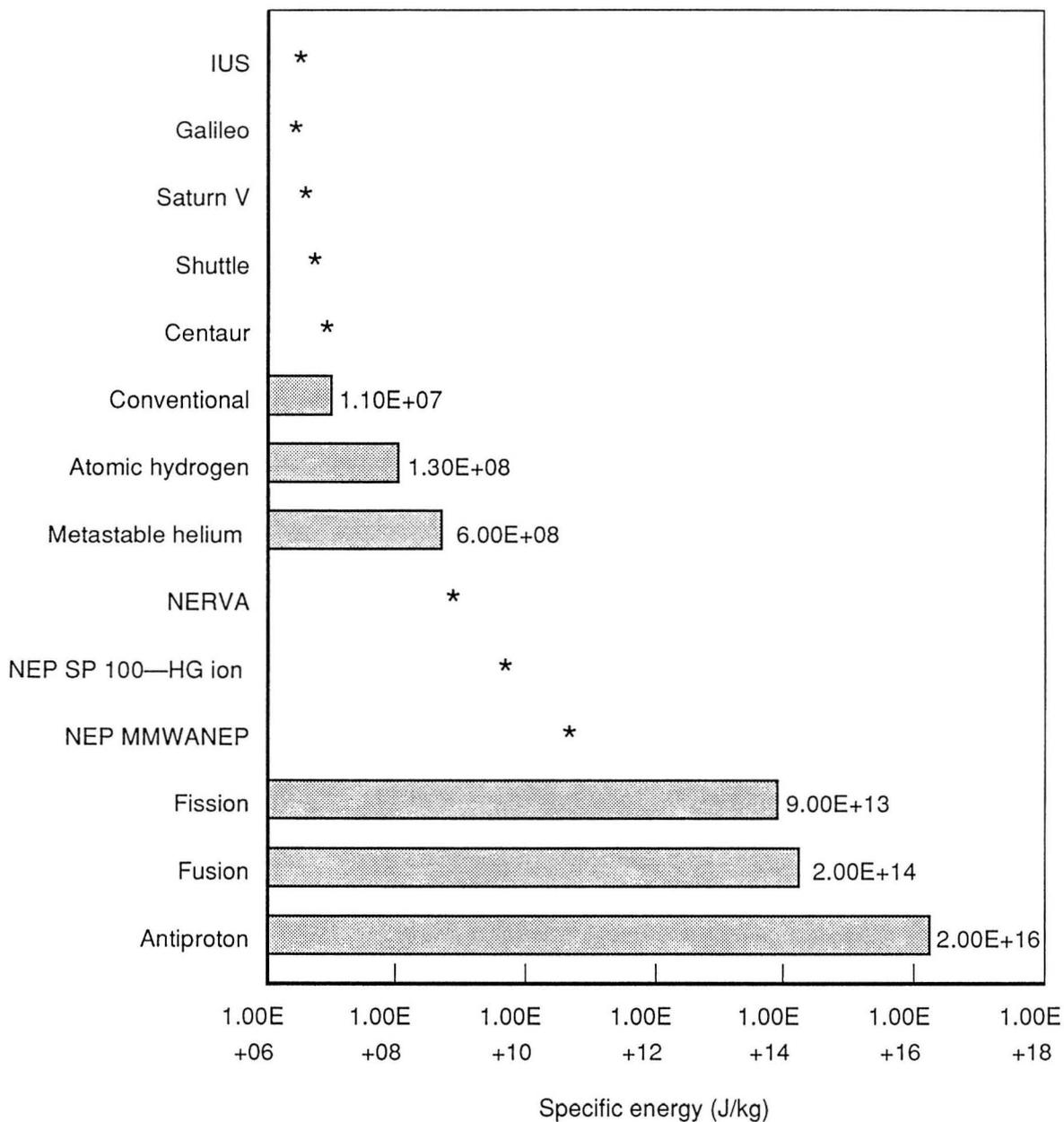
reactor carried at launch should pose no significant nuclear safety risk, provided that the reactor is not started until a "safe orbit" is reached and no plutonium fuel is used. Plutonium is a by-product of U-235 bombardment and is typically not in a reactor unless the reactor has some burnup fraction or plutonium is used as the primary fuel.

Plutonium (unlike uranium) is a very potent poison and is particularly hazardous if inhaled. However, the uranium isotope U-233 is also a fuel that has safety concerns connected with it, due to the general presence of U-232 as a result of its production process. U-232 is a strong gamma source. If one restricts the fissionable material to U-235 without previous burnup, the reactor is relatively safe for launch.

Some submissions fell into both the Power panel and the Transportation panel subject areas. For various space missions, various  $\Delta V$ s are needed. These are provided by the specific energy (energy density) of the propellant systems. Figure 4.1 provides an overview of the comparative energy densities of various propellants, from conventional and advanced chemical propellants to various nuclear options, including speculative fusion and antiproton options. Conventional chemical propulsion is not an attractive option if we examine its propellant density in terms of achievable  $\Delta V$ s, as shown in Fig. 4.2. On the other hand, atomic hydrogen and metastable helium could provide a possibility for a 40-day Mars mission. However, there are safety and feasibility questions about such fuels. Several of the nuclear options indicated are possible time-savers for a Mars trip, but safety requirements must remain paramount. The gaseous core rocket is not demonstrably feasible in the SEI time frame, as discussed in App. N, although it is of high utility. Orion could possibly be developed in the SEI frame, but it has serious treaty implications and potentially adverse environmental consequences. An inertial-confinement fusion approach to nuclear pulse propulsion is speculative and has higher technological risk, but it does not carry the same nontechnological disadvantages as Orion. In particular, aneutronic fuels would virtually eliminate nuclear safety concerns.

### **Power Beaming**

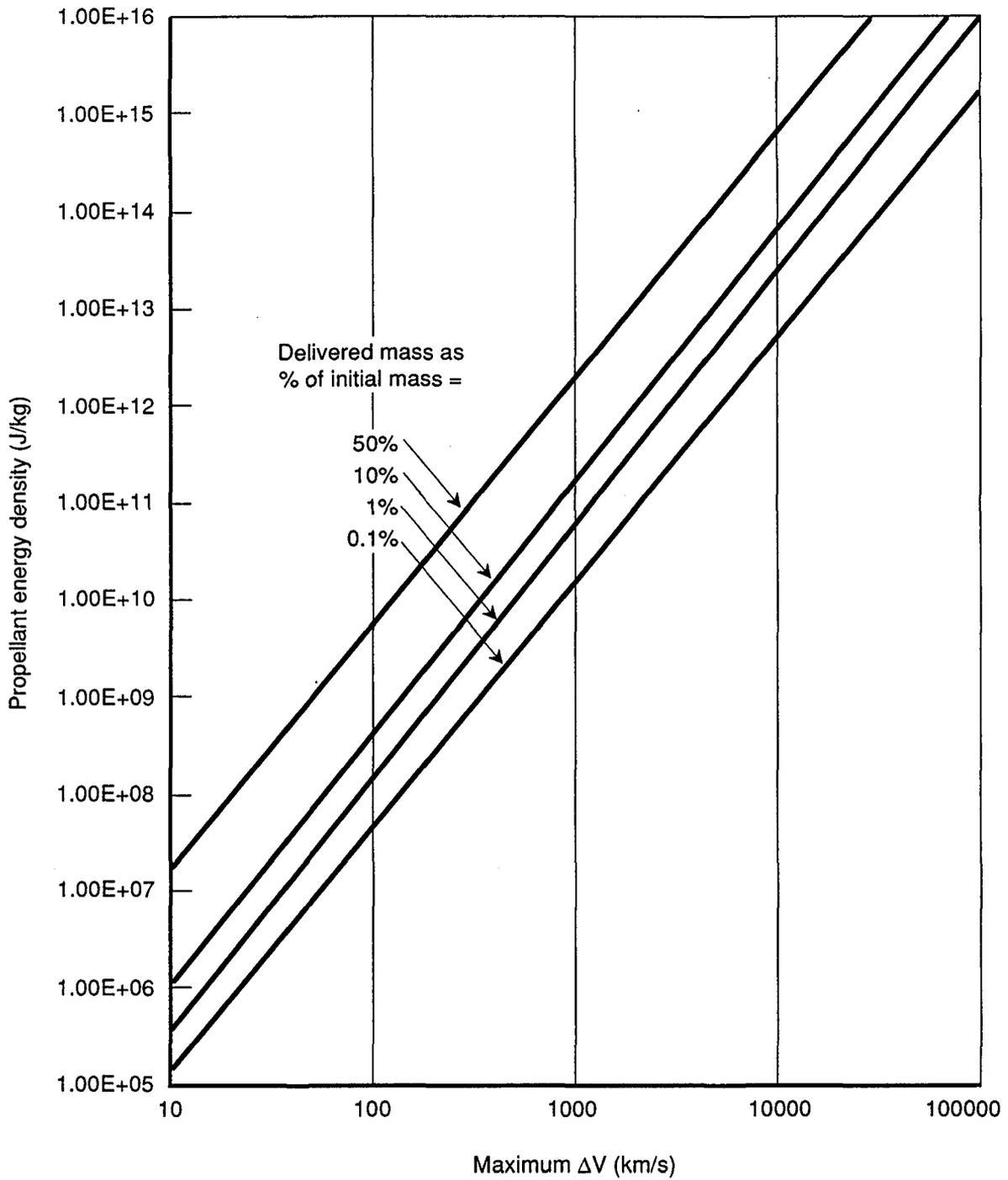
A number of submissions proposed power beaming concepts. There may be strong motivation to use power beaming for local surface broadcasts to overcome the need to construct networks in harsh environments. To beam power from Earth to the Moon or nearby spacecraft, atmospheric effects (for lasers) must be overcome, and to maintain safety, aircraft and biota must be kept out of the beam. Power beam propulsion is generally limited to nearby orbit transfers, except when sunlight is utilized to propel a spacecraft fitted with an optically reflective sail.



SOURCE: Frisbee (1987).

**Fig. 4.1—Inherent Energy Densities of Selected Propellants**

The general idea of power beaming presented by submission #101243 can be extended to a number of applications. One of the more extensive proposals (e.g., #100704), a speculative commercial application of power beaming, is the Criswell-Waldron idea for supplying power to Earth by building elaborate solar-powered microwave transmitters on the Moon. Large rectennas would also be built on Earth to provide up to 20,000 GW for Earth-



SOURCE: Frisbee (1987).

**Fig. 4.2—Conventional Chemical Propellants Are Limited in  $\Delta V$**

based applications. Besides reducing consumption of fossil fuels on Earth, this concept, if feasible, would provide a substantial return on investment in Lunar-based industries. However, full-scale development of this concept would require a time schedule that goes far beyond SEI and an enormous investment of capital in a Lunar-based infrastructure. Although extreme, this idea is nevertheless representative of the potential benefits power beaming could one day provide. Environmental safety is an issue that needs to be resolved for such an application of power beaming. The source proposed is solar, but the power beaming concept applies as well to nuclear sources (e.g., fusion based on  $^3\text{He}$ ). This concept requires long-term national will and is motivated by concerns about global warming and the impact of the green house effect on the Earth's environment. We suggest such ambitious applications of power beaming be considered by the Synthesis Group as a long-term goal of Lunar SEI activities (see Table 4.1).

### **Thermal Management**

The areas of thermal management and handling received a number of good submissions. High-capacity heat pipes and low-temperature performance enhancement of electric components both appear to be interesting and feasible concepts.

One finding of the Power panel was that there are a number of innovative or potentially high-utility concepts proposed that do not give clear evidence of feasibility in the near term, but that might return a high payoff over a period of research and development covering as long as several decades (e.g., to determine the extent to which in-situ resources can be used will take extensive research). Liquid sheet and droplet radiator submissions are examples of concepts that might not take as long but are not yet clearly resolved.

### **EXOTIC AND HIGH INNOVATION/UTILITY CONCEPTS**

A number of innovative submissions presented high-potential utility concepts. These included proposals for fusion research, long-distance power beaming, and nuclear propulsion engines. An example of a submission concept that can stimulate innovation is power beaming for orbital transfers between the Earth and Moon. Compared to the requirements for launch, the relatively small energy requirements of this concept could make it attractive.

Antimatter research is more risky during the SEI time frame than research into nuclear power sources, including fusion power, but constitutes an illustration of the concern that potentially important areas of research not be dismissed. Fusion is another example of an area that is highly risky but not clearly dismissable. Although success has not been demonstrated, progress has been made and it is possible that the next couple of decades may see success. The requirements for space propulsion applications are not as stringent as for

**Table 4.1**  
**Summary of Beamed Energy Propulsion Concepts**

CONCEPT	COST	FEASIBILITY	AVAILABILITY
LASER (IR or VIS)			
HEAT XCHG	MED-HI	MED-HI	2000
COMBUSTION	MED-HI	MED	2010
DETONATION	MED-HI	MED	2010
SAIL	MED-HI	MED-HI	2000
MICROWAVE			
ECR	MED-HI	MED	2000
MIC. ARCJ	MED-HI	MED	2000
SAIL	MED-HI	HI	2000
USING SUNLIGHT			
SOLAR-ROCKET	LOW	HI	1990
SOLAR SAIL	LOW-MED	HI	1990

SOURCE: Frisbee (1987).

those commercial applications, since the same price per unit of energy is not required for competitiveness.

Wind power is an option that, at first glance, might be considered for Mars since it has an atmosphere.<sup>3</sup> However, the atmosphere there is very thin and the winds are not reliably high enough to produce significant power. This proposal is not likely to prove viable for a near-term Mars mission.

It may be worth considering modest research support in some of the more exotic areas in the next decade to determine if any are capable of development in a reasonable time for the more demanding SEI missions, such as a manned Mars mission. These areas include power beaming on the surface and nuclear propulsion options (including the more exotic variants, such as fusion).

#### **NEED FOR MISSION FOCUS TO DETERMINE UTILITY**

The submissions received take on different relevance if one compares the case whose goal is a manned mission to Mars with the case in which power systems are being used for satellites in LEO. To assist the reader in categorizing the submissions by these different needs, we would like to point out that many of the highly ranked submissions have marginal utility for a Mars mission, where major innovations in power system performance are proposed (e.g.,  $I_{sp}$ s of several thousand seconds may be desired). However, these same submissions could be of great significance for the LEO environment, where the main concern

<sup>3</sup>The Altamont Pass in California with its 7500 wind-turbines illustrates that in some Earth locations gigawatt-class total power production is possible from windmills.

is not new high-performance propulsion systems, but rather the attainment of cost-efficient savings from more conventional technologies (e.g., improving the performance of PV arrays by a factor of two).

Appendix A

**SUBMISSION HANDLING, EVALUATION METHODOLOGY, AND POWER PANEL CRITERIA  
FOR EVALUATING SUBMISSIONS**

Submitters were asked to select the appropriate category for their ideas from among those listed in Table A.1. The table shows that all categories received a fair number of submissions. Of the 1697 submissions received, 149 (less than 9 percent) were judged to be incapable of being screened. Another 105 submissions were received after the cutoff date of August 31, 1990.

A submission was ruled incapable of being screened if it (1) was marked as classified or proprietary or (2) contained no supporting information of any kind. A submission marked as either proprietary or classified was automatically destroyed by the subcontractor. In such cases, the subcontractor noted who destroyed it, the date, and any particulars, then informed the submitter of the destruction of the submission and the reason for it.

As shown in Table A.2, the majority of submissions (63 percent) came from individuals, with 22 percent coming from for-profit firms and 5 percent from educational institutions. The relatively few submissions from educational institutions may have been a problem of timing, because Project Outreach's publicity and submission process began in the

**Table A.1**  
**Submissions Distributed by Category**

Category	Screened	Not Analyzed
Architecture	290	1
Systems	52	0
Transportation	350	0
Power	138	1
Life support	156	2
Processing	75	3
Structures	119	1
Communications	45	1
Automation	52	1
Information	21	1
Ground support	28	0
Others	194	4
Undetermined	28	134
Total	1548	149
Received after 8/31/90	105	

**Table A.2**  
**Sources of Submissions**

Source	Submissions	
	Number	% of Total
Individuals	1061	63
For-profit firms	381	22
Educational institutions	89	5
Nonprofit organizations	72	4
Other	46	3
Groups of individuals	48	3
Total	1697	100

summertime, when most lower-level schools are closed and most universities have reduced staffs and enrollments.

Nevertheless, Project Outreach generated broad national interest. All of the states except Alaska, Arkansas, and Wyoming were represented, as were five foreign countries—Argentina, Australia, Canada, Israel, and Scotland. Interestingly, 40 percent of the submissions came from three states—California with 26 percent, Texas with 9 percent, and Florida with 5 percent.

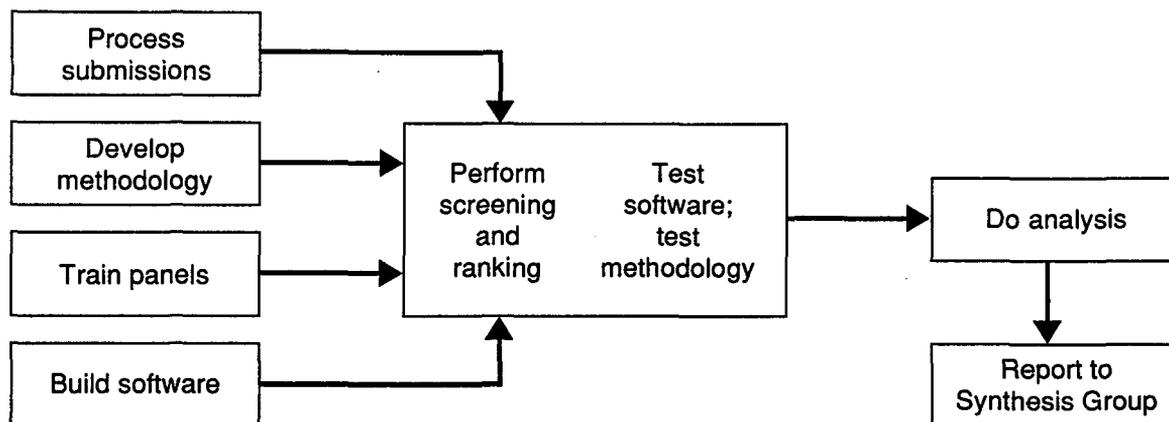
NASA personnel also contributed to Project Outreach: submissions were received from the Johnson Space Center, Goddard Space Flight Center, Marshall Space Flight Center, Lewis Research Center, Ames Research Center, Jet Propulsion Laboratory, Langley Research Center, the Reston Space Station Program Office, and the Stennis Space Center. A total of 121 submissions were received from NASA locations.

### **SUBMISSION FORMAT**

Submitters were asked for a two-page summary and simple outline of their idea. Submitters were also given the option of submitting an additional ten-page backup explanation of their idea. Only 22 percent of the total submissions included backups. This had implications for the analysis process, which we discuss below.

### **SUBMISSION HANDLING**

Because of time constraints, RAND was obliged to follow an abbreviated six-month schedule. Figure A.1 shows the flow of the process we developed and implemented for handling the submissions. Our task involved simultaneously processing the submissions, developing a methodology, training the panels, and building the software. This time frame allowed no margin for error.



**Fig. A.1—Flow of Submission Handling**

During our screening and ranking process, we were, in effect, testing the software and the methodology, a highly risky process. We are happy to report they both performed well.

#### **Submission Database**

For each submission, pertinent background information was logged into the database, including the unique ID number of the submission, the reviewer, the date, the name of the panel performing the review, and the title or subject of the review. To remove any bias from the process, the panels did not have information concerning the submitter's name or organization. Reviews of the submissions were entered in a text field. Each reviewer was required to briefly explain the reasons for scoring a submission as he or she did.

#### **PANEL RANKING OF SUBMISSIONS**

##### **Primary Ranking Method**

Submissions were ranked initially using a method based on weighted sums of five attribute scores. In this case, the attribute weightings were numbers between zero and one that summed to one over the five attributes. These weightings represented the consensus of each panel concerning the relative importance of the attribute for the panel's particular technology/mission area.

Table A.3 presents the screening process weights determined by each panel for each of five common attributes. Each submission received a composite score, computed by summing over all attributes the product of the attribute score (1–5) and its weight. Thus, cardinal rankings represent the overall score of a submission relative to all the submissions within its panel. Rankings by composite score can be sorted within the Fourth Dimension database and recomputed using different attribute weights to perform sensitivity analysis.

**Table A.3**  
**Screening Process Weights Determined for Each Panel**

Panel	Utility	Feasibility	Safety	Innovativeness	Cost
Architecture	0.30	0.30	0.15	0.20	0.05
Transportation	0.30	0.25	0.25	0.05	0.15
Power	0.25	0.25	0.25	0.10	0.15
Human support	0.40	0.25	0.08	0.25	0.02
Structures	0.30	0.25	0.20	0.10	0.15
Robotics	0.30	0.25	0.01	0.04	0.20
Communications	0.50	0.25	0.01	0.04	0.20
Information	0.29	0.23	0.11	0.20	0.17

### Prioritized Ranking Method

To test the robustness of the screening process, each panel also ranked submissions using prioritized attribute ranking methods. In ordinal ranking, the *most important* (primary) attribute is selected, and submissions are ranked according to their scores for that attribute alone. Submissions with equal scores on the primary attribute are then ranked by their score on the next most important, or secondary attribute. The panels found that it was rarely necessary to use a third attribute to rank all the submissions by this process. The prioritized ranking of a submission can then be compared with its general ranking results to determine if there are significant differences. The lack of significant differences in the two ranking systems would indicate that the results are somewhat robust.

In addition, a secondary prioritized ranking was created by reversing the order of the first two attributes in the primary ordinal ranking. Thus, if safety was the most important and utility the second most important attribute for a given panel, the order was reversed. This provided a further check on robustness.

### Comparison of Methods

Figure A.2 compares the results of the rankings from the Structures panel submissions. The vertical axis represents the primary rank of a submission, and the horizontal axis measures its prioritized rank. The intersection points of these rankings are shown by small black boxes or squares. The figure contains a 45-degree line from the origin out through the total number of submissions. Submissions that had the same primary rank and the same prioritized rank would fall directly on the 45-degree line. The "best" submission for this panel would be the one closest to the origin, because it would be the one that ranked first in the primary rankings or first in the prioritized rankings, or first on both.

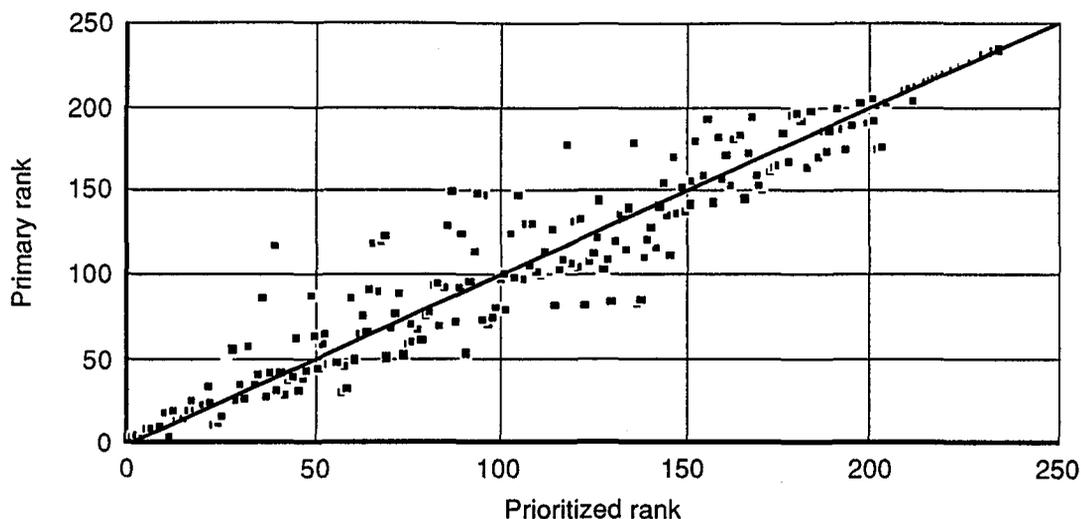


Fig. A.2—Example of Primary Versus Prioritized Ranking

Thus, the closer that each of the small black boxes falls to the 45-degree line, the better the congruence of the two ranking methods. Figure A.2 shows that the dark blocks representing the top 20 or 25 submissions are in the lower left-hand corner, indicating good agreement. The agreements of the two ranking methods become less congruent as one moves out into the lower-ranked submissions, which is to be expected.

Table A.4 compares the percentage of common submissions found in the lists of the top 20 submissions as created by the three ranking methods just discussed. The left-hand column shows the percentage of submissions that appeared on both the primary and “primary prioritized” lists; it indicates that the percentage of overlap of the top 20 submissions on both lists ranged from 75 to 85 percent. The right-hand column shows the commonalties among three lists: the primary rankings, the “primary prioritized” rankings, and the “secondary prioritized” rankings discussed above. This comparison was made as a more stringent test of robustness; it also reveals a fairly high correlation among the three ranking methods.

This correlation gives confidence in the consistency of the evaluation method used to screen submissions. It shows that whether we extracted the top 20 submissions using the primary or the prioritized methods, they would still be nearly the same.

### POWER PANEL CRITERIA FOR EVALUATING SUBMISSIONS

The five criteria used in evaluating the Power panel submissions were utility, feasibility, safety, relative cost, and innovation.

**Table A.4**  
**Comparison of Ranking of Top 20 Submissions for Each Panel**

Panel	Percentage of Submissions Appearing on	
	Two Lists <sup>a</sup>	Three Lists <sup>b</sup>
Architecture	75	40
Transportation	75	35
Power	85	75
Life support	80	55
Structures	85	80
Communications	85	55
Robotics	85	55
Information	80	80

<sup>a</sup>Primary and prioritized.

<sup>b</sup>Primary, prioritized, and reverse prioritized.

### Utility

A concept's utility (usefulness) was considered relative to the perceived mission for a given application/idea. The scoring was as follows:

- (1) indicated the concept totally failed to meet its perceived mission or was discontinued from the mission purpose.
- (2) indicated the concept offered little toward meeting the requirements of the perceived mission.
- (3) indicate the concept met the mission requirements adequately.
- (4) indicated the concept provided added benefits, such as a longer mission time at a given rated power.
- (5) indicated the concept exceeded perceived mission requirements and provided some spin-off benefits as well.

### Feasibility

Feasibility was considered with regard to the laws of physics, engineering principles, perceived reliability of the concept, power-to-weight ratio required by the concept, concept's freedom from reliance on a narrow set of unproven approaches/technologies, robustness of system development (e.g., freedom from dependency on one or two critical components), and whether a basis was provided for additional developments (e.g., an advanced space-based nuclear power system might aid in developing propulsion power systems).

The scoring was as follows:

- (1) indicated the concept was not considered to be feasible or reliable.
- (2) indicated the concept was considered to have poor feasibility or reliability.
- (3) indicated the concept was considered to be of average feasibility or reliability.
- (4) indicated the concept was considered to be of better than average feasibility or reliability.
- (5) indicated the concept was considered to be of superior feasibility or reliability.

### **Safety**

Safety was considered in terms of (1) safety during manufacture, (2) crew safety, (3) safety for the general population, (4) safety for the environment, and (5) safety for support personnel. The scoring was as follows:

- (1) indicated an unsafe, unacceptable technology concept.
- (2) indicated a technology concept that had some safety concerns.
- (3) indicated a technology concept as safe as competitive conventional technologies.
- (4) indicated a technology concept of above-average safety.
- (5) indicated a technology concept considered very safe.

### **Relative Cost**

Concepts were examined in terms of how their costs and potential payback times compared to those of competitive concepts. "Cost" was defined as a vector made up of developmental, operational, and maintenance costs. The scoring was as follows:

- (1) indicated the concept had a much greater cost and/or a significantly longer payback time than competitive concepts.
- (2) indicated the concept was somewhat more costly and/or had a somewhat longer payback time than competitive concepts.
- (3) indicated the concept was equal in cost and had a payback time roughly equal to competitive concepts.
- (4) indicated the concept was somewhat less costly and/or had a somewhat shorter payback time than competitive concepts.
- (5) indicated the concept was considerably less costly and/or had a significantly shorter payback time than competitive concepts.

## **Innovation**

In terms of concept innovation, the central question was whether the concept would add to the state of technical knowledge. The scoring was as follows:

- (1) indicated the concept was well below the state of the art.
- (2) indicated the concept was somewhat below the state of the art.
- (3) indicated the concept was roughly equal to the state of the art.
- (4) indicated the concept was somewhat more advanced than the state of the art.
- (5) indicated the concept was highly novel and innovative.

## **Baseline Reference**

Where possible the concepts were compared to the baseline cases of the 90-Day NASA study on Human Space Exploration (NASA, 1989). Submissions competitive with or offering something in addition to those reference points scored a 3, 4, or 5.

Nuclear power was considered for space and surface applications. The SP-100 is a baseline reference point for space and surface nuclear reactor power concepts up to 5 MWe, depending on the conversion system chosen and whether modularity is employed to combine several units. This baseline is complementary to the multimegawatt particle bed reactor under development. The ROVER and NERVA solid-core nuclear thermal rocket programs serve as a baseline for nuclear power for transportation. RTGs or DIPs up to 5 kWe will be considered a reference point for radioisotope power, particularly for such applications as rovers.

No baseline was chosen for nuclear fusion since a reactor has not been demonstrated. However, pulse nuclear concepts such as Orion might be considered as a reference for transportation given past research and development.

The baseline for initial nonnuclear power calls for a combination of photovoltaic array and regenerative fuel cell assemblies providing 25 kWe during the day and 12.5 kW at night, allowing for multiple assemblies for additional power. Power generation and rejection of 75 kWe was considered an initial baseline for space systems. Growth to 50 kWe solar dynamic were considered a baseline concept.

Cryogenic hydrogen/oxygen systems were also considered a baseline. Several submissions proposed variations on this concept.

The use of in-situ materials where feasible was also a baseline consideration, although the possibilities have not been fully understood and will require exploratory missions as well as innovative concepts.

**Appendix B**  
**LIST OF ALL POWER PANEL SUBMISSIONS**

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Submission #	Title/Subject
100016	Getting John Q Public in Support of the Space Projects
100104	Counter Rotating Kinetic Storage Beams
100193	Fluid Gyro Wheel Propulsion
100194	Laser Beamed Energy Driver
100195	Low Temperature Energy Conversion
100196	Reevaluation of Reich's Theory of Orgone Energy
100197	Space Electrical Power Using a D- <sup>3</sup> He Field Reversed Configuration Fusion Reactor
100198	Out-of-Core Thermionics: STAR-C
100199	A Solar Powered Station at a Lunar Pole
100200	High-Orbit Solar-Power Satellites
100201	Lunar Power
100202	Cheap Power
100203	Dwellings and Laboratories
100204	Millimeter Wave Power Beaming for Space Power Distribution
100205	Introducing Lunar Polar Solar Power
100206	A Solar System that would Provide Energy from the Sun to Supply the Earth
100207	Space Power for the Space Exploration Initiative
100208	An Alternative for Photovoltaic Solar Cells
100209	Increasing Degree of Platinum Utilization in Solid Polymer Fuel Cells
100210	Human Power
100211	Powering a Moon Station with Microwaves
100212	Space and Lunar/Planetary Surface Power Generation Systems
100213	In-Core Thermionic Power Systems
100214	Fusion (Thermonuclear) Propulsion
100215	High Efficiency Solar Power
100216	Regenerative Solid Polymer Fuel Cells
100218	Liquid Sheet Radiator

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Submission #	Title/Subject
100219	Thermal Energy Storage for Nighttime Power Using Lunar Cast Basalt
100220	Regenerative Fuel Cell Energy Storage
100221	Wind Energy Systems for Mars Surface Power
100435	Perpetual Motion Electrical Generating Superconductor
100451	Waste Handling/Disposal in a Low Gravity/Atmosphere Context - Project "A"
100452	Waste Handling/Disposal in a Low Gravity/Atmosphere Context - Project "B"
100490	New Energy Possibilities
100560	Solar Electrical Power System
100573	The Mass Distribution Construction System Space and Surface Power
100578	Reduced Area Photovoltaic Power Supply
100579	Propulsion - Fuel
100580	Switchless DC/AC Motor
100581	Solar Power - A Stable Basis for a spacefaring Nation
100582	Space Reflector Augmented Solar Energy for Surface Power
100583	The Mass Distribution Construction System space Transportation, Launch Vehicles
100584	Unified Hydrogen/Electric Energy Utility System for Space
100585	Laser Power Beaming from Martian Orbit to the Martian Surface
100586	Laser Power Beaming from Martian Orbit to the Surface of Phobos
100587	Laser Power Beaming from Lunar Orbit to the Lunar Surface
100610	High-Capacity Heat Pipe Radiator
100673	Enhanced Phase-Change Processes Using Ultrasonic Vibrations for Space Power Systems
100674	Regenerative Fuel Cell Energy Storage
100675	Potential Energy Sources for Extraterrestrial Colonization
100676	Matter/Antimatter Propulsion
100677	Zero-Point Energy to Electricity
100704	Lunar Based Power system for Earth and Space
100708	A I-Tru-I Productions Diversified, the Atom
100724	Development of High Intense Cooling Technology for Space Power Systems
100770	Mars Rover Vehicle

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Submission #	Title/Subject
100771	Untitled
100772	Gas Generators for Emergency Use
100773	Use of In-Situ Lunar and Mars Materials for Hybrid Rocket Propellant
100774	Lunar/Mars Return Vehicle Retro System
100839	Solar Powered Generator
100873	Electrical Power Systems for Lunar and Mars Missions
100874	Supplies for Permanent Settlements on the Moon
100875	Activated Heat Source Concept for Space Power Applications
100947	Controlled Thermonuclear Fission/Fusion
100948	Development of In-Situ Energy Storage
100949	Nuclear Power for Space-Based Systems
100950	Cascade Thermionics for Space Solar Power
100951	Fiberoptically Coupled Integrated Structure Solar Array
100952	Lunar Oxygen Production Power system Optimization
101034	High Rate, High Cycle Life, Rechargeable Lithium Batteries
101035	Backup Flight and Cruise
101036	Emergency Flight and Cruise
101037	Mars/Lunar Base Power Supply Commonality via Modular Design
101038	Untitled
101039	Modular Power System for Energy Growth
101040	Closed Brayton Cycle Bottoming Cycle for Industrial Processes
101041	Solar Dynamic Power Generation Using Lunar Materials for Energy Storage
101042	Virtual Parabolic Solar Array
101057	Tether System for Traffic, LEO-Moon and LEO-Mars
101136	Binary Working Fluid Heat Pipes from 500 to 650 K
101139	Common Condition Monitoring System
101141	Ultra-Light Micro Passage Heat Exchangers
101217	Lunar/Mars All-Solar Central Power Station
101218	High Efficiency, Standardized dynamic Isotope Power System (DIPs) with Reusable
101219	An Energy Factory Near the Sun
101220	Storing Energy for Lunar Nighttime Use

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Submission #	Title/Subject
101221	Modular SP-100 Reactor Dynamic Power System for Lunar and Mars Surface Power
101222	Integrated Lunar Power Center and Simulator
101223	Power Beaming System for Lunar Surface Power
101224	Solar Power System in Lunar Orbit for Power Beaming
101225	Flexible Thinfilm Photovoltaic Array with Inflatable Structures
101226	Primary Fuel Cell (PFC) Powered Mobile Vehicles
101227	Dynamic Isotope Power System Module for Precursor/Satellite Power System
101228	PV/Battery Power System for Lunar Rover
101229	Power Cart for Early or Emergency Power
101230	PV/RFC Power System
101231	Thermally Regenerative Alloy Cell for Electric Power Generation
101232	Nuclear Auxiliary Power System for Mars Chemical Propulsion Transfer Vehicle
101233	Refuelable Nuclear Power System for Lunar/Mars Surface Power
101234	Incore Thermionic Reactor Power System for Lunar and Mars Surface Power
101235	High Temperature Superconductors for Power Transmission
101236	Superconducting Energy Storage
101237	Low Temperature Enhanced Electrical Storage for PV Space and Surface Lunar/Mars Power Systems
101238	In-Situ Mars Surface Power
101239	PV Array System for Lunar Surface Power with L1 Reflector for Nighttime Power
101240	Dynamic Isotope Power System for Dedicated Emergency Power for Habitat
101241	Heat Pipe Thermal Storage
101242	Combined Solar Concentrator/Space Radiator for Solar Dynamic Systems
101243	Surface Power Beaming for Utility Power Distribution on the Lunar/Mars Surface
101244	Modular Nuclear Power System for Lunar/Mars Environment

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Submission #	Title/Subject
101245	High Temperature Variable-Conductance Heat Pipes for Nuclear Decay Heat Removal
101246	Energy Storage Using In-Situ Lunar Resources
101247	Integrated Power System Condition Monitoring
101248	Light-Weight, High-Temperature Carbon-Carbon Heat Pipes
101249	Common Systems or Subsystems for Lunar and Mars Power Systems
101250	Solar Dynamic/Regenerative Fuel Cell Power System for Lunar Applications
101251	Power Beaming to Space and Exploration Facilities
101252	Solar Dynamic Auxiliary Power Mars Chemical Prop
101253	Modular Dynamic Isotope Power System (DIPs) for Rover
101254	Application of Space Station Freedom (SSF) Closed Cycle Brayton Power Conversion
101255	Planetary Surface Power
101256	Combined Regenerative Fuel Cell
101257	Project SELENE
101258	Space and Surface Power
101259	Attenuation Method of Thermal Energy Storage for Space and Lunar Solar-Dynamic
101260	Orbital Solar Power Transmission to Earth Surface
101261	Space Station Freedom (SSF) Electrical Power Upgrade
101262	Integrated Lunar Excursion Vehicle (LEV)/Lunar Station Power System
101263	Inflatable Solar Array Technology
101264	Thermal or Chemical Energy Storage with Lunar Materials
101265	Power System Based on Cold Fusion Investigations
101266	Solar Pumped Laser Concept for Power Beaming
101338	Replacing Carbon Fuels as Major Purpose Lunar Base
101346	Lunar Radioisotope Production
101361	Structural Dimensions/Reflective Arrays
101362	Thermomechanical Generator
101402	Pegasus II: A Multimegawatt NEP System
101403	High-Utilization Platinum Electrocatalysis for High-Efficiency Regenerative Fuel Cells

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Submission #	Title/Subject
101404	Mechanical Cell Bypass Device for Nickel-Hydrogen Batteries
101405	Improved Performance of Nickel-Hydrogen Batteries by Employing Electrode Plaque
101406	Self-Contained Forced Gas Flow in Nickel-Hydrogen Batteries
101407	Improved Performance of Nickel-Hydrogen Batteries Using Controlled Variation of Gas Pressure
101408	Nickel-Hydrogen Battery Performance Improvement Using Mechanical Energy
101409	Bubble Membrane Radiator
101410	Advanced Ceramic Fabric Heat Pipes
101423	Radiation Hardened Solar PV Cavity Converter
101458	Sub-Electronic
101459	Thermal Differential Power Supply
101523	Solar Power Satellites to Justify the Lunar Base
101524	Development of Optical Waveguide Solar Power System for Exploration of the Moon
101525	Lightweight Photovoltaic Power System
101575	Solar Power Utilization
101576	The Protection Force
101623	Untitled
101656	Propulsion in Space
200163	Integrated Power and Propulsion Systems Based on Hydrogen and Oxygen
200450	Energy Impulse Engine
200462	Antimatter Driven Fusion Propulsion System
201127	Combined Lunar Transfer Vehicle Electric Propulsion and Lunar Surface
201130	Water Based Economy Lunar Outpost Architecture
300453	How to Build a Flying Saucer
300456	Space Plane
300457	Untitled
300461	The Future of the World and its Economy
301476	Space Exploration Vehicle
301569	Exploration of Mars and the Moon

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## Appendix C

### ANALYSIS OF "CASCADE THERMIONICS FOR SOLAR SPACE POWER"

Submission #100950 proposes the stacking of three thermionic devices as a feasible way to increase the efficiency of thermionic conversion devices by reducing collector temperature. This concept may more readily find surface applications than space applications due to the trade-off of radiator size for the bottoming cycles (in space, heat rejection from the total system depends on radiation, which varies as the fourth power of absolute temperature). The submission predicts that efficiency will be increased from about 15 percent to perhaps as much as 51 percent. (Another method of increasing efficiency described in other submissions is to collect infrared flux).

All elements of the proposed concept (the high-temperature barium-cesium stage, the intermediate cesium stage, and the low-temperature cesium-oxygen stage) have been demonstrated in the laboratory. The upper stage, however, has only been tested up to 2000 K; projected performance at higher temperature is solely analytical. The cascade configuration concept is also analytical and has not yet been operated experimentally. The bulk of work in the advancement of thermionic technologies applicable to this concept has been done in the USSR.

The concept is theoretically feasible. However, it faces several significant practical barriers, four of which are described next.

The very small operating clearance between the emitter and the collector in the highest-efficiency middle stage (5 to 25 microns) has been achieved experimentally, but maintaining it for useful operational lifetimes in the high temperature range of interest (up to 1800 K) has yet to be demonstrated. Testing of the proposed concept, in which the clearance is maintained by differential thermal expansion of the emitter and collector, has been done in the emitter temperature range of 1100 to 1600 K, with only one test as high as 1750 K.

Cascading will require nearly equal current densities in the three stages, but optimum current densities vary widely (e.g., 2 to 8 A/cm<sup>2</sup> for the middle stage vs. 32 for the upper stage). It is not likely that the claimed efficiency can be achieved at uniform current densities, nor can the cascade geometry be varied sufficiently to accommodate the wide difference among the three stages.

Maintaining thermal balance among the three stages is likely to prove difficult, leading to "hot spots" that could cause cell failures. Either the heat source (a nuclear fuel

element or solar concentrator, perhaps) and the sink (e.g., a heat pipe radiator) must be extremely uniform, or the cell's already complex geometry must be tailored to match the source's and the sink's thermal profiles. Either approach seriously limits operational flexibility.

Startup, shutdown, and partial-power operation pose a whole series of operational requirements and attendant problems in maintaining proper gas pressures and temperature distributions in the three interactive cell stages.

Even though this proposal is based on solar power, the idea may be usable with other heat sources (e.g., waste heat). Its use needs to be thought out in detail for each alternative source to determine feasibility and potential advantages (particularly in cost) over other proven alternatives. On the surface, the lower part of the cycle might be used to help with habitat heating during the night.

While details on Earth-bound experiments are provided, details on adapting the concept to the space environment are missing. Weight, power-to-weight ratios, and the issue of spectral temperature distribution need study. Raising the temperature to 2600 K is an issue. A large collector would be needed.

The high-potential efficiency of the proposed cascade concept makes it extremely interesting as an avenue for major performance improvement. However, because of the complex cell geometry, high peak operating temperature, and vapor compartment control requirements, it is not at all certain that this higher efficiency will result in lower system mass or cost. Moreover, it is almost certain that the cascade concept will not be as reliable or robust as more conventional lower-cost thermionic approaches or other power conversion cycles. It is also likely that technology advancement and development of the proposed cascade concept will be both costly and time consuming.

The proposed concept should be subjected to a focused experimental research program to demonstrate its various technologies and their operational characteristics. The author suggests that such a program be conducted jointly with the Soviet Union. In view of the considerable Soviet capability in thermionic technology, this would appear to be an excellent idea.

Because of the concept's complexity and the advanced nature of its component technologies, it is not recommended for consideration as a near-term opportunity for Lunar or planetary surface power. The results of the recommended research and demonstration program must be evaluated first.

## Appendix D ANALYSIS OF "PROJECT SELENE"

Submission #101257 is a high-utility proposal for providing energy on the Moon, or to electric propulsion systems transferring payloads from LEO to Lunar orbit, via laser power beaming from Earth to PV arrays that reconvert the laser power to electricity. The sources are situated at three points 120 deg apart to provide continuous megawatts of power, Lunar day or night.

The system is probably feasible, although adaptive optic systems with the pointing accuracy and collimation required to impinge on the Lunar array from a source over 400,000 km distant may turn out to be problematic. Also, PV arrays with the required accuracy have yet to be demonstrated.

Technologies for all elements of the proposed concept have been demonstrated, but to a very limited extent in several cases. For example, adaptive optics have been demonstrated through the Earth's atmosphere, but not over Earth-to-Moon distances, and the proposed phase-conjugation reference located on the Moon is as yet only conceptual. Similarly, hand-tailored solar cells capable of 30 percent efficiency at infrared wavelengths have been tested in the laboratory in concentrator-cell configurations, but manufacturing technologies for reliable multikilowatt arrays suitable to the Lunar environment have yet to be conceived. Continuous-wave (CW) lasers also have yet to be developed at power levels of the order of the proposed 10 MW.

Distinct advantages of this system are the avoidance of the construction of power-generating sources on the Moon or the transportation of generators to the Moon (the construction of power generators being simpler on Earth because weight or transport problems do not play a part). These advantages could bring substantial reductions in costs if the technical problems associated with atmospheric transmission can be solved. However, whereas use of ground-based lasers for propulsion appears promising because the laser's energy can be converted to thermal energy at relatively high efficiency, conversion to electric energy is not nearly so efficient, even if the postulated 30 percent conversion can indeed be realized operationally. Moreover, the cost of construction, maintenance, and operation of the complex high-power laser and adaptive optic system for long-term use (vis-à-vis the relatively short-term duty cycle for propulsion) is likely to far exceed the cost of simply using a conventional PV array with an area about six times that of the proposed concept. Such an array would produce the same power as the laser-illuminated array and also allow it to

charge conventional regenerative fuel cells for the Lunar night. It could also be used on the far side of the Moon, where the laser-illuminated relay cannot. Moreover, the development cost and time of the laser/PV system would far exceed those of the conventional array and fuel cell system, and its susceptibility to malfunction (and consequent loss of power) is considerably greater than the conventional system. Note, too, that the development of an in-situ manufacturing capability on the Moon, which is generally considered to be a "must" for any long-term Lunar exploration program, would strongly favor building a large Lunar-surface solar array rather than investing in costly new technology, even on Earth.

In any case, all PV systems suffer at high power levels compared with nuclear reactor systems, so the massive laser system investment might be better allocated to nuclear system development.

A penalty for solar power on the Moon is the above-stated requirement of either storage or some distribution system to deal with the two-week-long Lunar night. Storage again requires transport from the Earth (in lieu of suitable development of in-situ methods) and could have lifetime limitations. The construction of a distribution system is not a simple matter and may take more time to put in place than the proposed system, and whether levels of continuous power comparable to the present proposal (3 MWe) could be provided is open to question, although some baseline concepts would reach this by modular dynamic nuclear reactor systems. The ability to send emergency power within seconds is an advantage for SELENE over some baseline approaches.

The atmospheric distortion of the beam is handled by an adaptive compensation system that realigns the beam based on return information. This solution may be somewhat feasible, but since this problem is a difficult one, it is not clear how much confidence can be placed in quick solutions (i.e., it is unclear if the proposed time schedule of transmission to the Moon by FY 1994 is plausible). If this solution is successful, spin-offs would be applicable to possible SDI or high-power communication systems. The problem of thermal blooming effects has not been addressed.

The potential problem of possible damage by meteorites (large ones can pose the same threat to any Lunar site, but the smaller ones may be a threat to PV cells over time) is an issue that might be addressed by transparent shielding or concentration, if this issue is deemed a risk for a given mission time interval.

Although ground-based lasers appear interesting for directly heating a propulsion system's propellant and, possibly, for electric power supply to Earth-orbiting spacecraft, it is not likely that the low power density achievable at Lunar distances would merit development of such a laser power system for Lunar surface electricity. Hence, this concept is not deemed

worthy of dedicated research and demonstration support. Note, however, that laser and optical system development pursued for other purposes, if sufficiently successful, may warrant reconsideration of this concept at a later time.

## Appendix E

### ANALYSIS OF "ENHANCED PHASE-CHANGE PROCESSES USING ULTRASONIC VIBRATIONS FOR SPACE POWER SYSTEMS"

Submission #100673 addresses heat energy storage for later use and heat rejection and attendant heat transfer processes, which are of particular concern in the low-gravity, low-vacuum extremes of space. Phase-change storage methods offer great potential because of their high heat-capacity properties. The space environment, however, offers little opportunity for convective flows, thus potentially inhibiting phase changes and causing void regions (particularly during freezing). The result would be poor performance or, worse, damage to the heat transfer or storage systems.

The proposal to use ultrasonic waves, which has had prior success in a number of engineering and medical applications, has support in the heat transfer field through some limited experiments by the proposer, who acted as the principal investigator. In one, 50 kHz sound waves speeded up melting of a phase-change material (99 percent n-octadecane) by a factor of two over nonirradiated melting. Subtracting the energy costs of ultrasound generation, the enhancement factor is about 1.7.

A particularly desirable situation in the reverse solidification process is the nearly uniform temperature distribution over a medium. This minimizes the occurrence of randomly located voids. However, in heat storage situations with ultrasound, the remaining voids will occur in the centers of the phase-change materials, because the solidified external material increases the insulation around the heat-storing liquid centers.

In heat rejection situations, premature spotty crystallization of the phase-change material away from the heat removal surfaces is inhibited, enhancing the heat rejection performance.

The principles are sound, and experimental justification for the application exists. Development of a prototype system for space applications probably will require some time, but steps in that direction appear to be quite feasible and costs of fabrication may be quite reasonable. Weight factors (heat rejection systems or heavy heat storage masses) for an entire system, including the sound generators and structural integrity factors for space applications, are difficult to estimate at this time.

**Appendix F**  
**ANALYSIS OF "NUCLEAR POWER FOR SPACE-BASED SYSTEMS"**

Submission #100949 proposes the use of the ENABLER gas-cooled nuclear reactor for both prime power and propulsion. The proposal is to use a closed Brayton cycle. This type of power conversion unit employs a turboalternator, and a reference output of 100 kWe is postulated.

NERVA technology was an outgrowth of the ROVER project and was extensively developed from 1955 to 1973. This experience with solid core nuclear thermal rockets gives a basis for confidence in the plausibility of follow-on proposals involving solid core concepts, although the only U.S. in-space operational experience with a nuclear reactor has been the SNAP-10A.

The cooling system must handle very high power densities because the thermal output is several gigawatts, whereas for prime power the expected requirement is three orders of magnitude less. There will thus be a need to develop systems appropriate for both roles. It is difficult to achieve temperatures greater than those in NERVA, although much investigation into materials is under way. There is an issue of erosion at high power. Nuclear rocket reactors are intended for hours of use, not years, as a power source would be.

It is not clear that dual use of the transportation reactor for prime power is the right technology route for both space and surface power applications. Ships sometimes work by two separate power systems, using a distinct system for propulsion. Using the transportation reactor during flight for prime power is distinct from using the same reactor as a surface power unit that must be brought down from, and subsequently back up to, orbit. System mass is large for a carbon moderated-epithermal reactor; however, smaller masses are possible with fast reactors (e.g., tungsten fuel elements as in the G.E. 710).

The Brayton cycle is probably the right choice for 100 kWe to 1 MWe. An alternative power cycle is the Stirling cycle using pistons. The distinction in technology is akin to that between refrigerators and internal combustion engines. The efficiencies are roughly the same, but for longevity and simplicity the Stirling might be a better choice.

Achieving even a 200 sec  $I_{sp}$  increase over that of NERVA is desirable. The ENABLER may be more favorable solely as a propulsion source.

**Appendix G**  
**ANALYSIS OF "HIGH-CAPACITY HEAT PIPE RADIATOR"**

Submission #100610 proposes a heat pipe geometry that allows the heat pipe to be launched in a compact form (coiled) and then deployed in space simply by being pressurized. The geometry is also claimed to provide better operational flexibility than is true of more conventional heat pipes by reducing the thermal coupling between the condenser's vapor and liquid passages. The intention is to give substantial cost, size, mass, ease of fabrication, and ease of storage advantages. The engineering performance appears well thought out from both the space deployment and fabrication points of view.

Several high-temperature heatpipes have been built and tested, some of which have features comparable to those of the proposed concept—i.e., deployable structures, multigroove wicks, and variable capacity. However, the proposed concept is interesting in that it does not require expensive development and demonstration of its claimed capabilities.

The author claims to have demonstrated the manufacture of an inflatable, deployable structure and leak-tight welding of its seam, but demonstrations of operational lifetimes in the space environment (temperature, vacuum, thermal shock, atomic oxygen exposure, high-speed dust, etc.) are needed. Perhaps even more important, thermal performance benefits have yet to be demonstrated, and there is some question as to whether they would indeed be realized. For example, the proposed geometry does not appear to assure retention of liquid-passage "priming," as claimed by the author, and may require liquid-passage diameters small enough to prejudice the device's capacity. Also, the nonisothermal nature of the design, although it may provide some degree of operational flexibility, might also unacceptably reduce the design's efficiency. Hence, demonstrations are essential before feasibility can be established with confidence.

By replacing current monogroove heat pipe designs with an innovative, fine-capillary system, better heat transfer performance results from reduction of "vapor lock" in the liquid channels. The fabrication is also innovative in that the pipe and conducting radiator fins are seam welded, thin, lightweight, conducting (Al) metal sheets previously stamped with grooves that later become the capillaries when the pipe/radiator system is deployed. Capillaries in this system are 1/5 (0.05 mm) the width of the monogroove heat pipe slots, thus producing a greater pressure head in the liquid capillaries. Moreover, moving the heat transfer activity to the fins via the thin walls of the liquid channels, rather than in a relatively thick aluminum extrusion containing the liquid and vapor channels characteristic

of monogroove design, precludes the vapor lock possibility in the liquid channels in the radiator's condenser section.

Storage and deployment features are also innovative and produce space and weight advantages. In the launch environment, the radiator is configured in a compact, spirally coiled state, the spiral proceeding longitudinally along radiator fin channels connected endwise to the heat pipe arteries. This configuration gives the radiator structural strength from its own geometry instead of from added material, thus avoiding the weight and material costs of material for sufficient structural rigidity to withstand launch stress. Overall, this coiled cylinder is about 30 cm in diameter and 34 cm in length.

For deployment, the heat pipe liquid upon heating creates the pressure and consequent expansion that uncurls the radiator, much like the curled ticklers one sees at parties that unfurl as one exhales into the curled paper tube.

Protection against micrometeoroids has been provided by enclosing the working liquid and vapor channels within two walls: (1) a metal wall to fragment or vaporize the micrometeoroids and to conduct heat and (2) a high-strength ceramic wall to absorb the remaining micrometeoroid energies. Similar layers can be added if required. Layered protection results in considerable weight advantages.

The evaporator, which is quite flat for contact with the heat source but broad in cross-section to provide sufficient volume, is stiffened by a metal plate welded to the heat-receiving face, which also doubles as a heat conductor.

The feasibility of the coiled radiator concept appears to be quite high. The ability of vapor pressure to unfurl the radiator and the strength and leak tightness seem established and plausible. The cost for development, fabrication, and ground testing of a prototype of the radiator is estimated at \$600,000, which is a remarkably low figure.

It is not clear where and how this device would be specifically beneficial in exploring the Moon and Mars. It is not suited to high-temperature applications, such as heat rejection from most power conversion systems, and hence is possibly limited to environmental temperature control (in a relatively narrow range) for electronic devices or humans. Hence, specific applications analyses would be required (for both robot and manned spacecraft electronics and human support systems) before a decision could be made as to whether to pursue development specifically for space exploration purposes.

The concept has potential applicability beyond space for other thermal management requirements, which is a consideration in its use for a Lunar/Mars mission. The concept has sufficient novelty and potential general application to warrant modest support in

demonstrating its mechanical robustness in the space environment and the thermal performance of its proposed geometry.

**Appendix H**  
**ANALYSIS OF "FIBEROPTICALLY COUPLED INTEGRATED STRUCTURE**  
**SOLAR ARRAY"**

There is little question of the utility and innovativeness of submission #100951. Except for the possibility that a structure riddled "Swiss cheese-like" with fiberoptic channels may be weaker than one that is not (if this is a problem, a remedy may be possible and probably at low cost), there appear to be no safety issues. In principle, the concept is sound, but questions remain.

The submission does not discuss the issue of presentation of the fiber ends to collect enough energy to make a serious difference. Potential degradation of the fiber optic material itself in high radiation environments also is not discussed. Of course, for a Mars mission this situation may not be so critical with regard to solar radiation, but galactic cosmic radiation may be an issue. Fiber optic systems have been used in particle detectors at high-energy accelerator laboratories, so presumably performance could be shown to be quite reasonable.

The cost of a system in space is also unclear. In essence, the proposal amounts to a request to continue research in this area. Thus, if some of the above questions and others that may arise in the course of the work are addressed, the proposal is reasonable.

**Appendix I**  
**ANALYSIS OF "IN-CORE THERMIONIC POWER SYSTEMS"**

Submission #100213 presents a potentially high-utility system that would add relatively little incremental weight to the reactor itself. Applications to both space and surface systems appear to be feasible. High total power appears to be feasible, which is not true for some conversion devices.

Details on adaptation to space applications are lacking. It would appear that the proposers expect further studies to resolve some pertinent questions, specifically those involving space applications. Shielding dependent on a specific application is an issue. Weight of the overall system would appear to be resolved by choice of a reactor. Lifetime of components and materials in the nuclear environment is an issue. Commitment to a space reactor implies a desirability for long lifetimes (beyond the 23,000-h test cited) for all components essential for the working of a system. Presumably, since the proposal is largely for further Earth-bound testing and development, some of these questions may be resolved before commitment to a launchable system. Overall feasibility appears to be very high in view of long previous research in this area (e.g., the 5- to 10-kWe TOPAZ thermionic reactor systems the USSR has operated). The submission proposes varying the power level from kilowatts to megawatts by adding more thermionic cells as desired. The offer of various scales of power is an attractive feature, particularly since there may be different application demands for different missions.

The simplicity of a thermionic system with respect to a dynamic system is a reliability advantage. However, the D-cell-size thermionic devices have very small gaps, which would imply a chance of failure under loads over a lifetime. There is thus a need to protect thermionic elements against shocks or vibration.

**Appendix J**  
**ANALYSIS OF "DEVELOPMENT OF IN-SITU ENERGY STORAGE"**

Submission #100948 proposes the intensive study of Lunar regolith properties and advances an argument for exploiting the regolith for thermal storage in conjunction with use of a solar dynamic power system based on the Brayton cycle. Lunar materials offers much potential, and their use appears to be quite possible. The technologies required are metallurgical testing and development of a concentrator, receiver, Brayton engine, radiator, and thermal energy storage.

Costs are an uncertainty, however, and the requirement for construction activity on the Lunar surface is a consideration. In that regard, this concept may be of value more to an evolutionary mission that calls for an extended habitat and manned presence, since initial power systems will be able to address only initial needs with a reasonably small amount of activity by the crew.

The use of solar dynamics will require that an adequate collector be delivered to the Lunar surface and erected. As the proposal indicates, there has been some Earth-based experience with collectors. At a specific power of 100 kg/kW, the mass of a 25-kWe unit is 2.5 metric tons, which is somewhat indicative of the magnitude of material that must be delivered. It seems reasonable to deliver 10 metric tons for a 100-kW system, although SP-100 may offer a higher specific power at the same power level. However, the system offers specific power advantages over battery and fuel cell systems combined with PV arrays.

Issues to be answered include the performance of materials (including chemical compatibility) and systems in the reduced Lunar gravity, the design of the thermal storage in basalt and regolith, and whether any comparable approach is feasible for Mars. The heat transfer properties of the material under repeated use, including any phase change, must be understood. The study of the behavior of voids, migration, and cracks is part of this issue. The Martian surface is substantially different from the Lunar surface, and presumably there will be less opportunity for Mars exploration than for Lunar exploration in the near term.

The requirement for a long-term presence on the Lunar surface naturally suggests the use of indigenous resources to the fullest extent possible to minimize transportation costs. The use of in-situ materials should not be ruled out and is certainly worthy of further study.

## Appendix K ANALYSIS OF WIND POWER ON MARS

One difference between the Moon and Mars is the presence of a somewhat appreciable Martian atmosphere, and several submissions (e.g., #100221, **Wind Energy Systems for Mars Surface Power**) proposed the use of windmills to generate power. We found that the concept's utility is insufficient for any near-term Mars habitat.

Power in the wind per unit area,  $P_{\alpha}$ , is the product of dynamic pressure and speed and is given by

$$P_{\alpha} = \frac{\rho v^3}{2}$$

where  $\rho$  is the atmospheric density and  $v$  is the speed. To determine the power extracted by the windmill, this power density must be multiplied by the windmill cross-section and the power coefficient, which is a measure of the efficiency. Betz theory (as an estimate) gives a maximum efficiency of 59 percent, and such effects as tip-speed ratio variations are likely to push this figure lower.

Winds are extremely variable on Mars on daily, seasonal, and annual bases. However, according to many observations (mostly over 200 per region) in 12 different zonal and 12 different meridian strips after the Northern winter solstice, 99.9 percent of the speeds were below 20 m/sec overall, 90 percent were below 10 m/sec, and 50 percent were below 1.4 m/sec. Moreover, the much higher speeds that cause dust storms are rare; sometimes more than a year goes by without even one occurring. Thus, most of the time, winds on Mars are not strong, although because of the topography one may expect to find sites that have higher winds. Nevertheless, such differences are not as likely as they are on Earth, with its more varied topography and land and sea features. In addition, the atmospheric density at the Martian surface is about  $2.5 \times 10^{-5}$  g/cm<sup>3</sup>, or 25 g/m<sup>3</sup>, which is substantially less than that of the Earth—1220 g/m<sup>3</sup>, or about 50 times the Martian density. The low density and prevailing low wind speeds on Mars do not present an optimistic outlook for wind power generation on Mars.

Wind power density is shown in Fig. K.1 as a function of wind speed. (Technically the relevant parameter is the root mean cube speed due to the variations in the wind, not the average wind speed.) Consider a turbine with two blades with a radius of, say, 50 m. The

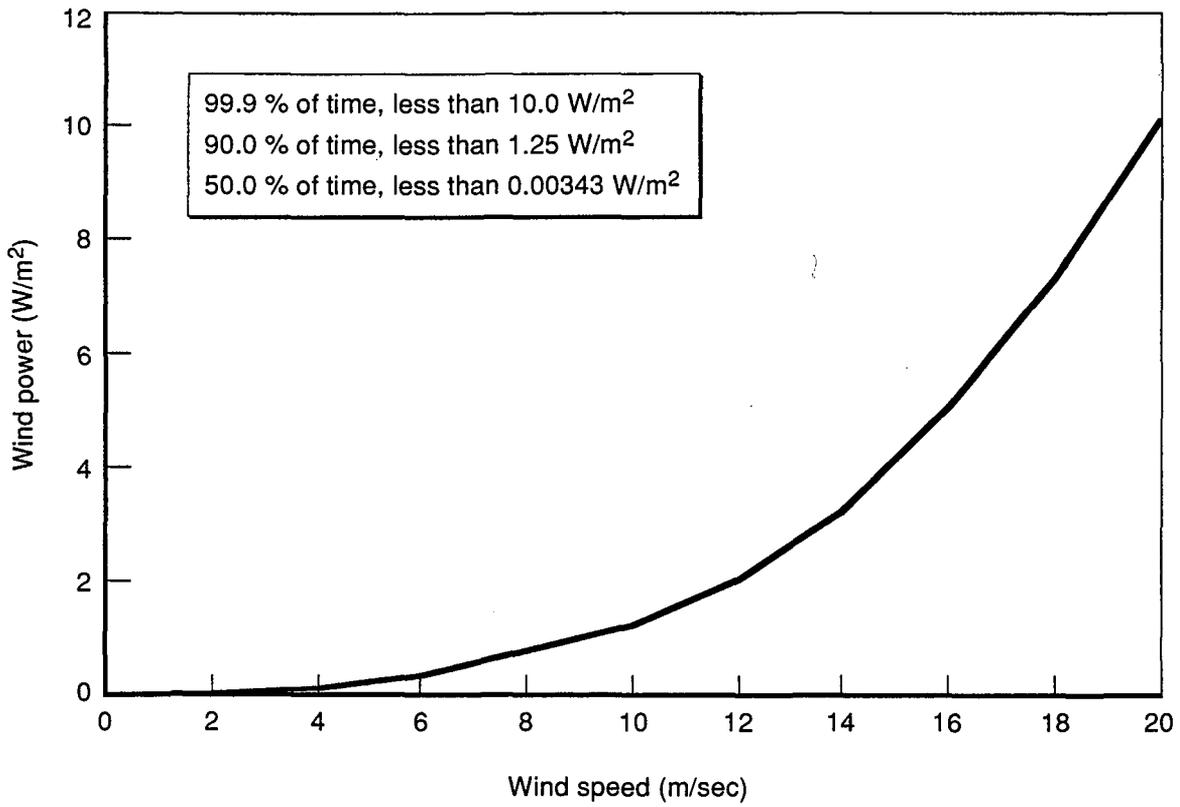


Fig. K.1—Theoretical Wind Power on Martian Surface

fan area (neglecting the hub to which the blades are attached) is then 7854 m<sup>2</sup>. The peak power efficiency coefficient ranges from 0.15 to 0.4, where the upper value is for ratios of blade-tip speed to wind speed of around 5 to 6 (high speed, and the lower values are for ratios of 1 to 3 for different turbine blade configurations).

Ignoring the best siting, but taking an average, such a turbine would produce useful power of less than 10 W 50 percent of the time at the very best, using a 0.4 coefficient. The variability of the wind would actually make this number even less.

What weights would such a turbine come to? A pre-World War II American project for a 1250-kW generator with a 175-ft-diameter two-bladed propeller weighed over 15 tons. It supplied electric power at various times until one of its 7-1/2 ton blades broke off in a 25-mph wind. (One expects lower speeds on Mars 90 percent of the time.) The blades of that propeller were about one-half the length of those of the hypothetical propeller. While wind forces of the Martian atmosphere are substantially below those on Earth, a substantial mass is still needed for the hypothetical propeller described above.

Other machines are possible. A NASA Darrieus machine resembling a seven-story-high eggbeater was developed in the 1970s and put out about 60 kW at 32 mph. Its cost and overall weight are expected to be substantially lower than those of the standard propeller-type machines. However, we are still faced with the lower wind speeds and densities on Mars, with concomitant lower output power. There is also the cut-in speed for power production, which is 4.5 m/sec, a value achieved less than 10 percent of the time on Mars.

## Appendix L THE CONCEPT OF FUSION AS A POWER SOURCE

A number of proposals suggested the use of nuclear fusion for transportation or prime power. Some of these proposals (e.g., submission #100197, **Space Electrical Power Using a D-<sup>3</sup>He Field Reversed Configuration Fusion Reactor**) involve extension of present magnetic confinement approaches, including advanced aneutronic fuels involving <sup>3</sup>He. The difficulty with using <sup>3</sup>He is that the ignition requirements are higher than those for deuterium-tritium or deuterium-deuterium reactions. Containment issues of magnetic fusion systems raise concerns about reliability. Such systems generally use massive confinement devices.

One submission, #200462, **Antimatter Driven Fusion Propulsion System**, proposed a hybrid of inertial confinement and magnetic confinement fusion with antimatter. The lack of demonstration of a fusion reactor to date caused low feasibility ratings; however, the utility was rated high.

The progress made so far (such as at Princeton's Tokamak Fusion Test Reactor or the Lawrence Livermore facilities) warrants continued interest in fusion. Comparative judging of the feasibility of controlled thermonuclear devices is beyond the scope of this study. For our purposes, all such devices were high technological risks, although they cannot be ruled out as infeasible. On the other hand, some submissions proposing the use of uncontrolled thermonuclear reactions had a very high degree of technological plausibility within the SEI time schedule.

Submission #100214, **Fusion (Thermonuclear) Propulsion**, advocated nuclear pulse sources for transportation. This concept is similar to the Orion project, except that large thermonuclear (as opposed to low-yield fission) explosives and inertial confinement fusion (ICF) pellets (the British Interplanetary Society's Daedalus design is one example, based on D-<sup>3</sup>He fusion) have been proposed. The explosive detonations must be repeated so as to average into a push against the rocket with acceptable material degradation of the opposing rocket plate. ICF requires a driver (e.g., laser or ion beam) to deposit energy on a pellet of fusionable fuel in a manner that compresses the pellet and causes appreciable fusion while the inertia holds the pellet together. This approach might be used internally rather than externally. The resulting heat from fusion could be used to drive a propellant for high specific impulse. Submission #100214 includes the concept of using a magnetic field generated by a superconductor to guide the charged fusion products. This approach is not

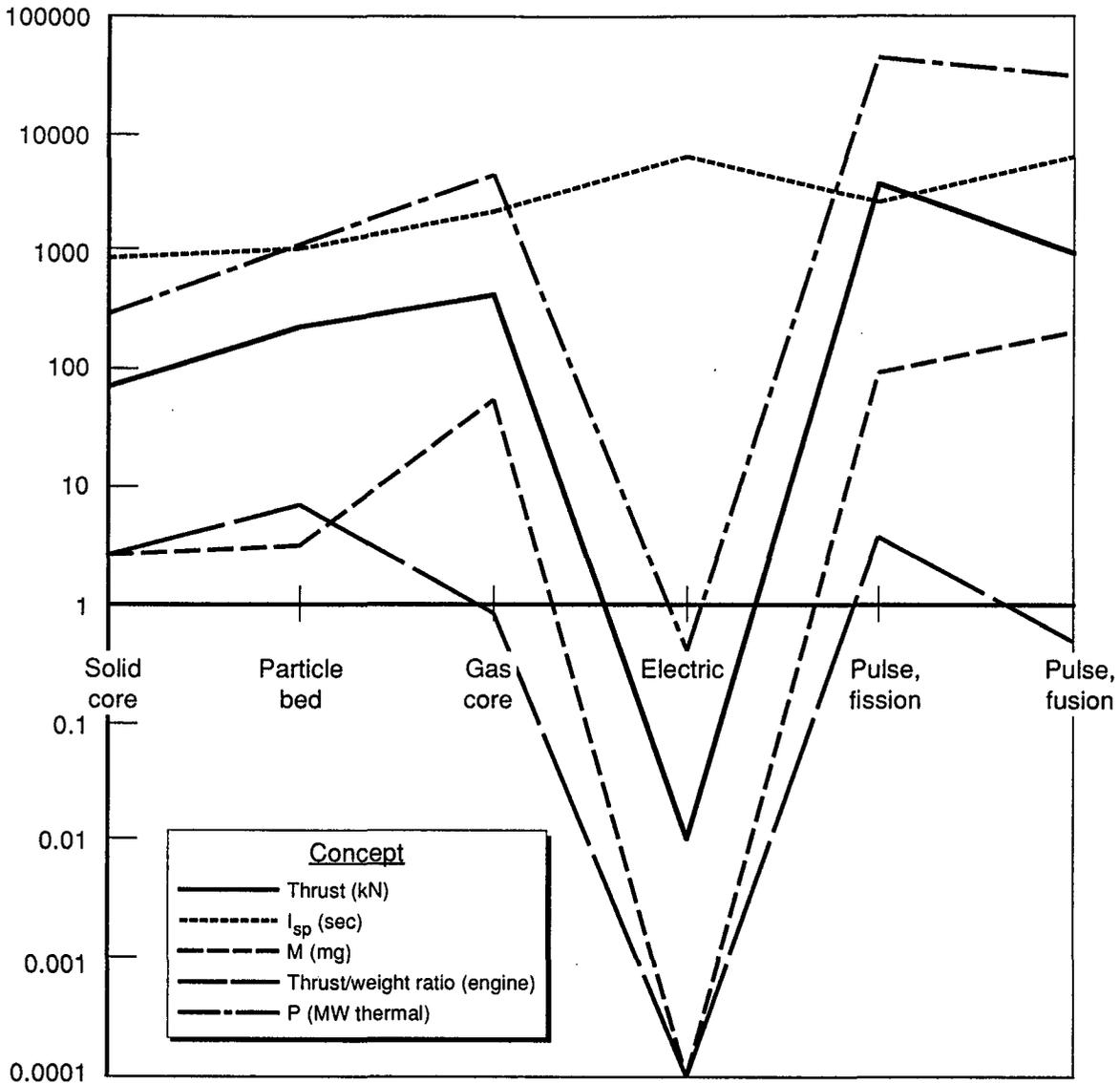
practical for the large thermonuclear yields suggested by the proposal, but might be considered for ICF pellets (particularly if aneutronic, essentially charged-product reactions are used).

The demands on the use of ICF would not be as stressing for space propulsion as for commercial fusion power since the same restrictions on cost per unit energy do not apply. Both driver and pellet technologies determine whether the gain from a pellet (i.e., the ratio of driver input energy to fusion yield) is encouragingly large. Driver technology in principle seems to be a straightforward technology to develop, but pellet design may require more effort, particularly if advanced aneutronic fuels are to be employed.

An Orion vehicle design had a launch mass of  $3.3 \times 10^6$  kg, an explosion repetition rate of 1 to 0.1 Hz, and, with subkiloton explosions, was predicted to attain specific impulses in excess of 4000 sec. The feasibility of #100214 was rated relatively low due in part to the large stressing explosions advocated in the submission (1- to 5-megaton charges in the submission). An Orion-type scheme, however, may be plausible during the time schedule of SEI. Rather than launching from the Earth's surface, the vehicle could be assembled in orbit and, if necessary, boosted to a higher orbit before Mars launch. The ICF approach would involve more technological risk, but without the drawbacks of Orion's reliance on nuclear explosives.

Figure L.1 compares several critical parameters—thrust,  $I_{sp}$ , mass, thrust/weight ratio, and power—for various nuclear power propulsion systems. These parameters are for an initial impulsive velocity for the Neptune orbiter mission with a 1500-kg payload. A maximum of five stages was assumed to reach the effective exhaust velocity of each system. The trajectories were ballistic except for the electric case.

The nuclear pulse approach can be conceived as a means of supplying surface power as well as vehicle propulsion. The PACER (e.g., early work by Los Alamos and RDA, and recent work by Szoke and Moir of Lawrence Livermore) employed 20-kiloton explosions every 7/hr to generate 1 GWe by underground explosions generating steam at 3000 psi and 1000°F. The depth of the 200-m diameter cavity was 2000 ft. On the Moon, a distance of somewhat less than 12,000 feet would be required because of soil and gravity differences. This could be a potential technique to generate large powers, were there a need. Gigawatt power levels on the Lunar surface from other methods would require considerable construction activity, although the digging and conversion systems required for a PACER-like approach on the Moon are no simple feat, and the use of nuclear explosives on the Moon might not be acceptable for nontechnological reasons. (A comparable solar power system requires about a



SOURCE: Garrison et al. (1982).

Fig. L.1—Nuclear Propulsion Concepts Comparing Alternative Parameters

1 km<sup>2</sup> collector or array. For a PV array, 5km<sup>2</sup> or more per gigawatt might be needed, depending on efficiency.)

There are other research routes for fusion in addition to magnetic and ICF methods. One approach is impact fusion. Guns (coil, electromagnetic, ion, etc.) are used to accelerate small fuel masses to tens of kilometers per second and impact them onto a target rich with fusion fuel.

Another approach raised by some of the submissions is cold fusion. Submission **#101265, Power System Based on Cold Fusion Investigations**, proposes further research into processes similar to those used in electrochemical experiments that resulted from the Pons and Fleischmann announcement in 1989. Cold fusion is not an established phenomenon, however. A different type of cold fusion is muon catalyzed fusion. The source of muons, however, would likely be a large accelerator (muons from pions released by proton-antiproton annihilation is another possibility). Further, it is not yet clear that breakeven can be attained by this method—the muon has a limited proper lifetime of only 2.2 microsec and consequently the number of fusion reactions catalyzed is limited.

Research in a number of fusion areas could lead to a breakthrough, although the history of fusion research claims can lead one to have some questions about the technological feasibility for the SEI time frame. In general, SEI might benefit from research sponsored by other agencies, although a study to determine if one of the methods is attractive to SEI might be warranted.

## Appendix M

### THE CONCEPT OF ANTIMATTER AS A POWER SOURCE

Antimatter was proposed by a number of submissions as a compact power source (e.g., #100676, **Matter/Antimatter Propulsion**). The form of antimatter being proposed is antiprotons. Antielectrons are less desirable because of the containment problem; i.e., the mass-to-charge ratio is much lower than for antiprotons. Bremsstrahlung losses and the safety and utility of gamma rays from annihilation are issues for any proposed use of antielectrons. One possibility would be a massive source of radioisotope-liberating positrons. The production of antielectrons to combine with antiprotons to form antihydrogen (for containment) would be one reason for a positron production facility if antimatter schemes were judged desirable.

Antiproton production must be demonstrated, since some proposals call for relatively tremendous quantities (e.g., submission #200462 requires on the order of 100 g of antiprotons for a Mars vehicle). Antiprotons are being produced in current high-energy accelerator facilities; however, the production rate is on the order of somewhat more than  $10^{14}$  per year (nanogram level), or about three orders of magnitude higher if you could correct for losses in production (see Fig. M.1).

Production is determined by the interaction rate,  $R$ , which depends on the luminosity,  $L$ , and the cross-section,  $\sigma$ . The latter is energy dependent.

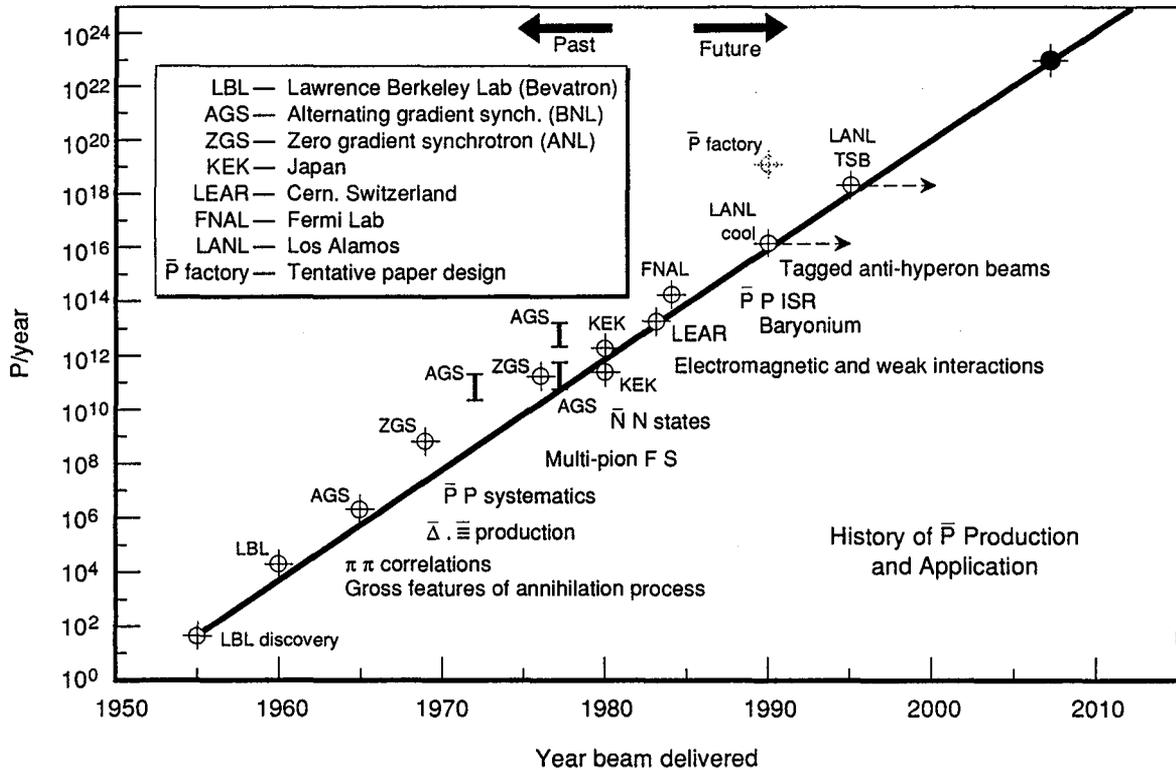
$$R = L \sigma$$

The current production rate is not a physical limit. It is dictated by engineering and is expected to be improved upon in future facilities.

At very high center-of-mass energies,<sup>1</sup> hadronic cross-sections are typically a few tens of millibarns (one barn =  $10^{-24}$  cm<sup>2</sup>) per nucleon. The branching fraction for antiproton production out of the total hadronic cross-section is rather small, and at a center-of-mass energy squared of about 100 GeV, the average multiplicity of antiprotons produced per pp inclusive interaction is only a hundredth. The luminosity is limited by beam-beam

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<sup>1</sup>Production must, of course, always be above threshold. For proton-proton collisions, kinematics gives a threshold center-of-mass energy of 5.6 GeV. A phenomenon known as Fermi motion makes antiproton production possible at slightly lower energy.



SOURCE: Forward and Davis (1988).

Fig. M.1—Antiproton Production

Fixed-target production might do five or six orders of magnitude better. Assuming operation for a few times  $10^7$  sec at a luminosity of a few times  $10^{37} \text{ cm}^{-2} \text{ sec}^{-1}$ , a target of medium-weight nuclei (or perhaps a beam dump) might greatly exceed microgram quantities. Collecting over all production angles is a problem and source of loss. Using beams or targets with mass numbers much higher than that of hydrogen could add one to two orders of magnitude to the production rate of antiprotons. A high-current linear collider might be one approach.

It may be possible to dedicate a facility using a version of some current technology to produce upwards of a milligram per year in the mid to far term, but doing so will require both the ability to collect and cool the antiprotons as well as the means to produce them. To

<sup>2</sup>In addition to ring-type colliders, linear colliders exist and may be relatively attractive. The mutual defocusing of particle bunches in the collider is governed by the charge per particle. Thus, luminosities for heavy ion beams tend to be correspondingly reduced, although the use of linear colliders and partial ionization are steps to limit this detrimental effect.

accumulate orders of magnitude more would require new accelerator developments, perhaps extensive heavy ion collider developments.

It is difficult to support a position that hundreds of grams of antiprotons will be available even in the foreseeable far term, although milligram to gram quantities might be feasible in the foreseeable future. However, it is quite possible that such quantities of antimatter will prove useful for driving inertial fusion and/or microfission pellets.<sup>3</sup> If this approach proves successful, the leverage offered by a small quantity of antiprotons will be enormous. Long-term and fail-safe containment must be demonstrated. Concepts requiring modest quantities may have viable applications. The possible antimatter conversion systems vary in feasibility, utility, and risk.

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<sup>3</sup>Some promising approaches were presented, for example, at the Sixth International Conference on Emerging Nuclear Energy Systems, held in Monterey, 16-20 June 1991.

## Appendix N

### THE CONCEPT OF GASEOUS CORE NUCLEAR ROCKETS

The use of a gas or plasma core in reactors was not proposed in any of the highest-ranked submissions, but was considered in submission #100947, **Controlled Thermonuclear Fission/Fusion Reaction** (the handling of the fusion concept in the submission had feasibility problems). The concept of using a gaseous nuclear reactor core is interesting to consider for propulsion because of the potential for a high- $I_{sp}$  engine and a short trip time.

Solid core reactors are generally limited by temperature properties of the materials to an  $I_{sp}$  below 1500 sec (e.g., graphite is limited to about 2500 K, or 800 sec  $I_{sp}$  for hydrogen propellant; a colloidal pellet bed reactor would do better, perhaps handling temperatures in the neighborhood of 3500 K). A gaseous core reactor with a temperature of 10,000 K or higher might offer an  $I_{sp}$  in excess of 5,000 sec. The parametric dependence of  $I_{sp}$  on temperature,  $T$ , and molecular weight,  $M$ , of the propellant is

$$I_{sp} \propto \sqrt{(T / M)}$$

If one considers only the fission concept of #100947, then the open cycle gas core reactor might be suggested.

A multigigawatt thermal reactor composed of perhaps 30 to 50 kg of fuel is suspended in a hydrogen flow contained by a pressure wall with a neutron reflector lining (this could be beryllium, beryllium oxide, graphite, or even water). The temperature profile is approximately constant throughout the uranium plasma (10,000 K, for instance) but drops near the surface to perhaps 5000 K depending, on the exact design and operating features. A seed material (e.g., carbon dust) in the hydrogen is used to make the gas highly opaque to the radiant energy from the plasma. The heating of the wall, moderator, and reflector by neutrons, gammas, and radiant energy can impose a limit on the  $I_{sp}$  due to the heat enthalpy of the materials. To take most advantage of the concept, the pressure wall must be cooled by a space radiator (which takes advantage of the high rejection temperature). Changes in hydrogen pressure could affect neutronics, containment, and cooling. A neutron control system might consist of drums. The use of rods is harder to conceptualize in this type of arrangement.

This concept relies on the formation of a stagnation point between the uranium plasma and nozzle throat from the flow of hydrogen gas about the radiating plasma as a containment mechanism. The degree and stability of the plasma containment are serious issues. Fuel loss rate and contamination of the exhaust are both concerns if containment is poor. Leakage of fuel into the hydrogen increases the molecular weight of the propellant and consequently lowers the  $I_{sp}$ . Radiation from the plume is an issue that is a function of the leakage. The engineering development problems are large, and it is not clear that plausible containment is predicted.

If the concept involves a vortex containment scheme of annular uranium, then it must be demonstrated that the flow on the wall is not excessively turbulent. Past work indicated that an adequate tangential Mach number could not be reached.<sup>1</sup> Reports on stability experiments are needed to evaluate the plausibility of containment.

The Light Bulb concept proposes eliminating the issue of containment by use of a transparent wall. Fused silica may have a limit as the temperature of a plasma increases respectably, shifting the frequency toward a cutoff. Beryllium oxide is one possible solution. It must be demonstrated that the wall can handle the pressure needed for operating conditions and not degrade catastrophically from contaminants deposited on the surface. The United Technologies Research Center has proposed, as an example, a neon gas flow to protect the wall, seeded with fluorine to react away anything approaching the wall.

An issue with the Light Bulb is that it cannot operate at the temperatures of the open cycle plasma reactor and may be limited to an  $I_{sp}$  of 2500 sec or even less than 2000 sec (somewhat better than the best solid core concept).

In any of these concepts, the suggestion has often been made that the use of U-233 rather than U-235 as a fuel would reduce the size and associated problems, because of the smaller critical mass. A difficulty with this fuel is that U-232, a troublesome gamma emitter, is a safety concern.

An issue common to all of the concepts is the durability of the nozzle (throat) given the high temperature and pressure hydrogen.

Other related concepts were presented at the Lewis Nuclear Thermal Propulsion workshop. The gas or plasma concepts offer varying degrees of high-utility performance, although they pose a high technological risk and are in need of a number of milestone demonstrations.

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<sup>1</sup>Jack Kerrebrock informed the panel of previous work on containment, including work at Oak Ridge on Mach numbers.

**Appendix O**  
**ANALYSIS OF "PEGASUS II: A MULTIMEGAWATT NUCLEAR ELECTRIC  
PROPULSION SYSTEM"**

Submission #101402 proposes the use of a 45-MWe fast reactor with a NaK coolant and a potassium secondary loop. There might be concern about leaks in such a system posing a safety problem. The proposed use of 40 percent enriched uranium suggests a small size that is not inconsistent with a positive temperature feedback coefficient. The issue of risk is a function of whether the vehicle is manned or unmanned.

The Rankine cycle has always looked good in preliminary design studies for space power systems. But problems arose in attempts to develop the systems. Two of the problems were corrosion of containment metals by liquid alkali metals and turbine blade erosion by wet alkali metal vapor. Unless the proposal has credible fixes for such problems, the Rankine cycle probably will not compete with the Brayton cycle even though from a thermodynamic viewpoint it is preferable for space power. In steam plants, superheating is used in the power cycle to avoid erosion, but in this case the cycle would be degraded.

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