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Enabling the Space Exploration Initiative: NASA's Exploration Technology Program in Space Power

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ABSTRACT

With the President's Space Exploration Initiative (SEI) of returning to the Moon and then going to Mars, NASA will need to develop a number of enabling technologies, chief among them being power for spacecraft and surface bases. The SEI power technology program will build upon ongoing efforts in the areas of advanced photovoltaics, energy storage, power management, nuclear power, and higher conversion efficiency systems. Recent studies have identified space nuclear power as a key technology for SEI. Nuclear power offers tremendous advantages for manned lunar bases and it greatly enhances manned Mars bases. Nuclear power can also be used to power nuclear electric propulsion (NEP) spacecraft such as piloted and cargo missions to Mars as well as unmanned science missions throughout and beyond the Solar System.

THE SPACE EXPLORATION INITIATIVE

President George Bush inaugurated the Space Exploration Initiative (SEI) with his speech on 20 July 1989 commemorating the 20th anniversary of the Apollo 11 landing on the Moon when he stated:

"And next -- for the new century -- back to the Moon. Back to the future. And this time, back to stay.

And then -- a journey into tomorrow -- a journey to another planet -- a manned mission to Mars".

National Space Policy

The President subsequently codified this vision in the National Space Policy which establishes as one of the overall goals of United States space activities the expansion of human presence and activity beyond Earth orbit into the solar system [White House 1989]. All of these activities had a foundation in earlier studies such as the report of the National Commission on Space [NCOS 1986] and the report to the Administrator of NASA by Dr. Sally K. Ride [Ride 1987]. This report was followed by case studies conducted by NASA's Office of Exploration.

General Goals and Architectures

Overall the Space Exploration Initiative establishes a long-term goal for the civil space program of returning to the Moon and carrying out human exploration of Mars. SEI provides a strategic horizon which can focus and integrate many current and future activities. In this sense SEI serves as a framework for guiding the investment of limited resources and for measuring progress in the space program. Figure 1 provides an overview of past and current SEI-related activities.

In general the various studies conducted on human exploration of the Moon and Mars have identified a number of technology developments (including power) required before the missions can be undertaken. While the studies differ in emphasis they generally identify the need for precursor robotic missions to scout the territory followed by human missions. These robotic missions can include orbiters, rovers, samplers, and penetrators or other surface stations. The human missions can be conducted in several ways including all-up missions and split missions in which the cargo is sent ahead on a robotic cargo vehicle to be followed by the lighter, manned spacecraft which typically goes on a reduced flight time trajectory. The human presence on the Moon and Mars will evolve from the initial landing installation to outposts and eventually full-up self-supporting bases. The power requirements will span the range from hundreds of watts for robotic precursor missions to tens of megawatts for permanent bases and for electric propulsion on piloted vehicles.

NASA 90-Day Study

The follow-on 90-day study by NASA, which synthesized several years of exploration mission studies and defined feasible mission options and their requirements, identified nuclear surface power as one of the key technologies required for lunar and Mars exploration. The general scenario described in the 90-day study envisioned the initial lunar base as being powered by photovoltaic arrays with regenerative fuel cells (RFCs). The RFCs would be used during the long (14-Earth-day) lunar night when solar cells would not be functional. As base power requirements increased to match the increasing activities of an expanded human presence on the Moon the power source would evolve into a nuclear reactor power system which can operate continuously day or night and is lighter than the equivalent solar/RFC power system [NASA 1989c]. Figures 2 and 3 show how such a lunar base might evolve while Figure 4 shows the mass advantage for nuclear reactors.

National Research Council Report

The Vice President in his capacity as Chairman of the National Space Council (NSpC) "requested that the National Research Council (NRC) assess the scope and content of the NASA 90-day study as well as alternative approaches and various technology issues". The NRC established a Committee on Human Exploration of Space which reviewed the NASA study and provided a number of findings and conclusions. In the power area the Committee concluded that "To meet the heavy demands for power on the Moon or Mars, nuclear electric power eventually will be essential" [NRC 1990].

AIAA Report

As part of the "outreach" program to solicit and evaluate new ideas that might be applicable to SEI, the American Institute of Aeronautics and Astronautics (AIAA) solicited ideas generated by individuals associated with the aerospace industry. The AIAA recommended advanced technology development on nuclear power, specifically continuing the development of the SP-100 space nuclear reactor power system with advanced converters, for use as a power source on the surfaces of the Moon and Mars. The AIAA also noted a number of other technologies that could be applied to SEI missions such as photovoltaic arrays, RFCs, dynamic isotope power systems (DIPS), power beaming, and improved thermal management [AIAA 1990].

Technology Needs

In response to a Congressional request NASA submitted a report outlining specific technologies that will be needed to meet the development and operational requirements of the SEI. This report noted that surface operations are the primary purpose of the SEI and that surface operations required systems with high reliability and reasonable operations costs. Among the technologies requiring development to meet the requirements of surface operations were [Mankins and Buoni 1990 and NASA 1990]:

- space nuclear power
- planetary rovers (with surface mobility systems)
- surface solar power (with chemical energy storage)

Advisory Committee Report

The Advisory Committee On the Future of the U.S. Space Program (which was chaired by

Norman R. Augustine and is sometimes referred to as "The Augustine Committee") stated that ". . . we share the view of the President that the long term magnet for the manned space program is the planet Mars -- the human exploration of Mars, to be specific. It needs to be stated straightforwardly that such an undertaking probably must be justified largely on the basis of intangibles -- the desire to explore, to learn about one's surroundings, to challenge the unknown and to find what is to be found. Surely such an endeavor must be preceded by further unmanned visits, and by taking certain important steps along the way, including returning for extended periods to the Moon in order to refine our hardware and procedures and to develop the skills and technologies required for long term planetary living" [Advisory Committee 1990].

The Advisory Committee offered the following recommendations related to SEI [Advisory Committee]:

Recommendation 4: That the Mission from Planet Earth be established with the long-term goal of human exploration of Mars, underpinned by an effort to produce significant advances in space transportation and space life sciences.

Recommendation 5: That the Mission from Planet Earth be configured to an open-ended schedule, tailored to match the availability of funds.

Recommendation 7: That technology be pursued which will enable a permanent, possibly man-tended outpost to be established on the Moon for the purposes of exploration and for the development of the experience base required for the eventual human exploration of Mars. That NASA should initiate studies of robotic precursor missions and lunar outposts.

Recommendation 8: That NASA, in concert with the Office of Management and Budget and appropriate Congressional committees, establish an augmented and reasonably stable share of NASA's total budget that is allocated to advanced technology development. A two- to three-fold enhancement of the current modest budget seems not unreasonable. In addition, we recommend that an agency-wide technology plan be developed with inputs from the Associate Administrators responsible for the major development programs, and that NASA utilize an expert, outside review process, managed from headquarters, to assist in the allocation of technology funds.

The Synthesis Group

The Synthesis Group, which integrated the information developed during the outreach program, recommended initiation of "a space nuclear power technology development program based on the Space Exploration Initiative requirements" [Synthesis Group 1991].

Among the supporting technologies that The Synthesis Group identified as requiring development for the "safe and cost effective exploration of the Moon and Mars" were nuclear electric surface power to megawatt levels and nuclear electric propulsion for follow-on cargo missions [Synthesis Group 1991].

SPACE POWER REQUIREMENTS FOR SEI

The foregoing studies have identified a range of space power requirements for SEI missions. These will be summarized according to the specific application.

Robotic Missions

Before humans actually set forth back to the Moon and on to Mars it is planned that there will be precursor robotic missions to

- advance scientific understanding and develop the basis for human science exploration
- determine suitable/desirable landing and outpost sites
- provide design data for human mission elements

- demonstrate the technologies and operational concepts for human missions

Lunar Spacecraft

For the Moon the emphasis will be on selecting the landing/outpost site. For this purpose a Lunar Observer spacecraft (see Figure 5) would be needed to characterize the Moon globally from a low (~100-km) polar mapping orbit (with a gravity subsatellite in an elliptical orbit) since the Apollo data are limited to a band near the lunar equator. Such a Lunar Observer mission would be used to

- map the surface chemistry
- map the gravity field
- verify requirements for surface equipment and excursion vehicles
- select the outpost site
- plan lunar surface operations
- assess availability of resources
- select sites of scientific potential

The Lunar Observer spacecraft would be solar powered and it could benefit from some of the technology advances in higher efficiency solar cells and light-weight solar arrays.

Mars Spacecraft

For Mars the emphasis for robotic missions will be on science and human mission success. A candidate robotic mission set for Mars could include:

- Mars Observer
- Site Reconnaissance Orbiter
- Mars Landers
- Mars Sample Return/Rovers

The solar-powered Mars Observer has been scheduled for a 1992 launch. Similarly, other orbital spacecraft such as a Site Reconnaissance Orbiter can benefit from improved solar cell/array and battery technology. Just as the Viking Orbiters were solar powered while the Viking Landers, which operated in a more hostile environment (dust and temperature extremes), were powered by RTGs and batteries so, too, will nuclear power play a role in the robotic craft sent to the surface of Mars.

NASA's Office of Space Science and Applications (NASA/OSSA) has been studying SEI-related missions that will challenge the space power community. One mission set involves distributing a relatively large number (~20) of small robotic landers on Mars to explore the structural, mineralogical, and chemical characteristics of the Martian soil, search for evidence of subsurface ice, and collect long-term seismological and meteorological data over a period of ten years. These studies have been termed the Mars Global Network (MGN) at JPL [JPL 1989] and the Mars Environmental Survey (MESUR) at NASA's Ames Research Center [ARC 1990]. Typical power requirements are in the range of 2 We to 12 We per lander.

Rovers will allow humans to conduct advance exploration of the surface of Mars. In an assessment of the technology needs for human exploration missions it was noted that "Most, if not quite all, of the mission scenarios under consideration include the use of mobile surface vehicles to conduct exploration, gather samples, and deploy scientific payloads. Establishing permanent human presence on other worlds will require surface transportation systems to support both construction and surface mining operations. These systems may be autonomous, teleoperated, or piloted" [NASA 1989b].

One assessment of NASA's needs for advanced nuclear power sources categorized the following planetary surface rover power requirements [NASA 1989a]:

- Unmanned scientific rovers
  Power range: 0.5 kWe to 1.0 kWe
  Lifetime: 1 year
  Possible power source(s): RTGs with energy storage

- Unmanned advanced scientific rovers
  Power range: 1 kWe to 10 kWe
  Lifetime: >1 year
  Possible power source(s): Advanced radioisotope power source with energy storage

Figure 6 is an artist's illustration of a possible configuration for an unmanned scientific rover.

Recent analyses of the Viking Lander solar insolation data have shown that photovoltaics are a viable option for certain Mars surface operations [Appelbaum and Flood 1989].

Human Missions

Power will be required both for the trips to the Moon and Mars and for operations on the surfaces of the Moon and Mars. Round trip times for lunar missions will be on the order of seven days whereas round trip times for missions to Mars can be as long as two years. Power requirements for human missions will span the range of tens of kilowatts needed for manned spacecraft, landers, surface excursion vehicles and habitats to tens of megawatts for electric propulsion and self-sufficient bases with *in situ* resource utilization.

Initially a lunar outpost may only be manned during the lunar day but eventually full-time operation will be desirable even during the long (14-Earth-day) lunar night which places a premium on being able to supply power in the absence of sunlight. Supplying power for full-time operation on Mars will be somewhat easier because the Martian day is only slightly longer (24.6-h equatorial rotation) than that on Earth; however, unlike the Moon, Mars receives less than half as much solar energy flux as does the Earth.

Human missions to the Moon and Mars will undoubtedly include initial outposts, scientific laboratories, full-up operational bases, partially tended installations, and surface excursion vehicles [NASA 1989c, Petri et al. 1990, and Synthesis Group 1991]. Figure 7 illustrates a man-tended radioastronomy observatory on the lunar farside. In each case power will be critical. It has been noted that "a rudimentary lunar base for 6 people with a fully closed life support system would appear to require almost 100 kW for the astronauts to merely perform rudimentary work. Full industrialization will likely drive power demands into the megawatt class" [Brandhorst 1991].

In an assessment of NASA's needs for advanced nuclear power sources it was noted that utility power and manned rovers would require 10 kWe to 25 kWe with lifetimes on the order of 5 years. Possible power sources could include fuel cells, solar photovoltaic power with regenerative fuel cells, nuclear reactor power systems, and beamed power (satellite to surface) [NASA 1989a]. In a workshop on power for planetary rovers it was noted that exploration-class missions would require the following kinds of piloted rovers [Roberts 1989]:

- Piloted, unpressurized (4.3 kWe)

- Piloted, pressurized (10 - 30 kWe)

- Construction machines, general purpose (10 - 30 kWe)
  - Crane
  - Excavator/Dozer
  - Truck

- User accommodation equipment, special purpose (1 kWe)
  - VLFA (Very Low Frequency Array) construction device
  - Other

- Mining machines (undefined) (10 - 30 kWe)

These power levels are consistent with similar studies of vehicle power requirements [Petri et al. 1990].

The use of electrical power for electric propulsion systems is a possible candidate for transporting humans to and from Mars. Figure 8 shows some of the transportation options for manned missions to Mars. While electric propulsion for unmanned missions such as cargo vehicles to Mars can be accomplished with powers on the order of a few megawatts piloted missions will require tens of megawatts. NASA has defined a program to develop megawatt-class electric propulsion for piloted missions to Mars [Bennett et al. 1990a].

Because of the human presence the requirements on reliability will be even greater for the human missions. The Synthesis Group has stated that "Habitats must have their own highly reliable power source for safety. Base power includes power for mining, in situ operations, fabrication, emergency power for habitats and power for regeneration of fuel cells. Habitat power must be highly reliable, greater than 99.5%, while base power can be about 95% reliable. Power units should be made operational with a minimum of support activities, have lifetimes compatible with the base, be serviceable and, if nuclear, be refuelable and disposable. Evolutionary system designs are preferable to specific point designs without growth potential" [Synthesis Group 1991].

Based on its outreach activities and assessments of alternative architectures The Synthesis Group developed a set of functional power requirements which are summarized in Table 1 [Buden et al. 1991 and Synthesis Group 1991]. The next section describes NASA's planning to meet the estimated power requirements of the Space Exploration Initiative.

EXPLORATION TECHNOLOGY PROGRAM

The planning for exploration technology development has four themes [Mankins and Buoni 1990]:

- Capitalize on the existing national space research and technology foundation
- Begin now to make the necessary investments to meet the long-range technology needs and establish a commitment to long-term exploration technology development
- Seek out innovative technological solutions to exploration technology development
- Perform technology development in parallel with exploration mission design studies

The planning to meet the space power requirements of SEI follows the foregoing strategy for technology development. The space power program has been planned to address the technology development challenges and "drivers" such as

- Develop power systems for and extend their life in functional environments (LEO, GEO, Moon, planetary)
- Increase power density of power system
- Reduce power system mass
- Increase power system reliability
- Enable power system operation at higher temperatures

The technology benefits of this research include reduced launch mass; increased power for the same mass; increased lifetime; increased reliability; reduced costs; extended range of power system capabilities; and reduced volume. Some of the benefits of improvements in the electrical power system (EPS) can be seen in Figures 9 and 10 taken from Brandhorst 1991.

The EPS generally consists of the power source, energy storage, and power management and distribution (PMAD). Tied in closely with the EPS is the thermal management of the space system. All of these elements are important to improved EPS performance. Thus, the technology development approach that is being planned includes

- Development and evaluation of high-efficiency, radiation-hard solar cells and light-weight array system components

- Development of advanced, high-specific-energy, high-energy-density, long-cycle-life energy storage systems

- Development of improved thermal-to-electric conversion systems

- Development of light-weight, smart, high-temperature, compact power management and control (PMAC)

- Development of innovative, low-mass thermal transport and radiator concepts

- Development of the SP-100 space nuclear reactor power system

- Development of a laser power beaming capability

- Development of improved power system materials

- Development of models for environmental interactions and design guidelines for future space power systems

Under current planning the technology development would be carried out in two parallel thrusts. Firstly, NASA has an ongoing base research and technology (R&T) program in space energy conversion which is designed to provide the technology to meet power system requirements for future space missions, including growth Space Station, Earth orbiting spacecraft, lunar and planetary bases, and solar system exploration [Bennett 1989]. This base R&T program provides the technological foundation for the second thrust which covers focused space applications such as SEI.

The programmatic objective of the focused space power R&T program is to provide the focused technology to meet power system requirements for lunar and planetary bases, planetary rovers, penetrators, Earth-orbiting spacecraft, and deep-space missions. Figure 11 shows the organization of the space energy conversion R&T program to meet both technological and focused applications.

Base Research & Technology Program

The base R&T program is organized as shown in Figure 12. Table 2 summarizes the state-of-the art in each of the elements of the base R&T program and lists the objectives of these program elements. The basic elements will be described in the following sections.

Photovoltaic Energy Conversion

The objective of the photovoltaic energy conversion program element is to provide the technology for photovoltaic arrays with improved conversion efficiency, reduced mass, reduced cost, and increased operating life for advanced space missions. The photovoltaic element is organized around solar cell research carried out through NASA's Lewis Research Center (LeRC) and advanced solar array research carried out through NASA's Jet Propulsion Laboratory (JPL).

Research at LeRC has led to advances in cell technologies including thin gallium arsenide (GaAs) and indium phosphide (InP) cells. Studies of thin film technology show the potential to develop a 1000 W/kg flexible solar array blanket [Flood et al. 1989]. As part of the ongoing NASA-sponsored activity of developing a 300-W/kg solar array JPL and TRW have developed the advanced photovoltaic solar array (APSA) which for a baseline 5.8-kWe wing has a beginning-of-life (BOL) specific power and power density of 137.9 W/kg and 140.1 W/m^2 (based on total panel area) respectively. Corresponding end-of-life (EOL) values are 92.5 W/kg and 94.0 W/m^2 for a 10-year mission in a geosynchronous Earth orbit (GEO) [Stella and Kurland 1991].

Chemical Energy Conversion

The objective of the chemical energy conversion program element is to provide the technology base for advanced electrochemical energy conversion and storage systems required to support the low- to high-power needs and cycle life requirements for future space missions.

Work sponsored by LeRC has led to the successful completion of over 40,000 low-Earth orbit (LEO) cycles at 80% depth of discharge (DOD) in boiler plate nickel hydrogen cells and over 10,000 cycles in bipolar nickel hydrogen batteries [Smithrick and Hall 1991 and Manzo 1989]. JPL has successfully completed over 700 cycles at 50% DOD in 1-A-h lithium titanium disulfide cells [Halpert et al. 1991]. An overview of the NASA research and technology program on batteries may be found in Bennett 1990b.

Thermal Energy Conversion

The objectives of the thermal energy conversion program element are to

- Develop the technology base to provide advanced, high-efficiency, high-temperature, long-life solar dynamic Stirling/Brayton power systems
- Develop new thermoelectric materials with significantly higher figures of merit
- Investigate and demonstrate the feasibility of high-power, long-life alkali metal thermal-to-electric converter (AMTEC)

At LeRC research is being sponsored on advanced concentrator technology and advanced receiver technology for solar dynamic power systems. Under this program the feasibility of fabrication techniques for concentrator aluminum panels with microsheet glass has been demonstrated. This technology has application for both Earth orbital and lunar missions [Calogeras et al. 1991 and Richter 1991]. In the area of thermoelectrics, preliminary studies at JPL have shown that ruthenium silicide has the potential to provide figure of merit values four times higher than conventional silicon-germanium thermoelectric materials [Ohta et al. 1991]. Improvements in AMTEC electrode current collection have been achieved at JPL by using molybdenum grids to decrease sheet and contact resistance in the rhodium-tungsten and platinum-tungsten electrodes [Ryan et al. 1991].

Power Management

The objectives of the power management program element are to

- Develop the electrical power systems conditioning, control, and distribution technology for future space missions
- Develop the capability to model power systems (including environmental interactions)
- Develop advanced concepts (e.g., power beaming and advanced power management materials)

A number of accomplishments have occurred under this program element, including successfully testing a silicon-carbide metal oxide semiconductor (MOS) field effect transistor (FET) power switch to 723 K; developing a Monte Carlo model for atomic oxygen erosion; and demonstrating a seven-fold increase in atomic oxygen durability with chemical-vapor-deposited (CVD) silica on carbon/carbon composite radiator surfaces. Work is also proceeding on the development of monolithic power integrated circuits (PICs) technology for space applications. This effort offers the potential for up to 80% reductions in mass and volume and up to 90% reductions in the piece parts count in a typical PMAD system.

Separately, as part of the Power Management program element, researchers at NASA's Langley Research Center (LaRC) have been pursuing the use of solar-pumped lasers to transmit power [Kwon and Lee 1989]. Beam power may provide an alternative to nuclear and photovoltaic/chemical power sources for bases or rovers on the surfaces of the Moon and Mars [De Young et al. 1991]. LaRC has produced 14 W of continuous wave (CW) power at 1.3 μm from a solar-simulator-pumped iodide laser and LaRC has operated the world's first solar-pumped iodide laser amplifier.

Thermal Management

The objectives of the thermal management program element are to

- Develop the technology base for versatile thermal management systems for the next generation of space missions
- Provide advanced thermal management technology for both high and moderate temperatures, including technology for thermal control of instrument systems

Research carried out through NASA's Goddard Space Flight Center (GSFC) has resulted in the fabrication and successful testing of oxygen and nitrogen cryogenic heat pipes. Research carried out through LeRC has demonstrated the stability of a liquid sheet radiator at 1-G and verified the analytical predictions [Juhasz and Chubb 1991].

Focused Research & Technology Program

Figure 13 shows the proposed work breakdown structure (WBS) for the focused space energy conversion research and technology program. The following sections will describe the planned program elements.

Space Nuclear Power

As noted earlier space nuclear power has been identified as one of the key technologies for SEI. Accordingly, NASA has been participating with the Department of Energy (DOE) and the Strategic Defense Initiative Organization (SDIO) in the SP-100 space nuclear reactor power system program. The objectives of this program are to develop and validate the technologies for safe and reliable space nuclear reactor power systems to support lunar and Mars exploration missions. The payoff will be a flexible power source that can span a range of power levels up to 1 MWe for space and surface bases with improved specific mass and lifetime [Armijo et al. 1991]. Figure 14 is an artist's illustration of a lunar base powered by an SP-100 reactor using a Stirling conversion system.

High Capacity Power

To augment the SP-100 space nuclear reactor power program NASA is sponsoring the high capacity power program which has the objectives of developing and demonstrating low-mass, reliable, long-lived power conversion technologies for space nuclear reactor power systems. Specifically, this program is aimed at developing and demonstrating a 1300 K Stirling conversion system (35% efficiency) in time for early SEI use. This program will provide SP-100 with the conversion technology to scale up to 1 MWe [Dudenhoefer and Winter 1991 and Winter 1989].

Surface Power and Thermal Management

As noted in the discussion of the mission scenarios the initial lunar and Mars operations will probably be solar-powered. NASA is planning a surface power and thermal management program to develop solar-based power and low-grade-heat thermal management technologies to support lunar and Mars surface system operations. This program will provide a light-weight, reliable, solar-based power system for the first exploration/outpost missions to the Moon and Mars as well as providing a backup source of power [Petri et al. 1990]. Because the largest fraction of the solar-based power system for lunar applications is in energy storage the near-term focus for the surface power program has been on developing regenerative fuel cells with specific energies of 500 to 1000 W-h/kg with operational lifetimes of at least 20,000 h. The photovoltaic array goal is 300 W/kg. The goal for the overall power system is to achieve 25 kWe at 3 We/kg on the Moon and 8 We/kg on Mars.

Earth Orbiting Platform Power and Thermal Management

The objectives of this planned program are to develop and demonstrate integrated power and thermal management technologies for near-Earth missions. This program would allow initiation of a new thrust to develop planar and concentrator arrays immune to the space environment with 100 W-h/kg battery systems; integrated, high-efficiency autonomous PMAC; and integrated thermal management for high-temperature electronics. This program would benefit the Earth-orbiting platforms (such as data relay satellites) for SEI as well as other Earth-orbiting applications.

Spacecraft Power and Thermal Management (Deep Space)

The objectives of this planned program are to develop and demonstrate integrated spacecraft bus technologies for deep-space applications. (SEI does not stop with Mars.) This program would initiate a new thrust to

- Demonstrate a high-power-density solar array with deployment and low-intensity, low-temperature (LILT) resistance
- Develop advanced static or dynamic conversion systems for radioisotope sources and define integration issues/advantages of reactor-powered science spacecraft
- Develop energy storage subsystems for penetrators
- Develop advanced PMAC and thermal management for deep-space missions

The payoff will be the provision of high-specific-power solar arrays and high-efficiency converters with advanced PMAC and energy storage to reduce mass and/or increase the power of deep-space missions.

Laser Power Beaming

The Synthesis Group report noted that "Power beaming for surface-to-surface power distribution may greatly reduce the mass of rovers and other mobile surface systems, assuming line of site can be met. If nuclear electric propulsion is developed for use in the lunar or Mars cargo vehicle, the orbiting transfer vehicle may be a convenient power source for surface operations. If power beaming can be demonstrated at a reasonable cost, long term development could provide attractive benefits" [Synthesis Group 1991]. Accordingly a program on laser power beaming has been proposed to develop and demonstrate the technologies and subsystems for laser power beaming from the Earth to the Moon. Discussions of this approach have appeared before, most recently in Landis 1991. The use of an orbiting laser diode array to power a lunar rover has been discussed recently by De Young et al. 1991.

Mobile Surface Systems (Power)

Since surface exploration vehicles are anticipated to play a key role in SEI (see Figure 6) a mobile surface systems power program has been proposed to develop compact power technologies to a level of readiness sufficient to enable mobile and portable extraterrestrial surface power systems. This program will include work on system integration, power generation (both nuclear and nonnuclear), energy storage, tribology, PMAD, small free-piston Stirling engine, convective heat exchangers for Martian surface mobile and/or portable dynamic isotope power systems. The end objective is to provide mobile power system options that can span the range from <1 kWe to >20 kWe with varying power ratios and usages for a hostile, dusty environment.

Some of the specific technical objectives include development of a 14%-efficient thermoelectric element and a 30%-efficient solar cell. Energy storage goals are >50 W-h/kg for batteries and >350 W-h/kg for fuel cells.

SUMMARY AND CONCLUSIONS

The Space Exploration Initiative (SEI) will require several different types of power sources and energy storage systems to span anticipated power requirements ranging from hundreds of watts for robotic precursor missions to tens of megawatts for mature, manned bases and for electric propulsion on piloted vehicles. The ongoing NASA research and technology program in space energy conversion provides a foundation from which to build the focused technology programs to meet the SEI power requirements. An augmented program focusing on space nuclear power, high capacity power, surface power and thermal management, Earth orbiting platform power and thermal management, spacecraft power and thermal management for deep-space vehicles, laser power beaming, and mobile surface systems power has been defined to develop the specific focused technologies for SEI applications.

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Table 1. Power Requirements and Mass Allocation

[Buden et al. 1991]

Functions	Moon Power	Moon Mass Allocation	Mars Power	Mars Mass Allocation	Suggested Technology
Transportation					
Spacecraft					
Manned	to 20 kW	2 MT(1)	to 30 kW	2 MT	Fuel cells (Moon) Nuclear/ photovoltaics (Mars)(2)
Unmanned	5 kW	1 MT	5 kW	1 MT	Fuel cells (Moon) Photovoltaics (Mars)
Lander	20 kW	300 kg	20 kW	300 kg	Fuel cells (w/wo photovoltaics
Electric propulsion	to 5 MW	to 50 MT	to 5 MW	to 50MT	Nuclear
Surface Activities					
Day only	20 kW	150 kg			Photovoltaics
Habitat/lab					
IOC	to 30 kW	2 MT	to 50 kW	3 MT	Photovoltaics or nuclear (2)
NOC	50 kW	3 MT	100 kW	4 MT	Nuclear
Base Power					
IOC (3)	to 100 kW	4 MT	to 100 kW	4 MT	Nuclear
NOC (4)	to 800 kW	10 MT	to 1 MW	12 MT	Nuclear
Rovers					
Unloader/Construction	240 kW-hr	240 kg	240 kW-hr	240 kg	Fuel cells (5)
Pressurized					
IOC (per trip)	1900 kW-hr	2 MT	1900 kW-hr	2 MT	Fuel cells (5)
NOC (per trip)	4800 kW-hr	5 MT	4800 kW-hr	5 MT	Fuel cells (5)
Unpressurized	100 kW-hr	100 kg	100 kW-hr	100 kg	Fuel cells (5)

(1) 1 MT (metric ton) = 1000 kg
(2) Depends on final power level
(3) IOC stands for Initial Operational Capability
(4) NOC stands for Next Operational Capability
(5) In-situ methane and oxygen produced on Mars may substitute for fuel cells.

Table 2. State of the Art and Objectives for Space Energy Conversion Research & Technology

SUB-ELEMENT	STATE-OF-THE-ART	OBJECTIVE
PHOTOVOLTAICS	Comm: 20 W/kg (rigid) to 66 W/kg (flex.) Demo: 100 W/kg (rigid) to 130 W/kg (flex.) 240 W/m2	> 300 W/kg (flex.) 1000 W/kg (blanket) >300 W/m2 (concentrator)
CHEMICAL ENERGY CONVERSION	Comm: 10 Wh/kg Demo: >20 Wh/kg	150 Wh/kg (75 % DOD)
THERMAL ENERGY CONVERSION	< 7 % efficiency	> 10 % efficiency
POWER MANAGEMENT	< 0.03 W/cm3 <15 W/kg	> 0.6 W/cm3 > 20 W/kg
THERMAL MANAGEMENT	10 kg/m2	1-4 kg/m2

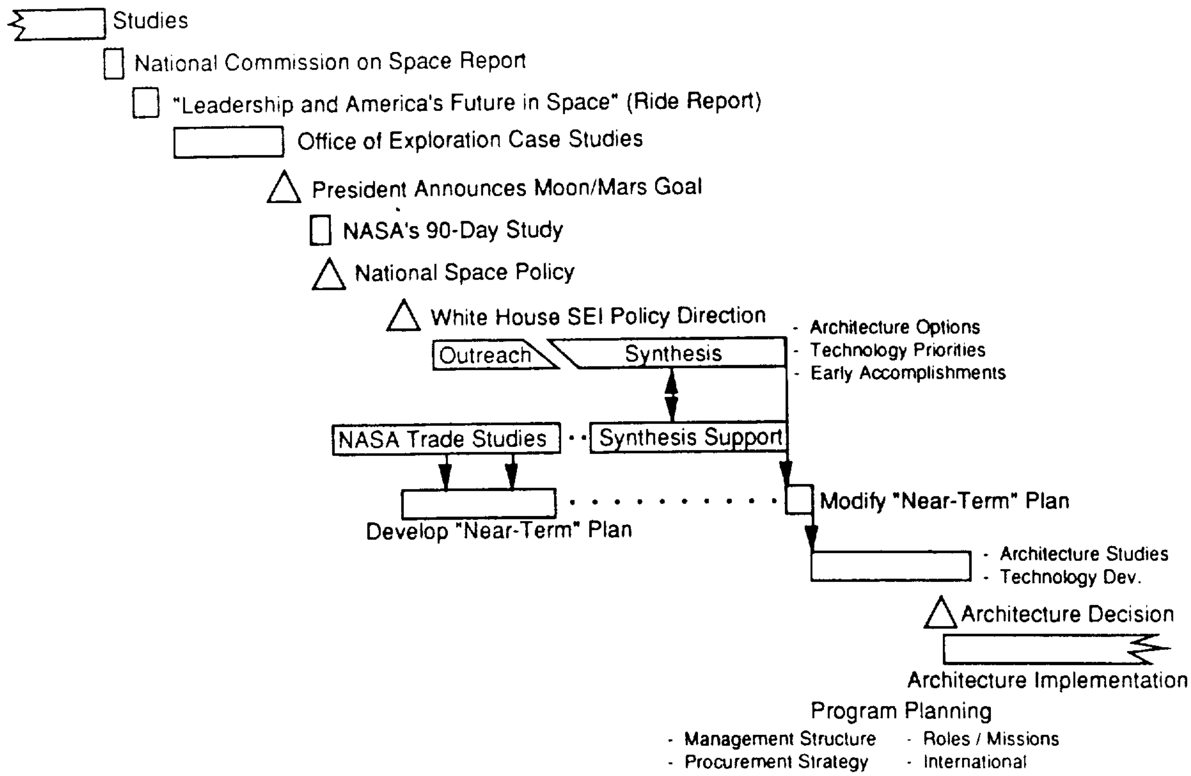
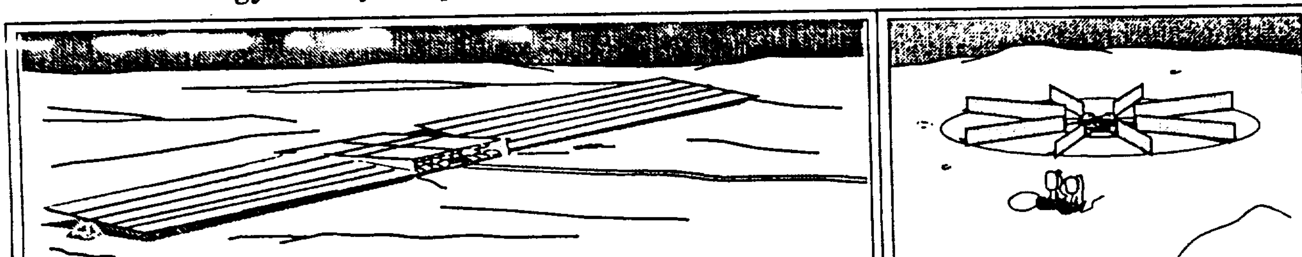


Figure 1. Overview of Past and Current Activities Related to the Space Exploration Initiative

Strategy: Early Outpost Power Needs → Later Outpost Power Needs



- **Power Generation**
  - Photovoltaic Arrays or Solar Dynamic Modules
    - Low-Moderate Mass/kW
    - Near Term Development
    - Can Be Located Near Outpost
    - Ease of Deployment

    - Daytime Power Only
    - Power Storage Required
    - Moderate Spares
    - Moderate Crew Support

- **Power Storage**
  - Batteries
    - Near Term Development

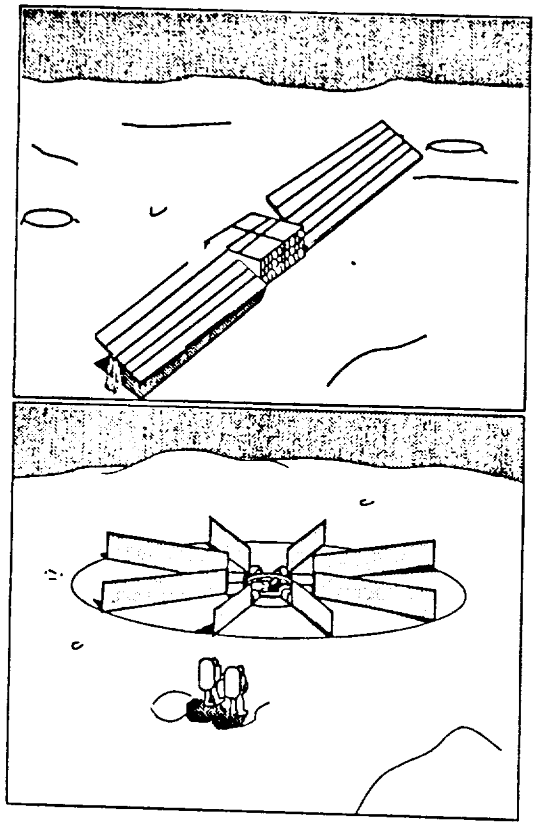
    - High Initial Mass/kW
    - Short Lived Systems
  - Regenerative Fuel Cells
    - Longer Term Development
    - Moderate Mass/kW

    - Short Lived Systems
    - High Spares/Resupply

- **Nuclear Power**
  - Continuous Day/Night Power
  - No Power Storage Required
  - Low Initial Mass/kW
  - Lowest Spares/Resupply
  - Long Life Systems
  - Minimum Crew Support

  - Longer Term Development
  - Must Be Remote to Outpost
  - Radiation Shielding
  - Political

Figure 2. Lunar Surface Power System Options



PHOTOVOLTAIC ARRAY/ REGENERATIVE FUEL CELL

- Initial outpost power source
- 25/12.5 kW day/night capability
- State-of-the-art technology with large experience base
- Low power/mass ratio (1.5-3 W/kg)
- High resupply and sparing mass requirements (1t/year/unit)

SP-100 NUCLEAR REACTOR

- Dynamic engine power conversion
- 100 kW day/night capability
- High power/mass ratio (25-60 W/kg)
- Long life, high reliability system (7 year life)

Figure 3. Surface Power Systems for a Lunar Base

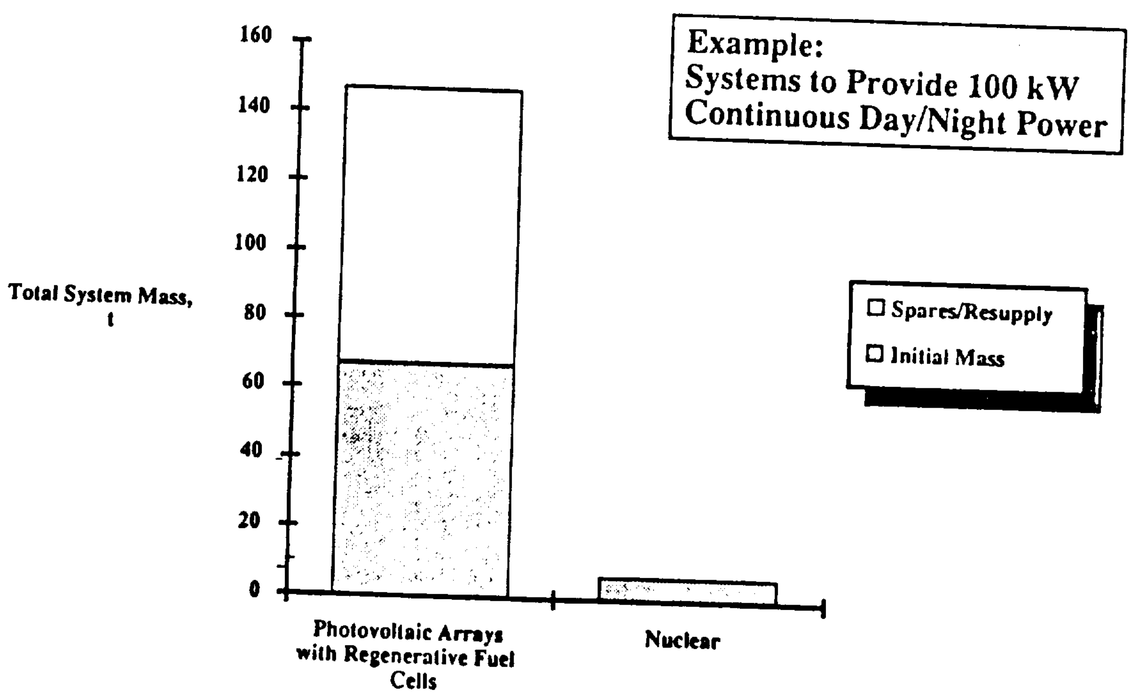


Figure 4. Lunar Surface Power System Options - 10-Year Life Comparison

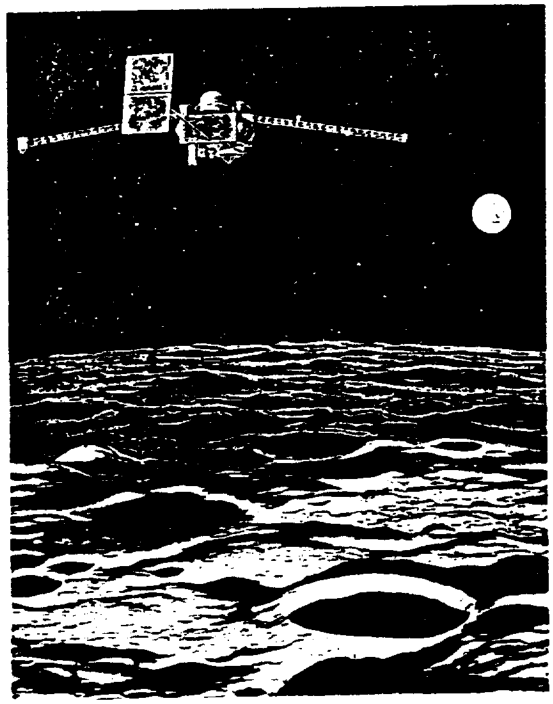


Figure 5. Artist's Concept of a Lunar Observer Spacecraft

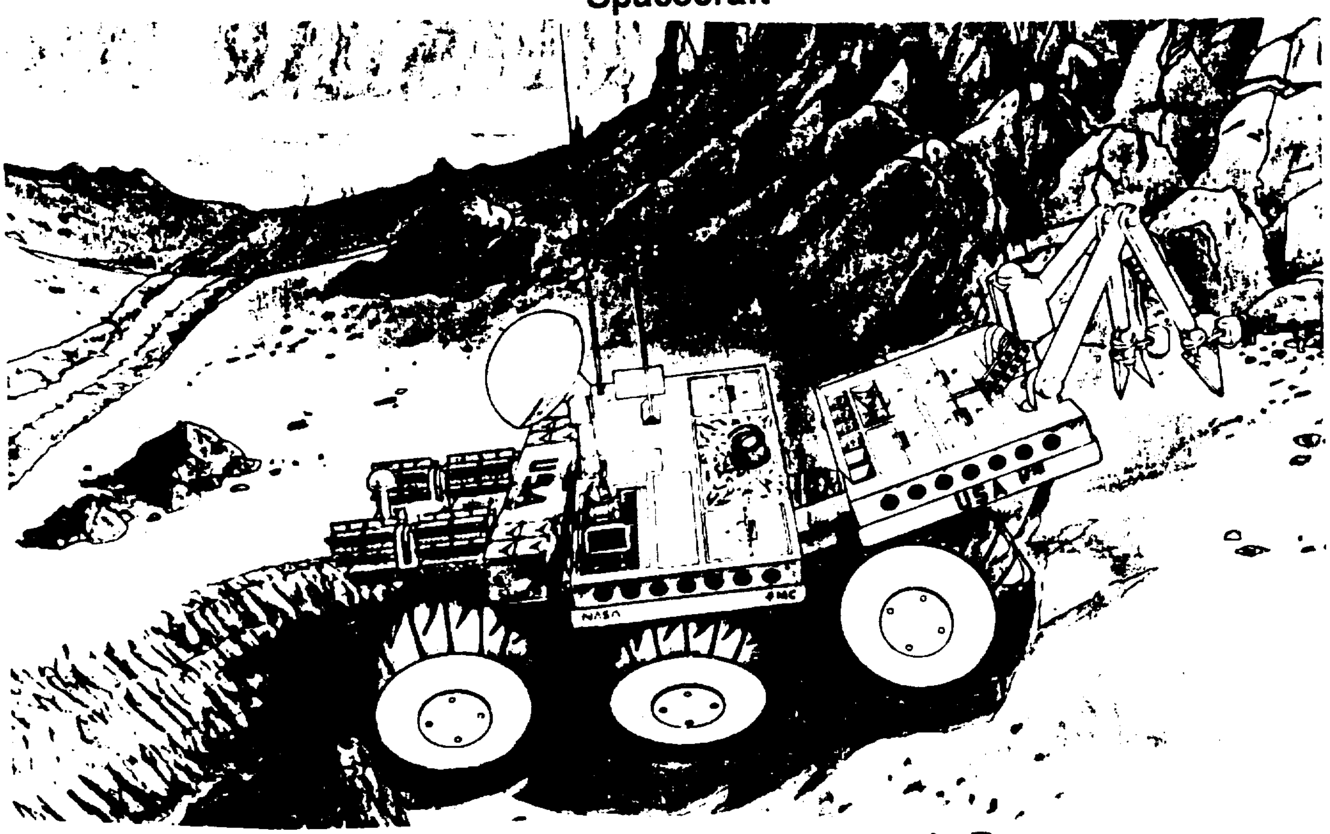


Figure 6. Concept for a Mars Robotic Rover

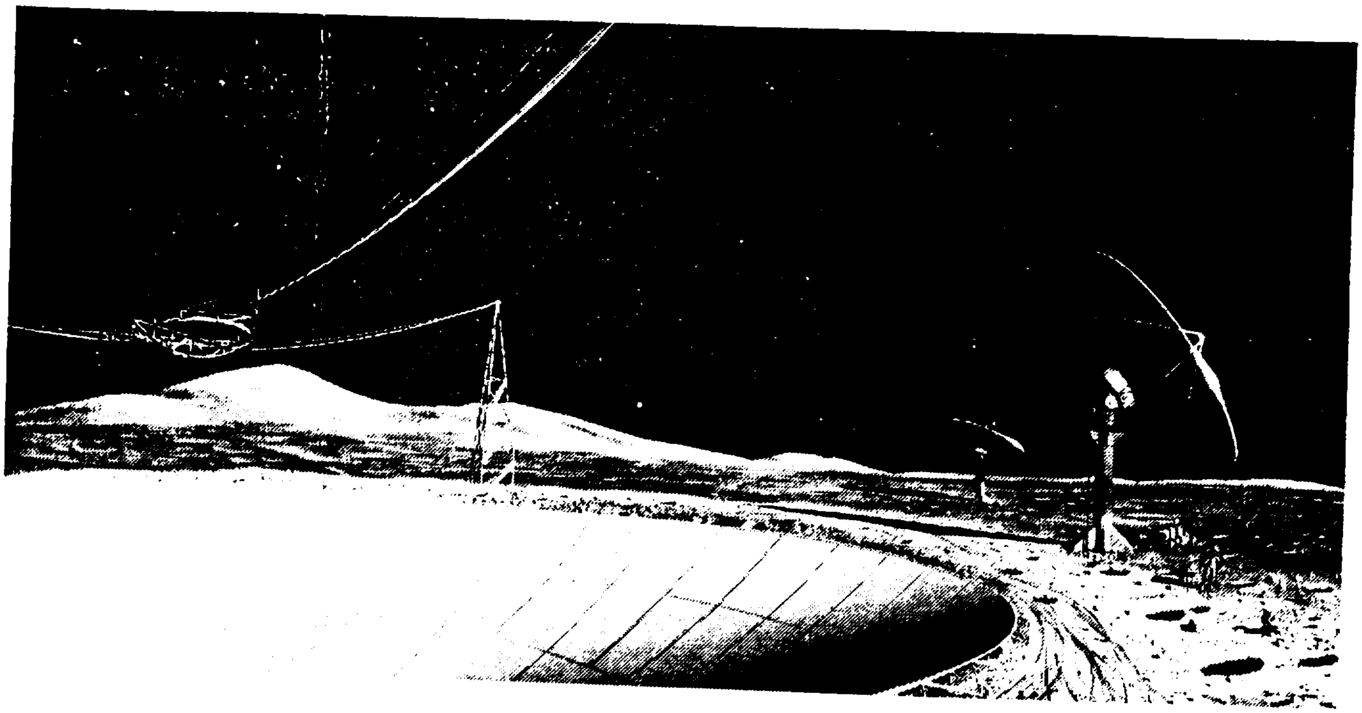


Figure 7. Lunar Radioastronomy Observatory

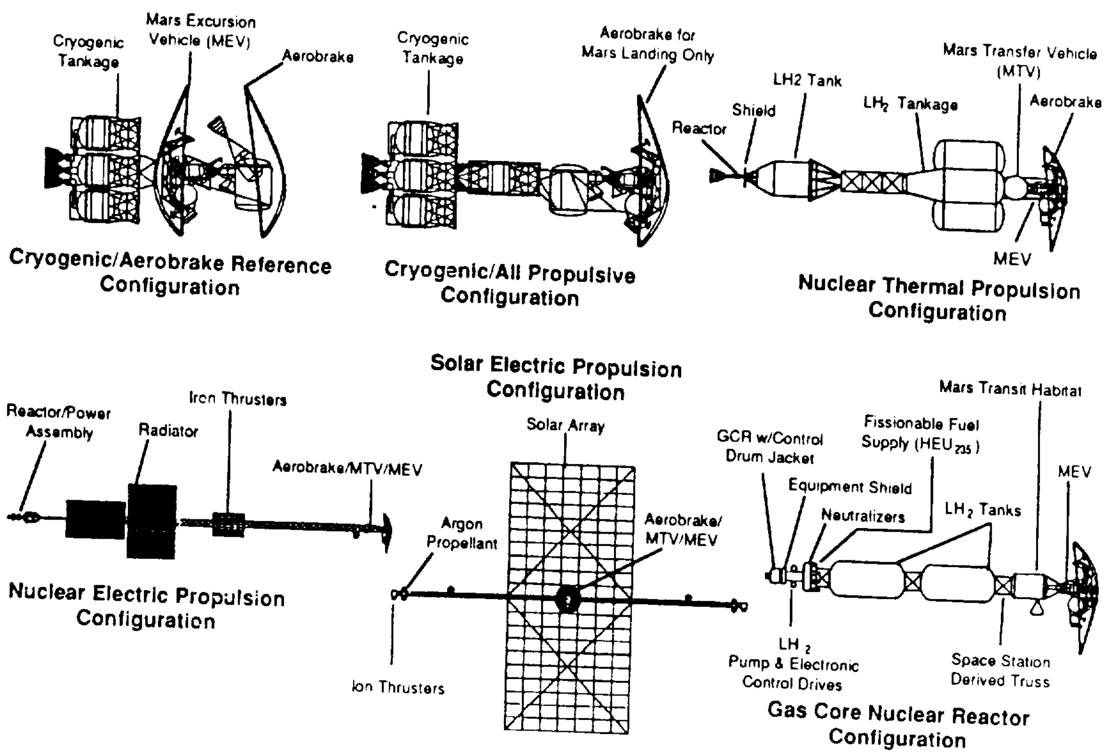


Figure 8. Mars Transportation Concepts

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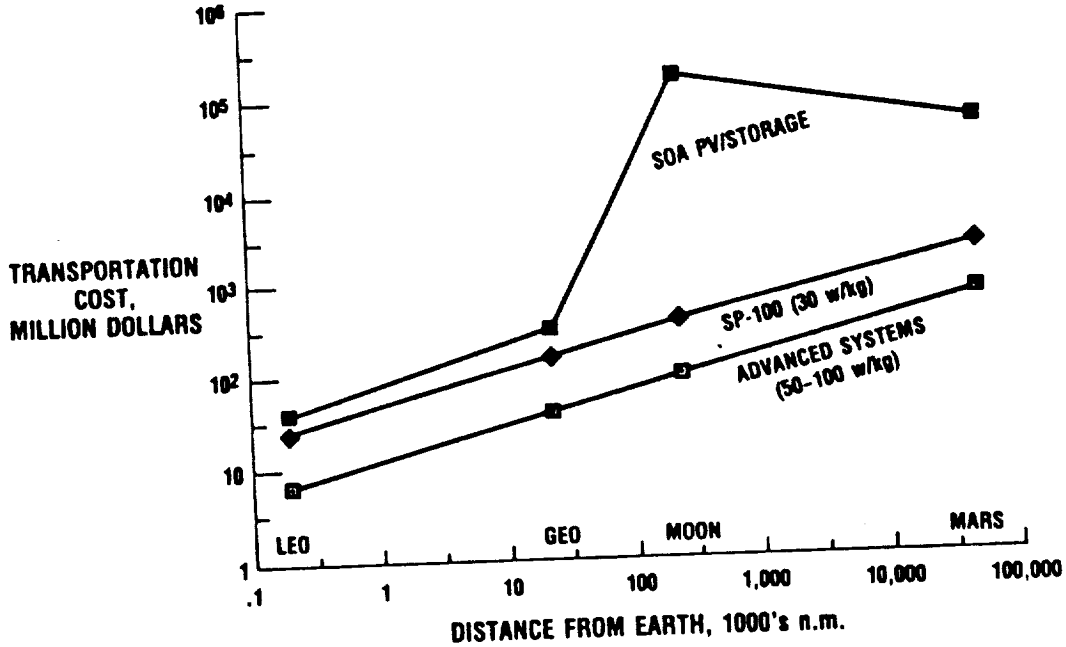


Figure 9. Cost of Delivering 100 kWe of Usable Power
[Brandhorst 1991]

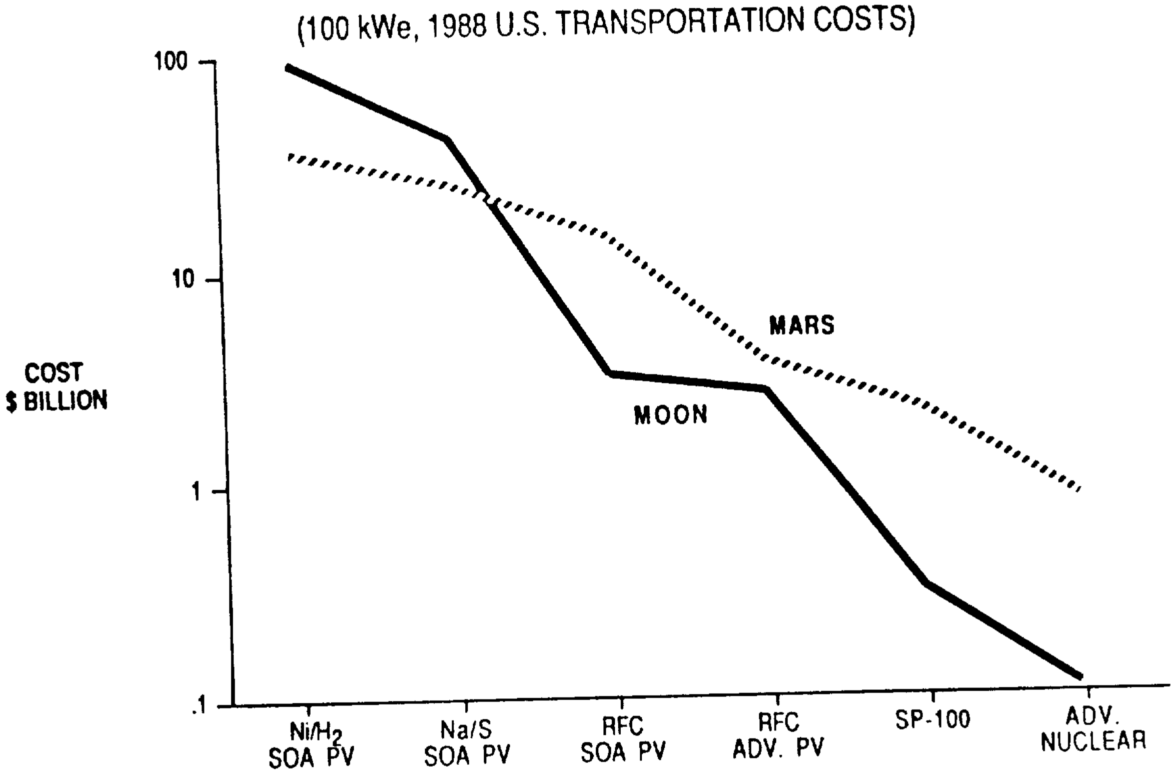


Figure 10. Impact of Power Technology Advances on Transportation Costs
[Brandhorst 1991]

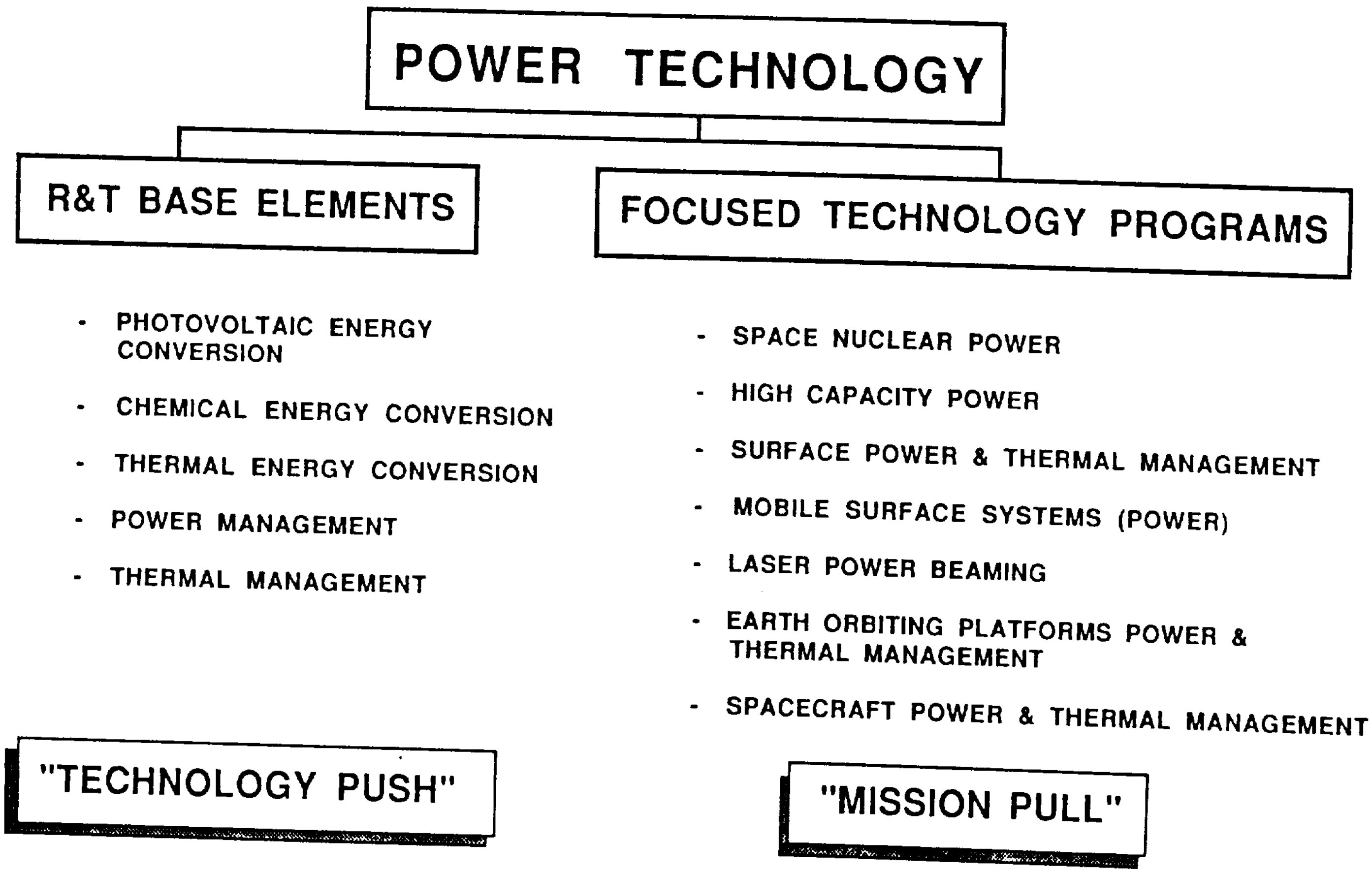
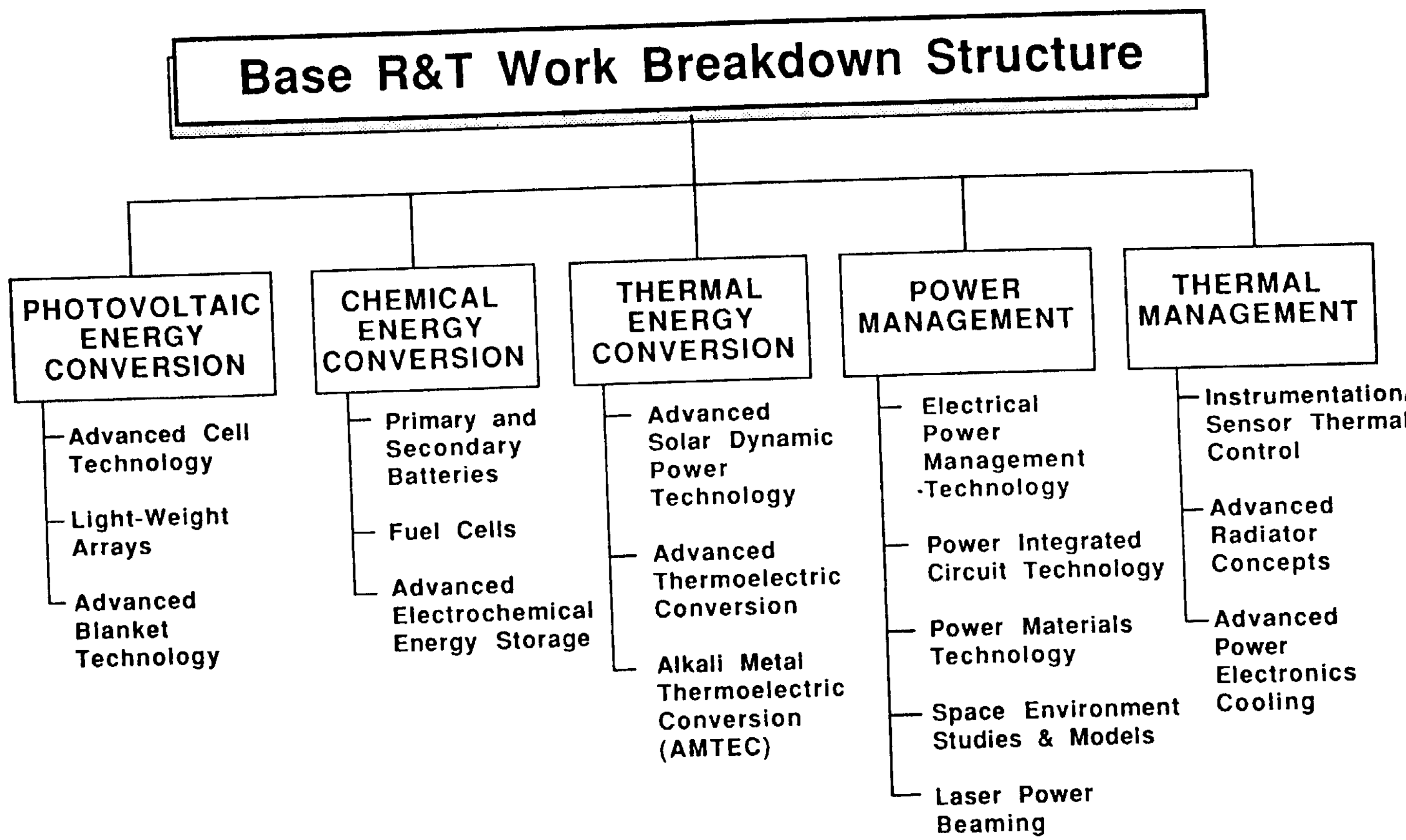


Figure 11. Proposed Organization of the NASA Space Energy Conversion Research & Technology Program

Figure 12.



Base R&T Work Breakdown Structure
PHOTOVOLTAIC ENERGY CONVERSION
Advanced Cell Technology
Light-Weight Arrays
Advanced Blanket Technology
CHEMICAL ENERGY CONVERSION
Primary and Secondary Batteries
Fuel Cells
Advanced Electrochemical Energy Storage
THERMAL ENERGY CONVERSION
Advanced Solar Dynamic Power Technology
Advanced Thermoelectric Conversion
Alkali Metal Thermoelectric Conversion (AMTEC)
POWER MANAGEMENT
Electrical Power Management Technology
Power Integrated Circuit Technology
Power Materials Technology
Space Environment Studies & Models
Laser Power Beaming
THERMAL MANAGEMENT
Instrumentation/ Sensor Thermal Control
Advanced Radiator Concepts
Advanced Power Electronics Cooling

Figure 13.

Focused Technology Work Breakdown Structure

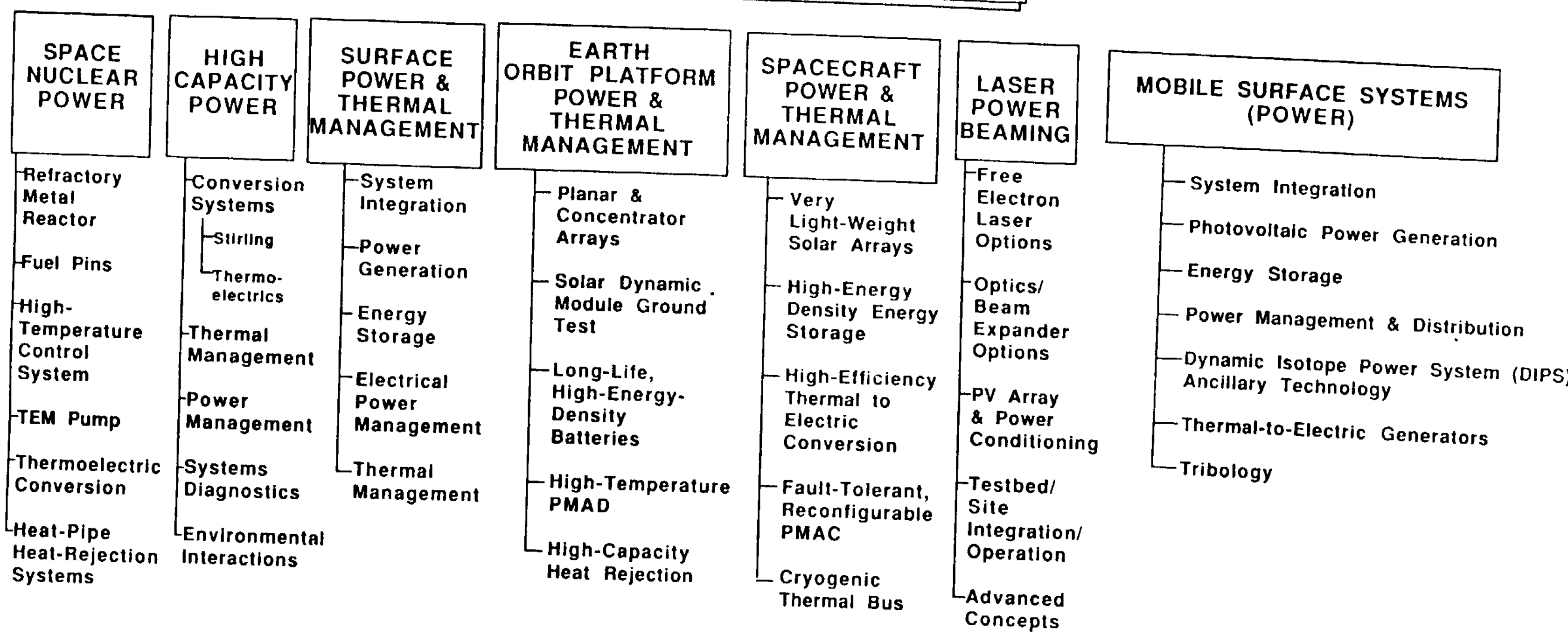


Figure 14. Artist's Concept of a Lunar Base Powered by an SP-100 Class Nuclear Reactor with Stirling Cycle Conversion

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13. ABSTRACT *(Maximum 200 words)*
With the President's Space Exploration Initiative (SEI) of returning to the Moon and then going to Mars, NASA will need to develop a number of enabling technologies, chief among them being power for spacecraft and surface bases. The SEI power for spacecraft and surface bases. The SEI power technology program will build upon ongoing efforts in the areas of advanced photovoltaics, energy storage, power management, nuclear power, and higher conversion efficiency systems. Recent studies have identified space nuclear power as a key technology for SEI. Nuclear power offers tremendous advantages for manned lunar bases and it greatly enhances manned Mars bases. Nuclear power can also be used to power nuclear electric propulsion (NEP) spacecraft such as piloted and cargo missions to Mars as well as unmanned science missions throughout and beyond the Solar System.

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