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Preliminary Survey of 21st Century Civil Mission Applications of Space Nuclear Power

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GLOSSARY OF ACRONYMS

AU	Astronomical Units
CFE	Continuous Flow Electrophoresis
C-ITV	Cargo Carrying ITV
CMAG	Civil Missions Advisory Group
C&T	Communications and Tracking
DSCG	Directional Solidification
ECG	Electroepitaxial Crystal Growth
ELV	Expendable Launch Vehicle
EOL	End of Life
EVA	Extravehicular Activity
g	gravity
GaP	Gallium phosphide
GEO	Geosynchronous Orbit
GNC	Guidance, Navigation and Control
IOC	Initial Operational Capability
I_{sp}	Specific impulse
ITV	Interplanetary Transport Vehicle
kW_e	Kilowatt electric
LDR	Large Deployable Reflector
LEO	Low Earth Orbit
L_{sep}	Separation distance
MFP	Mission Forecast Program
M-ITV	Manned ITV
MPFP	Materials Processing Factory Platform
MRDB	(Space Station) Mission Requirements Database
MW_t	Megawatt, thermal
NCS	National Commission on Space
NEP	Nuclear Electrical Propulsion
OMV	Orbital Maneuvering Vehicle
OTV	Orbital Transfer Vehicle
PMC	Permanently Manned Capability
RMA	Reliability, Maintainability, Accessibility
SEP	Solar Electric Propulsion
SiGe	Silicon germanium
SIRTF	Space Infrared Telescope Facility
SNDO	Safe Nuclear Disposal Orbit
SRPS	Space Reactor Power System (SP-100)
STS	Space Transportation System
TAU	Thousand Astronomical Units
UN	Uranium nitride
VCG	Chemical Vapor Transport
Vdc	Volts, direct current

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SECTION 1

EXECUTIVE SUMMARY

The purpose of this study was (1) to collect and categorize a forecast (10-30 years) of ambitious civilian space missions and their power requirements, and (2) to assess the applicability of an SP-100-class space reactor power system (SRPS) to those missions. A wide variety of missions were selected for examination, compiled principally from the reports of the earlier Civil Missions Advisory Group and the recent National Commission on Space; each mission represented a potential need for high levels of electrical power. See Figure 1-1 for a projected timeline of the chosen missions.

The applicability of an SP-100 type of nuclear power system was assessed for each of the selected missions; a strawman nuclear power system configuration was drawn up for each mission, the ability of the SP-100 SRPS to satisfy the mission requirements was assessed, and the tradeoffs of each application were identified.

The main conclusions of this study are:

- Space nuclear power in the 50 kW_e-plus power range can enhance or enable a wide variety of ambitious civil space missions projected for the 1995-2055 time frame. The SP-100 type of nuclear power system is broadly applicable to those missions selected for this study, and its subelement technologies are very applicable.

- Safety issues require additional analyses for some applications. The permanently manned Space Station is such an application, due to the planned extensive extravehicular activity (EVA) and vehicular proximity operations. This assessment addressed these issues by considering a scenario in which the high power level, commercial materials processing activities are accommodated on a coorbiting platform, rather than the Station itself.

- Safe space nuclear reactor disposal is an issue for some applications. Missions either operating in or returning to low Earth orbit will require safe handling and disposal of the SRPS. Surface operations such as the planetary bases may have to bury their reactors in place.

- The current baseline SP-100 conical radiator configuration is not applicable in all cases. For example, it might not function under variable gravity conditions.

- Several applications will require shielding greater than that provided by the baseline shadow-shield. The resulting increase in total system mass is an injected mass issue, but may be resolved at the planetary bases through the use of surface materials.

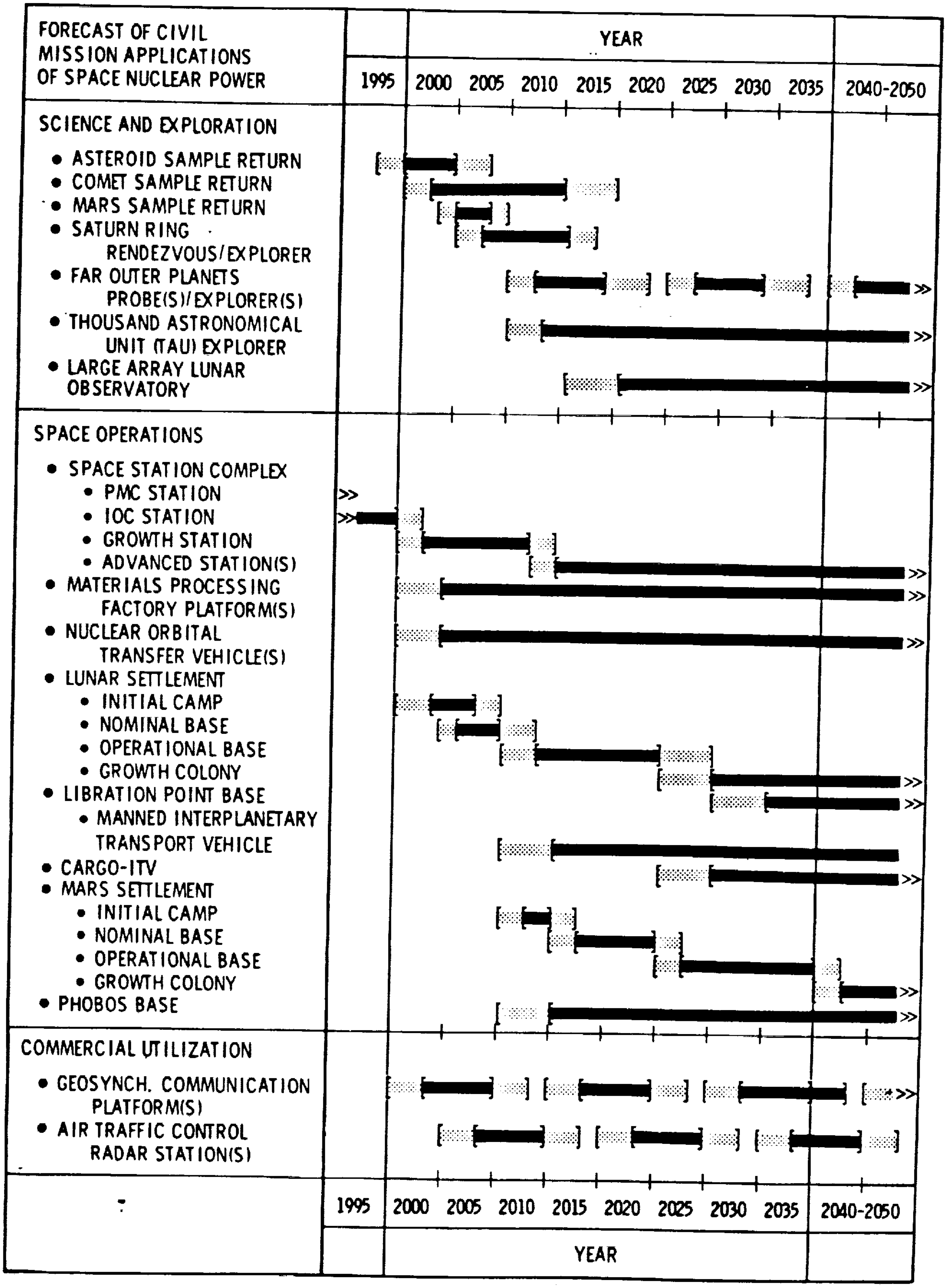


Figure 1-1. Projected Timeline for Study Missions

- Long-duration, continuous operation, high-RMA missions may exceed the currently designed SP-100 lifetime capabilities. In this study, such missions are represented by the Far Outer Planets Orbiters/Probes and the TAU Explorer. This issue might be addressed by the use multiple, smaller reactors to achieve comparable, long-term power levels with enhanced reliability.

As noted above, the missions examined in this study were chosen, in part, because they reflect the demand for higher power levels among civil missions during the 1995-2055 time frame. (Within that period, the span from 2000 to 2040 represents the timeframe of primary interest.) During the same period, a significant number of valuable science and manned space operations missions will be staged which do not require very high power levels; these may include the Space Infrared Telescope Facility (SIRTF), the Large Deployable Reflector (LDR), and a manned lunar exploration vehicle. Also, a number of the missions studied could be implemented under widely varying scenarios and/or trajectories, with considerably lower power requirements and alternative power technologies. These alternative power technologies (such as solar dynamic power or smaller reactor power systems), although potentially applicable to some of the missions studied, were not evaluated.

SECTION 2

INTRODUCTION

2.1 STUDY OBJECTIVES

The objectives of this study were:

- to collect and categorize a forecast of ambitious near- and far-term civil space missions and projected power requirements, and
- to assess the applicability of currently planned space reactor power systems to those civil missions.

The forecast of civil missions was compiled principally from the reports of the Civil Missions Advisory Group (1984) and the National Commission on Space (1986); Table 2-1 lists the missions which were included. The nuclear power assessments were made for each mission in terms of the ability of an SP-100-type Space Reactor Power System (SRPS) to satisfy that mission's requirements (alternative power technologies such as solar dynamic power systems were not assessed).

2.2 STUDY APPROACH

This study of potential civil mission applications of space nuclear power involved three principal activities: (1) definition of a current baseline SP-100 type of power system, (2) compilation of a forecast of ambitious civil missions and their power requirements, and (3) analysis and assessment of the application of nuclear power to each civil mission examined.

2.2.1 Space Nuclear Power Systems

Section 3 describes the SP-100 SRPS, which is the current U.S. space nuclear reactor technology development program. The discussion details the system capabilities, functional architecture, and subsystems. Configuration tradeoffs and special considerations are also addressed.

2.2.2 Potential Civil Mission Applications

The civil missions that were assessed vary greatly in terms of their objectives and operating procedures, yet each one contributes toward achieving the space goals set for the United States by the National Commission on Space. Those goals included:

- to advance our understanding of the Earth, the solar system, and the universe
- to explore, prospect, and settle the solar system
- to stimulate commercial enterprises in space.

Table 2-1. Proposed Civil Space Missions Selected for Study

Mission Type	Elements
SCIENCE AND EXPLORATION	
Asteroid Sample Return	Single Mission
Comet Nucleus Sample Return	Single Mission
Mars Surface Sample Return	Single Mission
Saturn Ring Rendezvous/Orbiter	Single Mission
Far Outer Planets Probe(s)/Orbiter(s)	Multiple Spacecraft
Thousand Astronomical Units Explorer	Single Spacecraft
Large Array Lunar Observatory	Single Mission
SPACE OPERATIONS	
Space Station Complex (LEO)	Permanently Manned Capability Initial Operating Capability Growth Station Advanced Space Station(s) Materials Processing Factory Platform
Lunar Settlement	Initial Operational Camp Nominal Base Operational Base Growth Colony
Libration Base	Single Mission
Nuclear Orbital Transfer Vehicle(s)	Multiple Vehicles
Interplanetary Transport Vehicles (ITV)	Manned ITV Cargo-Carrying ITV
Mars Settlement	Initial Operational Camp Nominal Base Operational Base Growth Colony Mars/Phobos Base
COMMERCIAL UTILIZATION	
Geosynchronous Communications Platform(s)	Multiple Platforms
Air Traffic Control Radar Station(s)	Multiple Platforms

Missions were divided into three categories: science and exploration, space operations, and commercial utilization. Science and exploration missions are those which will add to our knowledge of the solar system and beyond. Space operations missions deal with the outposts in space where humans will live and work; the discussion includes the technology supporting these endeavors. Commercial utilization missions are potential enterprises which will exploit the unique space environment for the benefit of private interests.

In Section 4, each mission category is discussed in turn, including individual mission objectives and selected operational characteristics. Conceptual illustrations and tables listing key mission parameters are also provided.

2.2.3 Power System Applications Assessment

In Section 5, the requirements of the civil missions and the capabilities of the SP-100 SRPS are compared. The applicability of space nuclear reactors to each mission is assessed, and advantages and disadvantages are described. A strawman configuration SP-100 SRPS is provided for each mission.

SECTION 3

NUCLEAR POWER SYSTEMS

3.1 INTRODUCTION

In this section, some of the advantages to be found using space nuclear power are discussed. This section characterizes the current state of the art in space nuclear reactors, the SP-100 Space Reactor Power System (SRPS). Starting with SP-100 SRPS capabilities and functional architecture, each functional subsystem and its associated subelement technology is described. Configuration trades are presented in order to permit a basic analysis of the SP-100 as applied to various civil space missions selected for study in this report.

The SP-100 project is a long-range joint program under the management of the National Aeronautics and Space Administration, the Department of Energy, and the Department of Defense. Phase II of the SP-100 program is comprised of several tasks which include the development of a ground engineering system for design testing and validation, the development of a flight demonstration reference system, and a program to evaluate and assess advanced technologies which would lead to evolutionary improvements in SP-100 performance. These improvments may include the substitution of different subelement technologies such as power conversion. The following discussion will encompass the subelement technologies that represent the current planned subelement technologies to be flown in the first SP-100 demonstration flight. In this report the use of the terms SP-100 or SRPS will apply only to those subelement technologies which comprise the flight demonstration system.

Finally, special considerations that may affect the application or deployment of the SP-100 SRPS are discussed. These special considerations include orbital delivery, system reliability, maintainability, and availability (RMA), system lifetime, and the end-of-life disposal of expended reactors.

3.2 POTENTIAL ADVANTAGES OF SPACE NUCLEAR POWER

Nuclear power is only one of a number of energy sources available for space applications. The power system selected for a particular mission depends on the duration, power requirements, operating environment, and other performance parameters of the mission.

At high power levels and longer durations, nuclear power has several inherent advantages over solar photovoltaics. First and foremost, nuclear systems are independent of the Sun. As a result, nuclear power systems do not require energy storage devices (batteries, regenerative fuel cells, etc.) and can operate efficiently anywhere in space. Moreover, nuclear power systems do not have large delicate panels that are characteristic of a photovoltaic power system. As a result, the nuclear power system offers lower drag in Earth orbit, better fields of view for pointing instruments, and enhanced survivability from meteorite and space debris bombardment. The compact size of nuclear power systems simplifies the problem of attitude control and orbit maintenance. This increases the accuracy of missions requiring instrument pointing and target tracking.

As well as being less susceptible to particulate hazards than photovoltaic array systems, nuclear power systems are also inherently hardened to the Van Allen belt radiation, which can seriously degrade the performance of photovoltaic cells. Finally, nuclear power systems may be more mass-efficient and more economical than solar array systems for very high power level applications [Civil Mission Advisory Group report].

High energy-density chemical power sources (i.e., fuel cells) are preferable for short-duration, medium power level manned operations, such as space shuttle (or a post-shuttle Earth-to-orbit vehicle), or a manned orbital transfer vehicle. Similarly, solar dynamic power systems will provide high power levels (without subsidiary energy storage devices) for a wide variety of inner solar system mission applications. The best example of the latter is the planned utilization of solar dynamics on the U.S. Space Station. However, nuclear power systems may offer longer-duration, lower maintenance, and lower cost operations in a number of applications due to the mechanical simplicity of the SRPS, and the capability to generate power in the short-term absence of sunlight (e.g., during the lunar night).

The SP-100 SRPS was chosen for this study because it represents the currently planned nuclear reactor space power technology. There have, however, been efforts to develop a space nuclear reactor power system since the 1950s. These reactors incorporated different fuel, thermal conversion, and heat dissipation subelement technologies. For the sake of brevity a historical summary of U.S. nuclear space reactors is not given here but rather is presented in Appendix A.

3.3 SP-100 SYSTEM DESCRIPTION

The SP-100 SRPS is a nuclear power source designed to provide electrical power to a variety of potential user space missions. The thermal energy generated by a fast-neutron spectrum nuclear reactor is converted to electrical energy by a thermoelectric process and provided to the user payload after conditioning. Radiators are required to dissipate the excess heat generated by the power system. Figure 3-1 depicts a simple, conceptual flight mission employing an SP-100 nuclear power system.

3.3.1 System Capabilities

The modular design of the SP-100 provides a wide range of electrical power to a user mission. The electrical output ranges from 100 to 1,000 kW_e. The thermal output of the reactor may also be utilized by the mission.

An important factor used in the comparison of power systems is the ratio of the power system mass to the power output of the system (mass-to-power ratio, or specific mass). As a design goal, the specific mass of the SP-100 is to be less than 25 kg/kW_e for thermoelectric conversion; however, more realistic estimates give the specific mass to be less than 32 kg/kW_e. The most important factor affecting the specific mass of the power system is the conversion efficiency of the thermal-to-electrical energy conversion process. A greater conversion efficiency could decrease the overall system mass for the same electrical power output level depending on the mass of the conversion

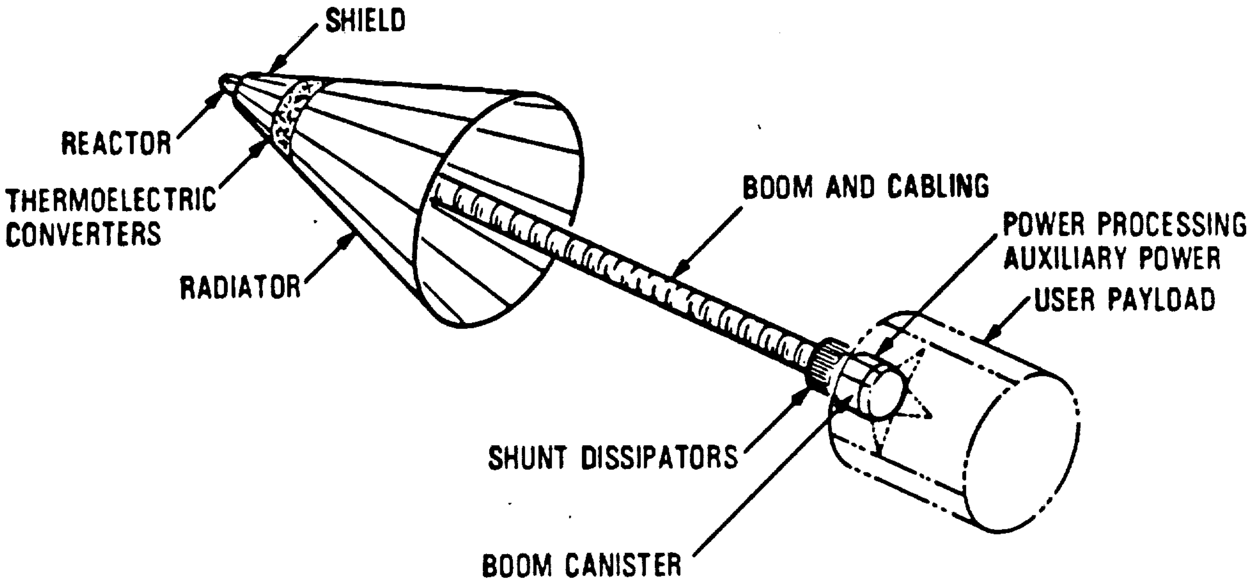


Figure 3-1. Simple SP-100 Flight Configuration

subsystem, and its required thermal power input. The specific mass of the SP-100 SRPS is certain to change as advanced technology developments are incorporated into the design.

The system life of the SP-100 is projected to be a minimum of seven years at full power and ten years total. The initial (first flight system) reliability of the SP-100 is greater than 95 percent for the first two years. Growth toward a 95 percent or better reliability over the entire full-power life in subsequent flight systems is a design goal.

3.3.2 Functional Architecture

The SP-100 SRPS can be divided into seven functional components: reactor, shield, heat transport, power converter, heat dissipating radiators, power conditioning and control, and a mechanical support structure for providing the interface to the user spacecraft. A functional block diagram of the SP-100 SRPS is shown in Figure 3-2.

3.3.3 Subsystem Descriptions

The following are descriptions of the functional subsystems of the SP-100 SRPS. It has been recognized that as advanced subelement technologies develop and are incorporated into the SP-100 design that many of the design parameters will change. For the purposes of this report the current flight demonstration subelement technologies will be discussed.

3.3.3.1 Reactor. The SP-100 reactor utilizes highly enriched uranium nitride (UN) fuel and operates with a fast (high-energy) neutron spectrum. The primary reactor control mechanism is beryllium oxide reflector drums

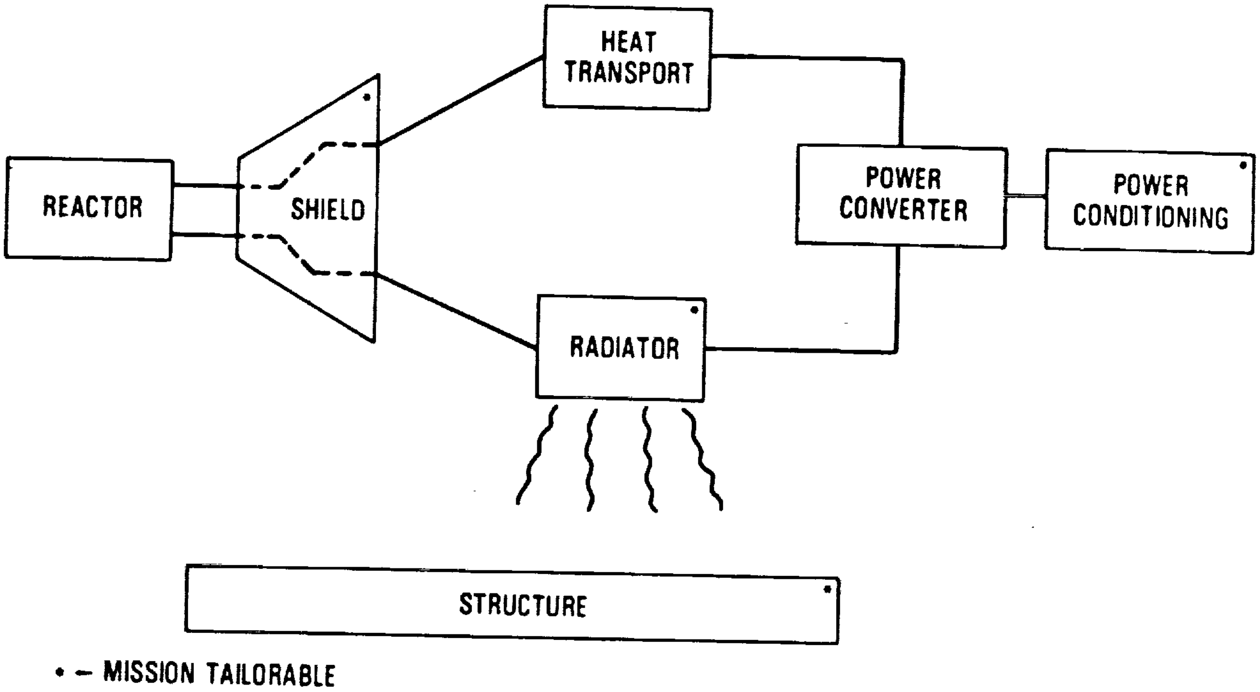


Figure 3-2. SP-100 Functional Block Diagram

located outside the periphery of the reactor vessel. The position of these drums determines the extent to which exiting neutrons are reflected back into the core.

Reactor control is achieved by altering the reactivity of the system. The reactivity of the system can be described in terms of an "effective multiplication factor" or amount by which the total number of neutrons in the system are multiplied by every generation (0.01 to 1 ms). The thermal power output of the reactor is directly proportional to the number of neutrons in the system. A multiplication factor of unity results in a constant power output. The degree to which the exiting neutrons are reflected back into the core impacts the reactivity of the system and the thermal output. The reactivity of the system is also affected by other factors that are not directly controlled; these are termed "feedback effects." The primary feedback effect is temperature. As the temperature of the system increases, the reactivity decreases. This effect allows the reactor to be easily controlled.

To increase the reactor power, the control drums are rotated to provide greater reflection, and the reactivity of the system increases. The neutron level and power of the reactor then increase. As a result, the temperature in the system increases and the reactivity of the system begins to decrease. The multiplication factor returns to a value of unity and the reactor stabilizes at a higher power level. The same control mechanisms allow reactor power to be decreased.

The fuel burnup is proportional to the reactor power. Higher power levels require greater amounts of fuel. However, it is easy to incorporate any required amount of fuel into the system by increasing the enrichment of the fuel and amount of excess reactivity in the reactor. Thus, the power level of the system is normally not constrained by the fuel burnup requirements. Rather, power limits are placed on the system by the thermal transport, conversion, or rejection subsystems.

3.3.3.2 Shield. The shield is generally composed of two different materials, each serving a different purpose. Mechanically reinforced lithium hydride is used to provide the neutron shielding, and tungsten is used to shield the payload from gamma radiation.

The quantity and configuration of the shielding is strongly mission dependent. Unmanned missions (such as planetary probes) that may utilize an SP-100 SRPS will typically require significantly less shielding than manned or man-tended craft and installations. Unmanned missions may be powered up remotely and therefore require only that level of shielding necessary to meet payload/mission requirements. Figure 3-3 illustrates the variety of shield configurations that may be used.

For unmanned missions the minimum mass shielding requirement is met by using a shadow shield. Figure 3-3 illustrates the various shield configurations. The shadow shield provides radiological protection only to the region within the shadow of the shield. The thickness of the shadow shield will determine the level of protection the shield will provide to the payload from power system radiation.

If there is a requirement to provide some shielding to a broader area, then either a two-pi or a preferential shield configuration may be used, depending on the requirement. A four-pi shield configuration is used if uniform shielding in all directions from the reactor is desired.

Manned or man-tended space missions have very stringent limitations on the exposure of human personnel to radiation, both naturally occurring and artificial. Generally speaking, manned missions will require more shielding for the reactor than any other type mission. The exact amount of shielding is dependent on the proximity of the reactor to personnel. Factors that must be considered when determining shielding requirements include naturally occurring radiation levels, total allowable biological radiation dosage, distance between operation centers and the reactor, desired minimum distance from the reactor during EVA and fly-by, and desired duration of EVA and fly-by activity. Fully man-rated shielding allows unlimited operations within physical reach of the reactor.

3.3.3.3 Heat Transport. The heat transport component of the SP-100 SRPS consists of pumped liquid lithium loops and potassium wick heat pipes. The liquid lithium is electromagnetically pumped to the thermoelectric converters, where electricity is generated. Residual waste heat from the thermoelectric converters is transported to and through the radiator panels by the heat pipes. Like the reactor, the heat transport subsystem is a constant design configuration.

FOUR-PI

TWO-PI

SHADOW

PREFERENTIAL FOUR-PI

Figure 3-3. Shield Configurations

3.3.3.4 Power Converter. The current flight configuration of the SP-100 SRPS power conversion system uses series-parallel connected silicon germanium/gallium phosphide (SiGe/GaP) thermoelectric elements. The thermoelectric elements have a relatively low conversion efficiency when compared to advanced power conversion technologies currently under development. However, the small size of the elements, the large numbers of them employed, and their series-parallel interconnection provides for continued operation in the event of a failure of one or more elements. Future flight systems may incorporate advanced, more efficient power conversion technologies.

3.3.3.5 Radiators. The radiator panels dissipate system waste heat in a direction away from the user payload. Potassium heat pipes are used to distribute heat across the panels. Heat pipes are sensitive to their orientation within a gravitational field; the evaporating section must be below the condensing section. This limits the radiator configurations allowed in gravitational fields (naturally or artificially induced). Figure 3-4 shows radiator configurations other than the simple conical configuration shown in Figure 3-1.

3.3.3.6 Power Conditioning and Control. The power conditioning and control system is responsible for the delivery of electrical power to the user mission payload as well as the command, control, and performance status telemetry. Two direct current power buses are made available to the user. The first is a 100-600 Vdc (200-Vdc nominal) fixed main bus. Second is a 28-Vdc secondary bus. Both are regulated such that any additional required power conditioning is user mission specific.

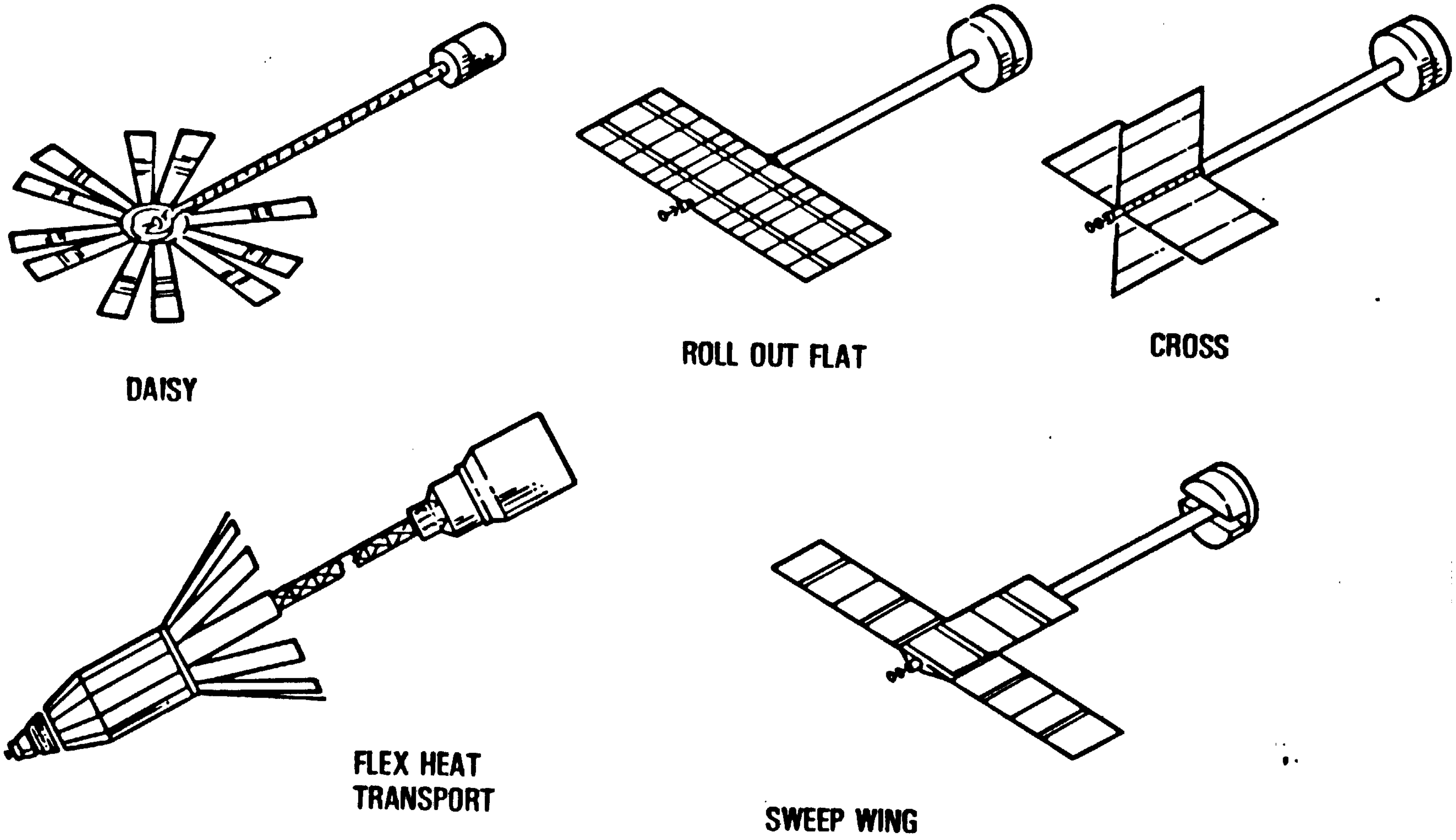


Figure 3-4. Additional Radiator Configurations

3.3.3.7 Mechanical Support Structure. The mechanical support structure design is driven by the flight or planetary surface application requirements. The support structure is an important factor in determining the level of shielding and the radiator configuration.

Figure 3-5 depicts a simple flight system configuration, defining the physical parameters common to all boom-mounted reactors. The user plane is defined as a planar circular surface perpendicular to and centered on the user module axis. Quantities such as neutron fluence, gamma dosage, and thermal radiation levels are defined at the user plane. The separation distance, L_{sep}, is the distance between the reactor and the user plane.

3.3.4 Reference Mission Parameters

For the purpose of comparison, it is convenient to define a reference system. If a flight configuration such as the one shown in Figure 3-5 is assumed, and if an electric power level of 100 kW_e is chosen, then the parameters defining a reference system are those shown in Table 3-1. The neutron fluence and gamma dosage are defined for the user plane assuming a 7-year system lifetime. The power output and specific mass are given as end-of-life values.

It is important to note that this reference system design is for the purposes of comparison only and is specific to this report. The values shown are representative of a typical SP-100 SRPS based on the current subelement

Table 3-1. Reference System Parameters

Feature	Parameters
Output power	100 kW_e at end of life
User plane	4.5-m disk
L_{sep}	25 m
Neutron fluence	1×10^{13} neutrons/cm^2
Gamma dose	5×10^5 rad
Total mass, excluding mission module	2,900 kg
Total surface area, excluding mission module	80 m^2
Thermal power	1.96 MW_t
Specific power	29 kg/kW_e
Shielding	Shadow configuration, not man-rated

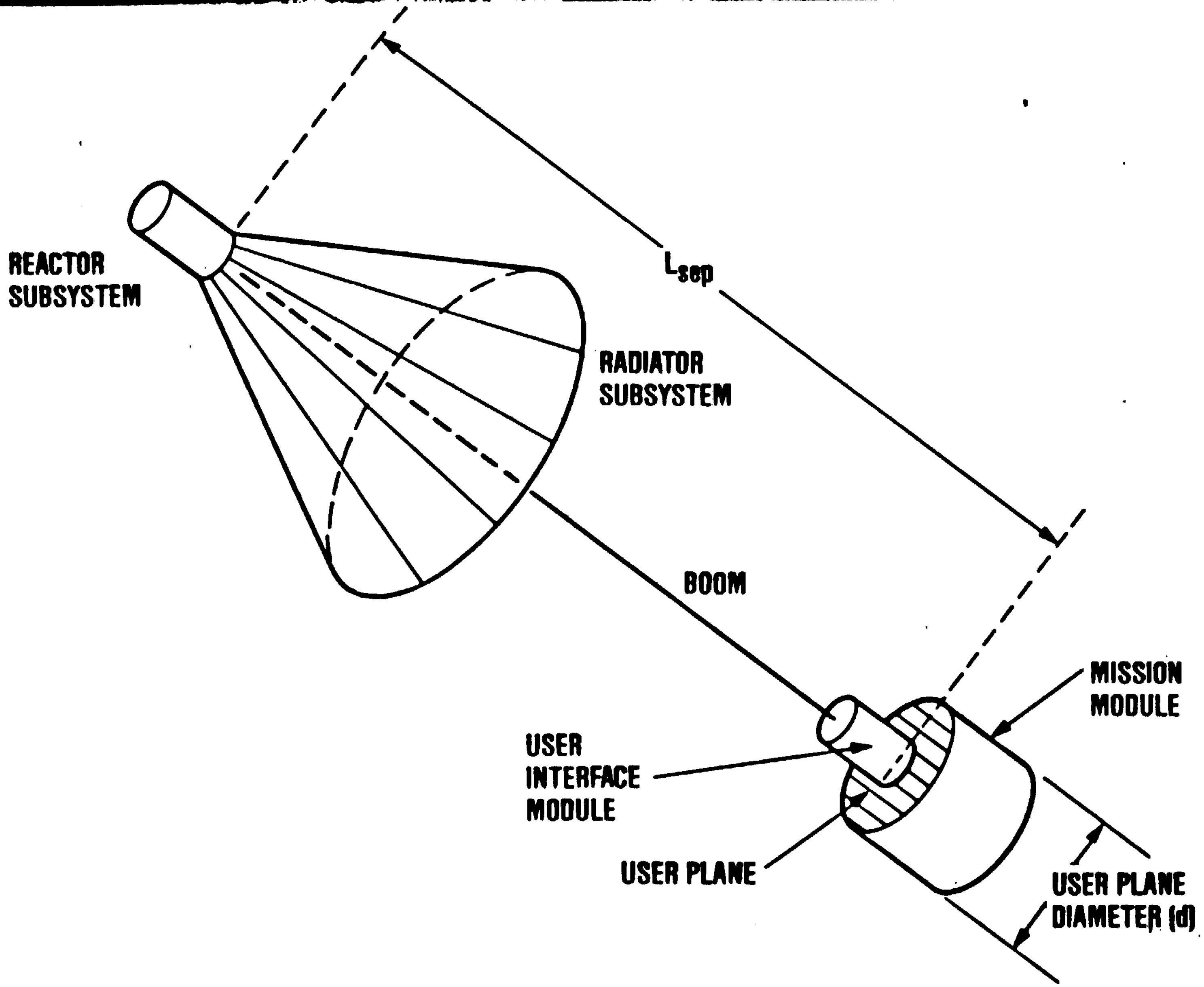


Figure 3-5. Flight System Physical Definition

technologies to be incorporated in the SP-100 reference flight mission for an electrical power output of 100 kW_e. The actual electrical power output and final design requirements of the SP-100 reference flight mission might vary slightly.

3.4 CONFIGURATION TRADES

As mentioned before, mass and specific power are important factors used in the comparison of power systems. Specific power is the ratio of the system mass to the available electrical power output. Mass and specific power are of particular importance to the spacecraft mission planners and designers. Therefore, the mass and specific power will be used to compare the effects of altering the reference mission parameters in response to different user needs.

3.4.1 Power Level

Figure 3-6 shows the relationship between system mass and required electrical output level. The system mass includes the reactor, heat transport and radiator mass, and the minimum required shielding to meet the reference mission radiation and user plane/boom-length requirements.

3.4.2 Shielding

Figures 3-7 and 3-8 illustrate a typical relationship between system mass and neutron and gamma fluence respectively. These trade-offs are for the comparison of unmanned missions; manned missions will typically limit dose at the user plane and thus the wide range of dosages illustrated in these figures may not be allowable.

As can be seen from Figure 3-7, the system mass is relatively insensitive to changes in neutron fluence requirements. This is fortunate in that a majority of electrical components are more sensitive to neutrons above certain threshold energy levels. Note that there are some electrical components that tend to be quite sensitive to gamma exposures. The insensitivity of system mass is attributed to the lithium hydride shielding, which is light in weight and thus contributes to only a small portion of the total shield mass. Increasing the neutron shield by a factor of ten, for example, may only add three to four percent to the overall system mass. Any reduction in neutron fluence is also accompanied by some reduction in gamma fluence.

The tungsten-based gamma shielding is an altogether different case. Reducing gamma dosage by a factor of 10 would cause significant increases in system mass because tungsten is a dense material. These increases are reflected in Figure 3-8, which shows an increase of 28 percent in system mass for the mentioned decrease in gamma dosage.

Figures 3-7 and 3-8 apply only to unmanned spacecraft. Manned missions have typically much stricter radiation requirements. Fully man-rated shields (i.e., no exclusion zone surrounding the reactor) drastically increase the system mass. A 100-kW$_e$ system may increase in mass by a total of 45,000 kg when fully man-rated shielding is employed. Since the radiation drops off at the user plane as a function of distance, increasing the boom length can decrease the shield mass as much as 20,000 kg (200-m boom or greater). However, decreasing the shielding introduces a manned EVA exclusion zone around the reactor.

The shielding necessary to meet man-rated requirements is completely dependent on the maximum allowed biological dose rate and varies with the factors mentioned in Section 3.3.3.2. Recent Space Station studies have set a limit of 20 Rem per quarter to the eyes. The radiation exposure due to the natural background radiation must then be calculated based on the desired duration of stay. The background radiation will vary with location on or around the station. These dosage calculations combined with the maximum allowable dosage provide the dosage margin to which the reactor shielding must be designed. The reactor shielding required for other manned or man-tended missions may differ because parameters such as duration of mission and required EVA will vary. A thorough analysis of Space Station shielding requirements may be found in NASA Lewis PIR-300.

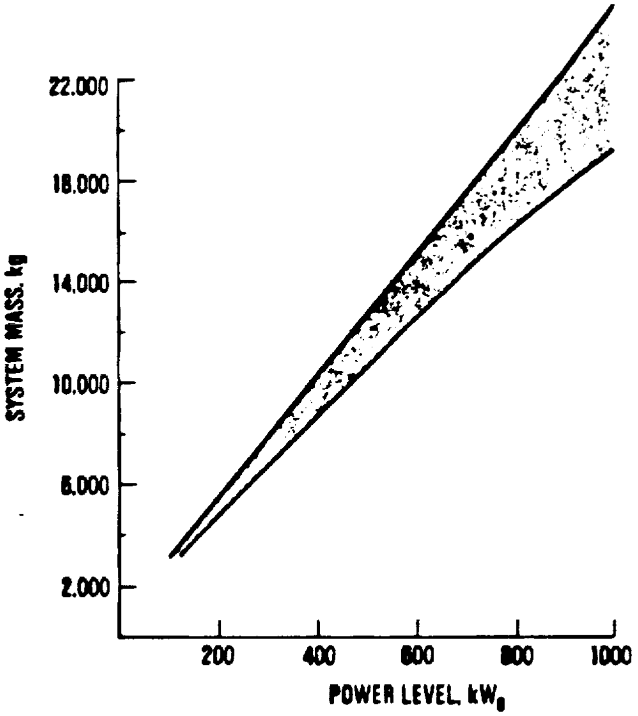


Figure 3-6. System Mass vs. Power Level (based on reference design)

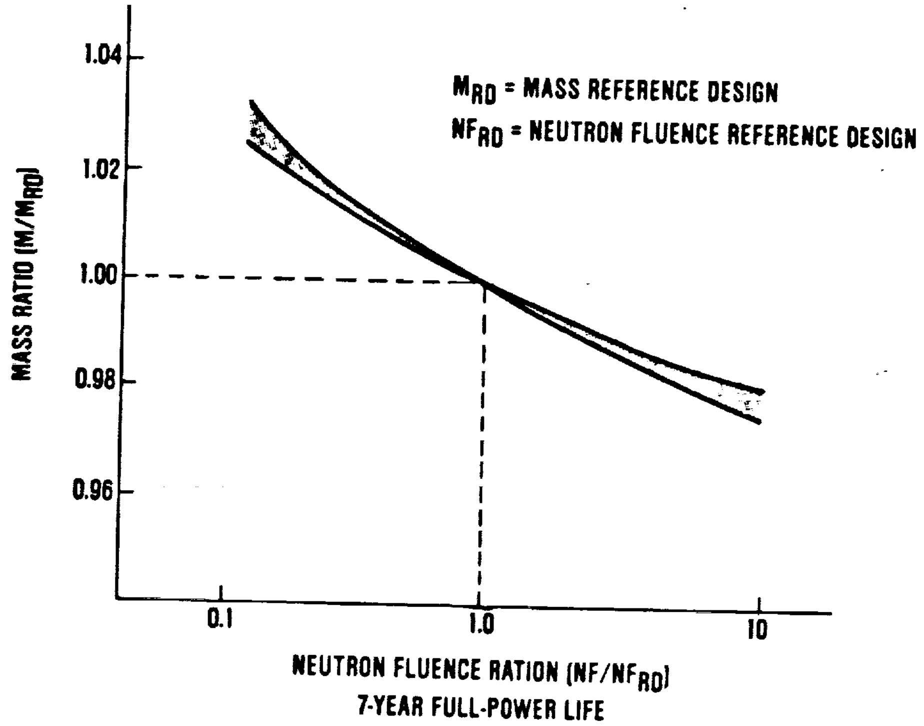


Figure 3-7. System Mass vs. Neutron Fluence

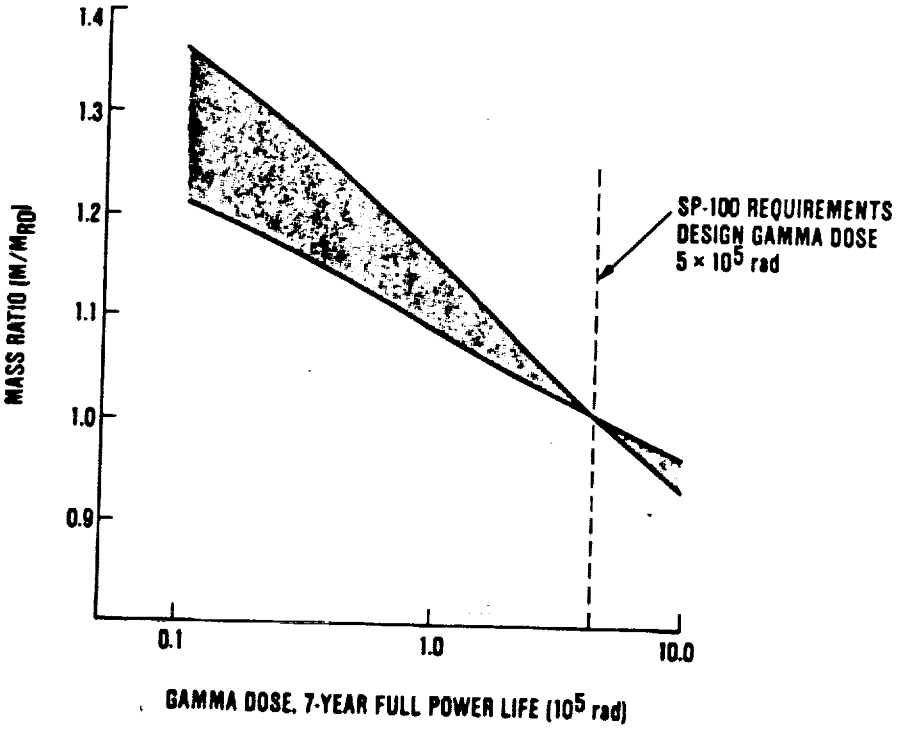


Figure 3-8. System Mass vs. Gamma-Dose Requirements

Unmanned missions, while not affected by exclusion zones, have little to gain by lengthening the boom. The shielding employed on the unmanned reference design is already the minimum needed to meet requirements, and increasing the boom length increases the overall support structure mass. Figure 3-9 shows that, at best, less than 500 kg can be saved by increasing the boom length, when minimum required shielding is used.

It must be assumed that some user payloads will require a user plane diameter greater than the 4.5 meters specified as baseline. Figure 3-10 depicts the change in overall system mass as a function of the user plane diameter.

3.5 SPECIAL CONSIDERATIONS

3.5.1 Orbital Delivery

Because of its mass, man-rated shielding has the disadvantage of needing to be assembled around the reactor while in orbit. Fully man-rated shielding requires several STS or expendable launch vehicle (ELV) flights to place the necessary shielding material in orbit. The reactor must be kept in its prelaunch dormant mode and thawed after the shielding is in place. Surface deployed reactors may be able to utilize local materials for shielding.

In order to minimize radiological hazards during preflight operations, the SP-100 is to be launched in a highly subcritical frozen state. Further, the reactor will have had essentially no power history and therefore no fission product inventory or decay heat. Once the desired orbit is achieved, the reactor is brought critical by a slow reactivity addition. Thermal power is increased and used to thaw the reactor and power conversion system, finally achieving full power.

Particular issues dealing with launch safety are dependent on the launch vehicle and its accepted practices. A discussion of possible launch vehicles and their capabilities appears in Section 5.3.3.

3.5.2 System Reliability, Maintainability, and Availability and Lifetime

An issue which affects the application of SP-100 SRP technology to particular missions is the reliability, maintainability and availability (RMA) and the lifetime of the power system. At present, the SP-100 is projected to have a 95 percent probability of success for the first two years of its life. Growth toward a 95 percent probability of success for its entire 7-year full-power life is hoped for as more units are deployed and the technology matures. This raises some concern for Class A scientific missions which utilize early SP-100 units. These concerns are addressed in Section 5.3.4.

3.5.3 End-of-Life Disposal

An expended space nuclear reactor can pose a long-lived radiological safety hazard. A means of safe disposal is required for low Earth orbit (LEO) and surface-deployed reactors. For orbiting reactors, there are alternatives to returning the SRPS to Earth. First, the reactor may be boosted to a

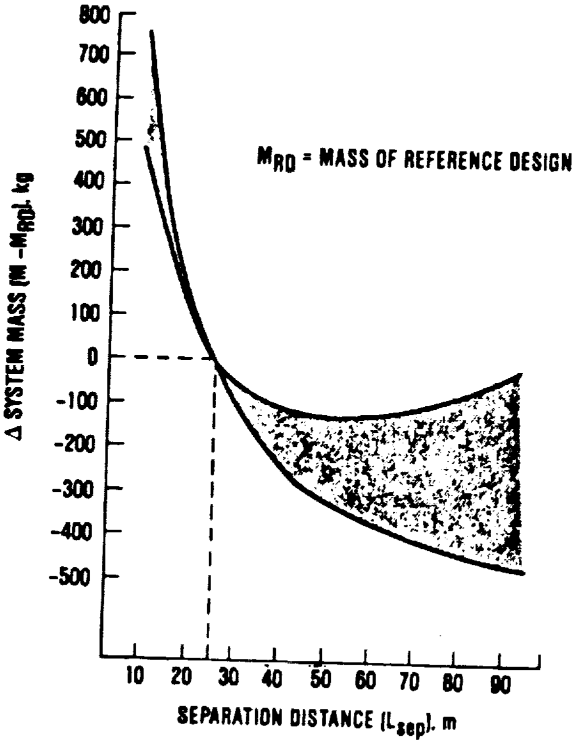


Figure 3-9. System Mass vs. Reactor/User Plane Separation Distance

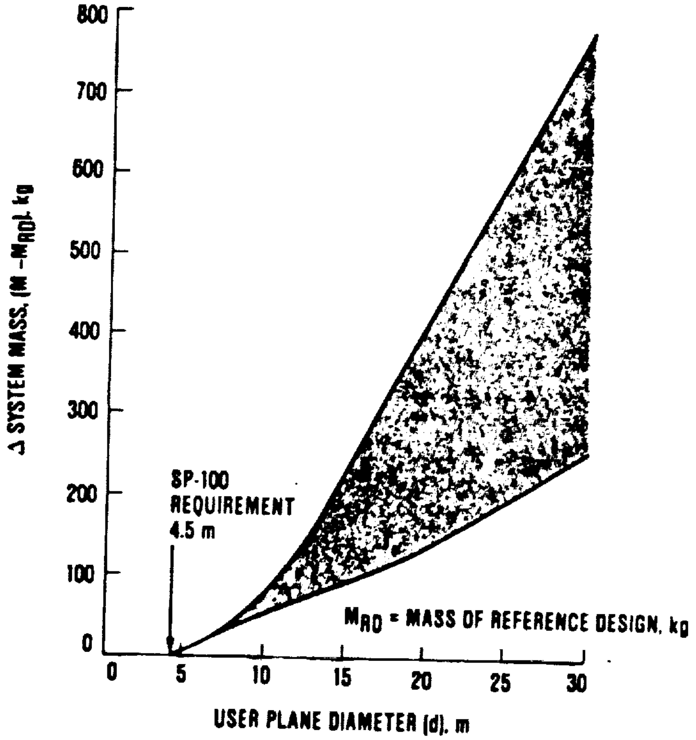


Figure 3-10. Change in System Mass vs. User Plane Size

heliocentric orbit. Once this is done, the reactor will not pose any danger of accidental re-entry or future risk to Earth-orbit operations. However, heliocentric SRPS disposal would involve large propulsion requirements (e.g., chemical propellant quantities).

Another alternative is to place the reactor into a far Earth orbit called a safe nuclear disposal orbit (SNDO). The duration of this orbit is calculated such that the time required for orbital decay and subsequent reentry allows the reactor fuel radioactivity to decay to acceptable radiation levels. The duration of a safe nuclear disposal orbit has been established as 300 years; however, the effects of the eventual reentry have not been fully investigated. SNDO disposal of the SRPS would entail considerably reduced propulsion requirements, versus heliocentric orbit disposal.

Surface-deployed reactors may be interred in situ. This requires that the reactor be deployed some distance from surface facilities in order to minimize long-term radiation exposure. This disposal approach also permits future salvage of the depleted reactor.

Other disposal options include the disposal of orbiting reactors on the lunar surface or by returning the reactor to Earth using the Space Shuttle. Missions operating entirely beyond Earth's gravitational influence require no special disposal (orbit transfer) mechanism.

SECTION 4

POTENTIAL CIVIL MISSIONS APPLICATIONS

4.1 INTRODUCTION

This section describes a few of the many U.S. civil missions which have been proposed for the coming decades. Only those missions requiring substantial levels of electrical power have been examined in this study. These missions have been divided into three categories: science and exploration (NASA), space operations (NASA and private), and commercial utilization (private). It was assumed that all missions requiring substantial spacecraft propulsion capabilities would employ nuclear electric propulsion. This assumption was made because of the quantity of electric power that would be made available by the introduction of an SRPS.

4.2 SCIENCE AND EXPLORATION

This section discusses selected science and exploration missions, i.e., missions which will add to our knowledge of the solar system and beyond. These missions are grouped into four areas: sample return; observation and exploration; extra-solar spacecraft; and large space observatories.

4.2.1 Overview

During the coming decades, the United States will send a wide variety of science and exploration missions using both probes and orbiters to further our investigation of the solar system. These missions will explore comets and asteroids, and conduct both global and on-site studies of the other planets. Some missions will gather material from these bodies and return it to Earth for more detailed study. Scientific knowledge of the solar system's origin and composition will greatly increase as a result of the detailed investigations of the structure, composition, and behavior of the solar system's planets and other bodies.

The primary science objectives for the planetary missions include:

- determination of the magnetic field of the planets, the magnetosphere of the system, and the magnetospheric interactions between trapped radiation, the planets, and satellites
- investigations of any unique features of the planets
- investigation of the interplanetary environment beyond Saturn
- determination of the internal structure, surface, and atmosphere of the planets and their satellites.

Asteroids and comets are of special scientific interest because these bodies may contain matter virtually unchanged since the formation of the solar system; scientists want to study this material in depth in order to learn more about its origin and evolution. Goals for the asteroid and cometary missions include:

- investigation of the condensation, accretion, and evolutionary processes which occurred in the solar system before and during planet formation
- determination of the composition, structure, and physical state of an asteroid or of a comet nucleus and cometary atmospheres
- investigation of the interaction of a comet and the solar wind
- determination of the origin of comets and asteroids.

The proposed science and exploratory missions have closely related objectives, similar operational procedures and power requirements. Each mission requires power for the electric propulsion and for operating the scientific payload. The power requirements of the payload will vary with the mission. The propulsion system's power requirements will vary with the choice of technology.

SRPS must be provided with some shielding in order to protect the scientific payload from nuclear radiation. Some of the instruments and scientific measurements may be radiation-sensitive and so require additional protection in order to produce accurate results. Similarly, samples being returned to Earth may require additional protection in order to preserve their original condition. Most of the exploratory spacecraft are near humans only during the planned orbital assembly and launch phase, remaining out in space at the completion of the mission. However, the sample return spacecraft, although also assembled and launched from low Earth orbit (LEO), will return to Earth orbit to deliver their payload.

4.2.2 Sample Return Missions

By studying samples taken from other bodies in our solar system, scientists expect to learn about the physical and chemical processes associated with the early development and evolution of the solar system. Moreover, sample return missions would also identify the presence of resources important to future exploration and settlement of space.

The material sampled must be representative of the body being studied. In order to select a suitable site for sampling, the orbiting spacecraft and lander will include a scientific package in addition to the sample collecting systems. The global studies conducted from the spacecraft would provide chemical characterization, imaging, and geophysical information. Surface chemistry experiments could further characterize the composition of the asteroid, comet, or planet.

Returning a sample to Earth allows scientists to conduct a more detailed analysis of the material than can be carried out remotely. These studies may include the following:

- water content and state of hydration
- identification of organic compounds
- mineralogy and petrography
- elemental assaying
- shock and irradiation effects
- age dating
- radioactivity and stable isotope measurements.

Identifying resources for future mining, development, and use is particularly important on the Moon and on Mars in order to prepare for potential human settlements. On the Moon, for example, prospector and probe missions will survey the Moon and investigate promising sites. Sample return missions will follow, further investigating the most intriguing sites and learning more about surface material composition. This data will be important for siting planetary bases and for such operations as mining and surface material processing.

Resources discovered on asteroids and other bodies may also be important to human space settlements. This material may be mined and transported for a variety of applications at a lower cost than comparable material launched from the Earth. Comets and asteroids will certainly contain material of great scientific interest.

4.2.2.1 Asteroid Sample Return. Main-belt asteroids are found primarily in orbits which lie between Mars and Jupiter. Astronomers believe that these nickel-iron bodies were formed in the inner solar system along with the other objects in the main asteroid belt. Studying these asteroids will give scientists important information about the formation of the Earth and the other bodies in the solar system.

In the asteroid sample return mission envisioned in this study, a number of main-belt asteroids would be surveyed and sampled. The main asteroid sample return spacecraft has been assumed to utilize nuclear electric propulsion. The asteroid sample return spacecraft (see Figure 4-1) will visit up to four main-belt asteroids, taking from five to nine years to visit them and to return to Earth orbit. The spacecraft carries a reusable lander and scientific package to a selected target asteroid of special scientific interest.

While station-keeping in the vicinity of the subject asteroid, the spacecraft conducts global science studies and selects a sample site. A lander craft approaches the asteroid surface, where it performs surface science experiments. It collects the samples and returns them to the orbiting spacecraft. After all targeted main-belt asteroids have been visited, the spacecraft returns to Earth orbit, where the samples are retrieved for scientific analysis.

Table 4-1 provides several key parameters which characterize the asteroid sample mission assessed in this study. Power levels are driven by the utilization of NEP by the spacecraft.

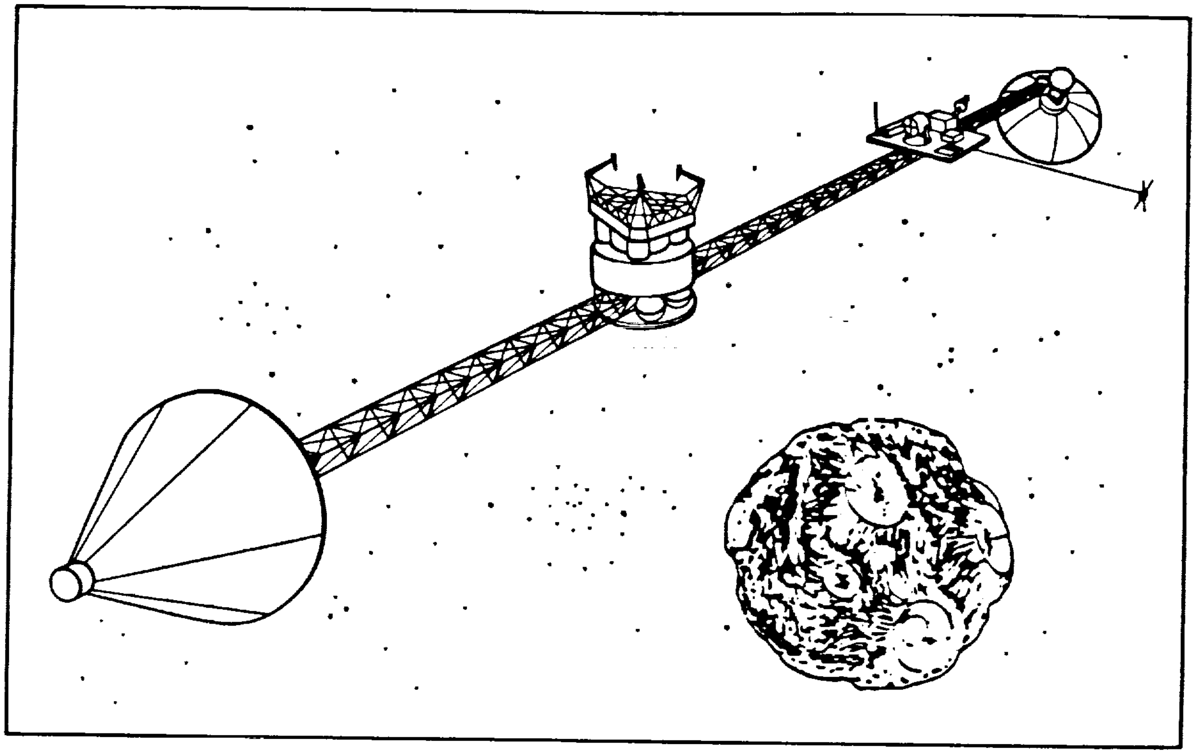


Figure 4-1. Conceptual Illustration of an Asteroid Sample Return Mission

Table 4-1. Key Parameters for Asteroid Sample Return Mission

Mission	Rendezvous with several main-belt asteroids. Acquire samples via reusable lander. Return them to Earth for analysis and resource evaluation.
Power Requirements	80-100 kW_e
Mission Life	5-9 years launch 1998+
Orbit	Not applicable
Shielding	Protect instruments and samples from radiation and heat
Spacecraft RMA	Reactor represents single point-of-failure Class A science mission; RMA critical

4.2.2.2 Comet Nucleus Sample Return. Comets are also believed to contain primordial material. The origin of both the solar system and comets will be better understood through studying comets. The comet sample return mission will acquire pristine samples of a comet for characterization of its ice, dust, and nucleus. A monitoring station will remain to study the comet behavior and nucleus surface activity.

The mission spacecraft (see Figure 4-2) travels to the chosen short-period comet, arriving about 50 days before aphelion and staying from 100 to 150 days. The primary spacecraft carries the following other craft and equipment:

- science payload - characterizes the nucleus; performs site documentation
- autonomous lander - performs surface science operations; drills into the nucleus to collect the one-meter core sample
- long-life science station - anchors itself to the surface on landing; remains through one period of the comet to observe nucleus surface activity over one complete orbit and to transmit its observations to Earth.

The lander carries the sample to the primary spacecraft, where it is hermetically sealed in a capsule in order to preserve its condition. The spacecraft returns to earth orbit and the samples are recovered.

Table 4-2 provides several key parameters which characterize the Comet Nucleus Sample Return mission assessed in this study. As in the case of the Asteroid Sample Return Mission (see 4.2.2.1), the utilization of NEP by the spacecraft presents the driving requirement for SRPS power levels.

4.2.2.3 Mars Surface Sample Return. The objective of this mission is to collect samples from the surface of Mars and return them to Earth. On-site studies and sample analyses will allow scientists to expand the existing base of knowledge regarding the surface and subsurface composition of Mars.

The Mars Sample Return spacecraft (see Figure 4-3 and Table 4-3) travels to Mars, and uses a spiral descent into a 500-km circular orbit around the planet. As in the other sample return missions, a lander craft leaves the primary (NEP-powered) spacecraft and descends to the surface for sample collection. However, in the Mars Sample Return mission assessed in this study, the lander craft is substantially larger than in the Asteroid or Comet Sample Return cases. The lander craft transports both a Mars rover and an ascent vehicle to the martian surface. The rover collects surface and subsurface samples from a wide range of martian territory surrounding the landing site; these are returned to the ascent vehicle and hence back to the primary vehicle waiting in Mars orbit. The primary spacecraft returns the samples to Earth orbit (probably to the U.S. Space Station) for quarantine and subsequent analyses, completing the four- to five-year mission.

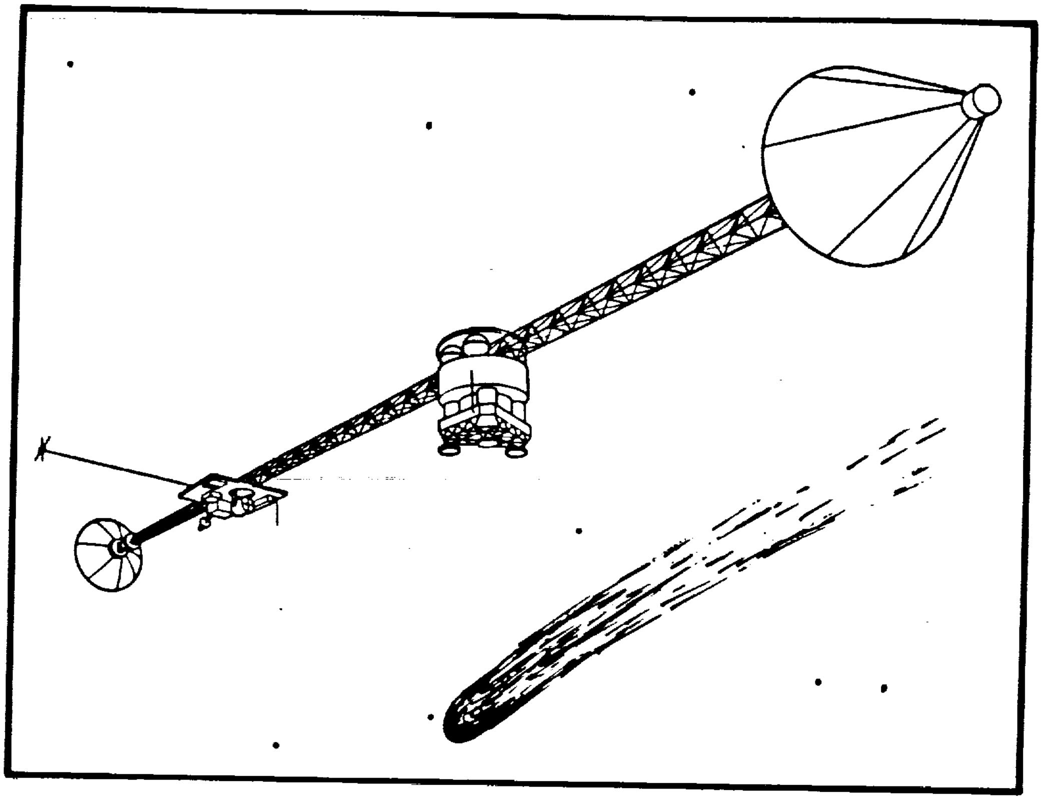


Figure 4-2. Conceptual Illustration of a Comet Nucleus Sample Return Mission

Table 4-2. Key Parameters for Comet Nucleus Sample Return Mission

Mission	Rendezvous with short-period comet. Collect sample of comet nucleus via reusable lander. Return it to Earth for analysis, leaving long-term monitoring station on comet surface.
Power Requirements	80-100 kW_e
Mission Life	12-18 years launch 2000+
Orbit	Not applicable
Shielding	Protect instrument and samples from radiation and heat
Spacecraft RMA	Reactor represents single point-of-failure Class A science mission; RMA critical

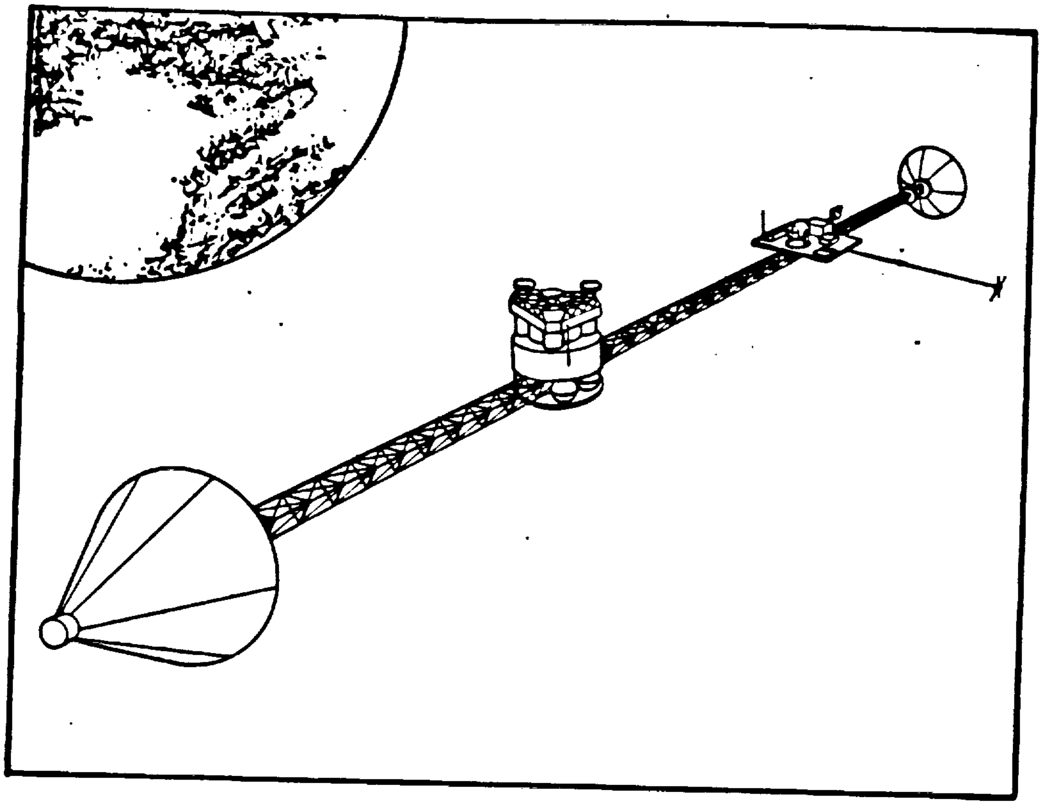


Figure 4-3. Conceptual Illustration of a Mars Surface Sample Return Mission

Table 4-3. Key Parameters for Mars Surface Sample Return Mission

Mission	Collect a sample from the surface of Mars and return it to Earth for analysis and resource evaluation.
Power Requirements	80-100 kW_e
Mission Life	4-5 years launch 2003+
Orbit	Not applicable
Shielding	Protect instruments and samples from radiation and heat
Spacecraft RMA	Reactor represents single point-of-failure Class A science mission; RMA critical

Because of the availability of solar radiation at the orbit of Mars, the Mars Sample Return mission is a strong candidate for non-nuclear implementation; for example, using solar dynamics and Solar-Electric Propulsion (SEP). Solar and chemical alternative scenarios, although viable, have not been considered as a part of this study.

Power for the Mars rover during exploration and in surface sample collection operations is a key issue that has not been addressed in this assessment. The robotic rover may require power in the 5- to 10-kW_e range; this could be provided by either an RTG or a small reactor power system. The assessment provided in Section 5 considers only the NEP-driven requirements of the primary spacecraft.

4.2.3 Observation and Exploration Missions

The Voyager Program has already given scientists an intriguing glimpse of Jupiter, Saturn, and Uranus. Additional orbiters and probes would provide long-term, remote observations of the outer planets. These missions would add to scientists' knowledge and understanding of these planets, their ring systems, and satellites.

4.2.3.1 Saturn Ring Rendezvous/Exploration. This mission will allow detailed observation of the rings of Saturn and studies of their origin, evolution, and composition. The basic mission would be the Saturn Ring Rendezvous Plus Radar, while enhanced options could include a Titan probe, Titan orbiter, and Saturn probe. The scientific objectives of this mission include the following:

- determination of the three-dimensional structure and behavior of Saturn's rings and magnetosphere
- investigation of the chemical composition, physical properties, and dynamical behavior of the atmosphere
- characterization of the physical and chemical properties of the ring particles.

The Saturn orbiter (Figure 4-4 and Table 4-4) arrives at Saturn after seven to ten years, and spirals inward via circular orbit in the ring plane. When the spacecraft reaches the G-ring, which lies approximately 109,000 km above Saturn, it begins to follow a non-Keplerian orbit 18 km above the ring plane, at the inner edge of the D-ring. The spacecraft orbit will pass through the E- and G-rings, and perhaps through the F-ring as well. This will be a hazardous maneuver even though the E- and G-rings are composed of micron-size dust moving at a relative velocity of less than 10 m/s because the E- and G-rings are 1,000-2,000 km thick. Little is known of the composition of the F-ring. Figure 4-5 details the ring structure and the spacecraft approach orbit. It is hoped that the nuclear power system (SP-100 SRPS, which is considered hardened to these low-level dust threats) will provide some dust shield protection to the payload and its instruments.

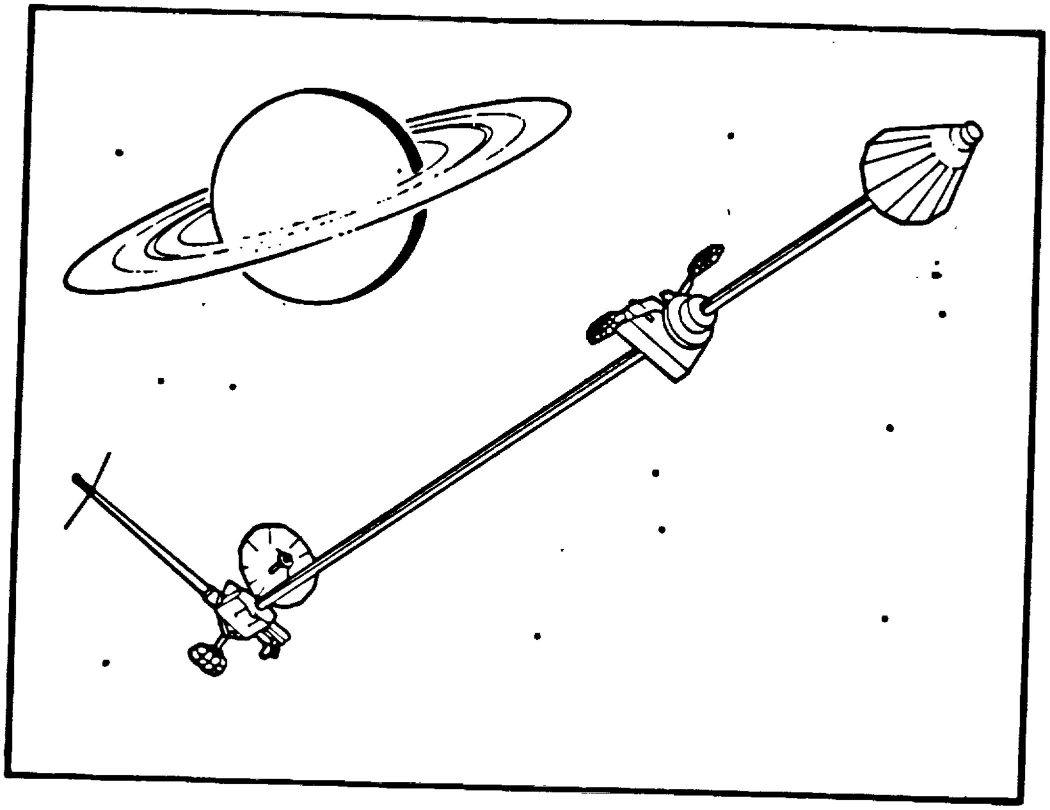
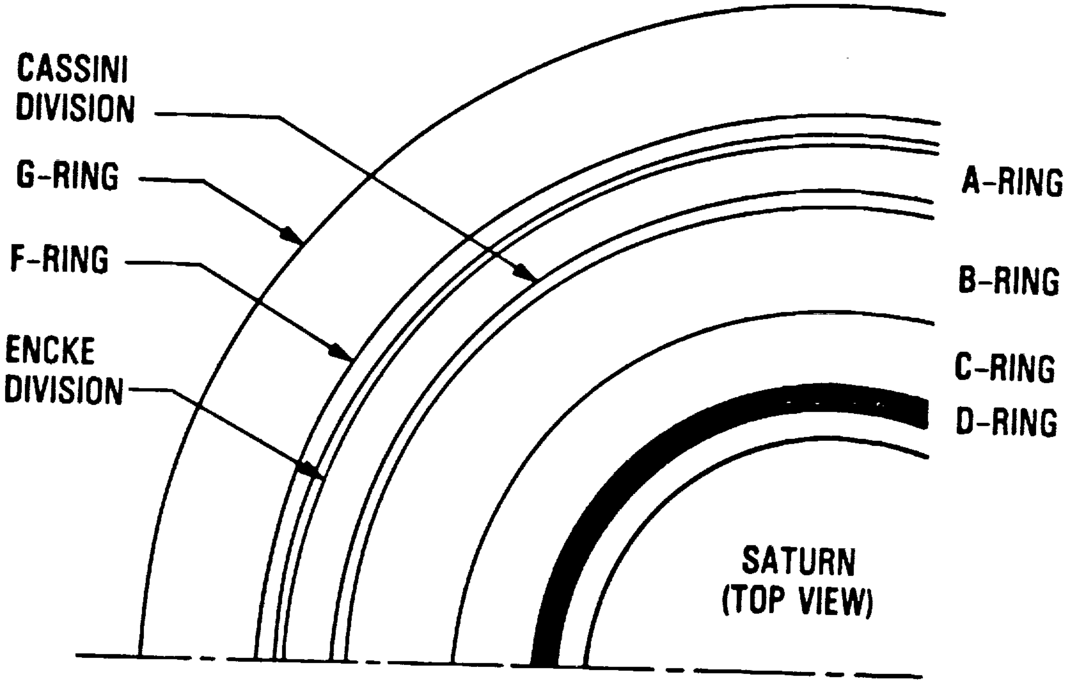


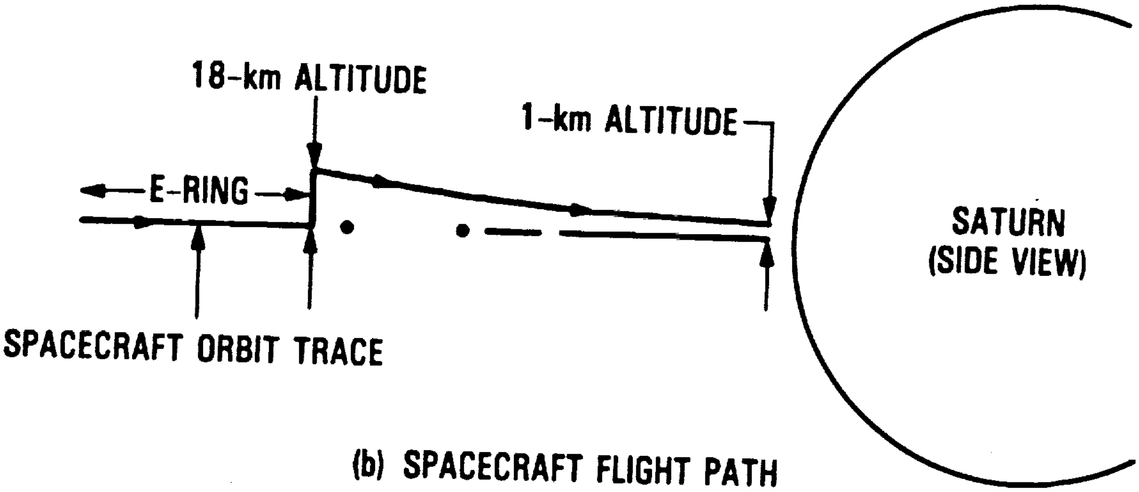
Figure 4-4. Conceptual Illustration of a Saturn Ring Rendezvous/Exploration Mission

Table 4-4. Key Parameters for Saturn Ring Rendezvous/Exploration Mission

Mission	Investigate ring structure and composition. Observe Saturn and Titan.
Power Requirements	80-100 kW_e
Mission Life	9-13 years launch 2005+
Orbit	Not applicable
Shielding	Protect instruments from radiation and heat
Spacecraft RMA	Reactor represents single point-of-failure Class A science mission; RMA critical



(a) SATURN RING PATTERN



(b) SPACECRAFT FLIGHT PATH

Figure 4-5. Saturn Ring Spacecraft Approach Path

4.2.3.2 Far Outer Planets Probes/Orbiters.

The far outer planets (Neptune, Uranus, and Pluto) are the least-explored planets in our solar system. Sending missions to the far outer planets would add to scientists' understanding of these planets and of the formation of the solar system. These missions would include payload packages studying the planets' atmospheres, magnetospheres, composition, and satellites.

The first Far Outer Planets mission would be a flyby/probe of Uranus, to provide a more detailed look at the planet and to continue the reconnaissance work accomplished by Voyager. The spacecraft (see Figure 4-6 and Table 4-5) would be launched from LEO, and would require 8 to 11 years to reach the planet. Follow-up missions might include orbiter/probe missions to Uranus, Neptune, and Pluto/Charon.

4.2.4 Extra-Solar Spacecraft - Thousand Astronomical Units Explorer

In addition to missions directed at the outer planets, space flight is rapidly achieving a level of maturity where missions beyond the boundaries of the solar system will become feasible. The Thousand Astronomical Units (TAU) Explorer will allow precision astrometry for ambitious studies of the universe. Through observations made by TAU, scientists can learn about the distance scale and age of the universe and the structure of the galaxy.

The TAU spacecraft (Figure 4-7 and Table 4-6) is launched during the early 2000's in one or more space shuttle flights. From low Earth orbit, the TAU explorer is deployed from the shuttle or Space Station, remotely activated, and launched. The spacecraft accelerates away from the Earth, leaving the solar system at over 100 km/s. The propulsion phase lasts ten years, after which the SRPS is expended. TAU reaches 1,000 AU from Earth after 55 years. At this point a second SRPS, piggybacking the first, is activated to provide power for scientific observation. From this distance, TAU provides a maximum baseline for parallax measurements and allows more precise astrometry.

As on the other missions, the propulsion and scientific instruments require electric power. However, TAU's propulsion system requires from 300 kW_e to 1 MW_e (depending on the final NEP design) considerably higher than other science missions. This mission is also unique in that it is the only proposed mission to carry out its mission and end its life far outside of the solar system.

4.2.5 Large Space Observatories - Large Array Lunar Observatory

While most of the principle science and exploration missions of the coming decades that will require significant power levels will be spacecraft of varying designs and objectives, large space observatories are also being planned, some of which will require the same high power levels.

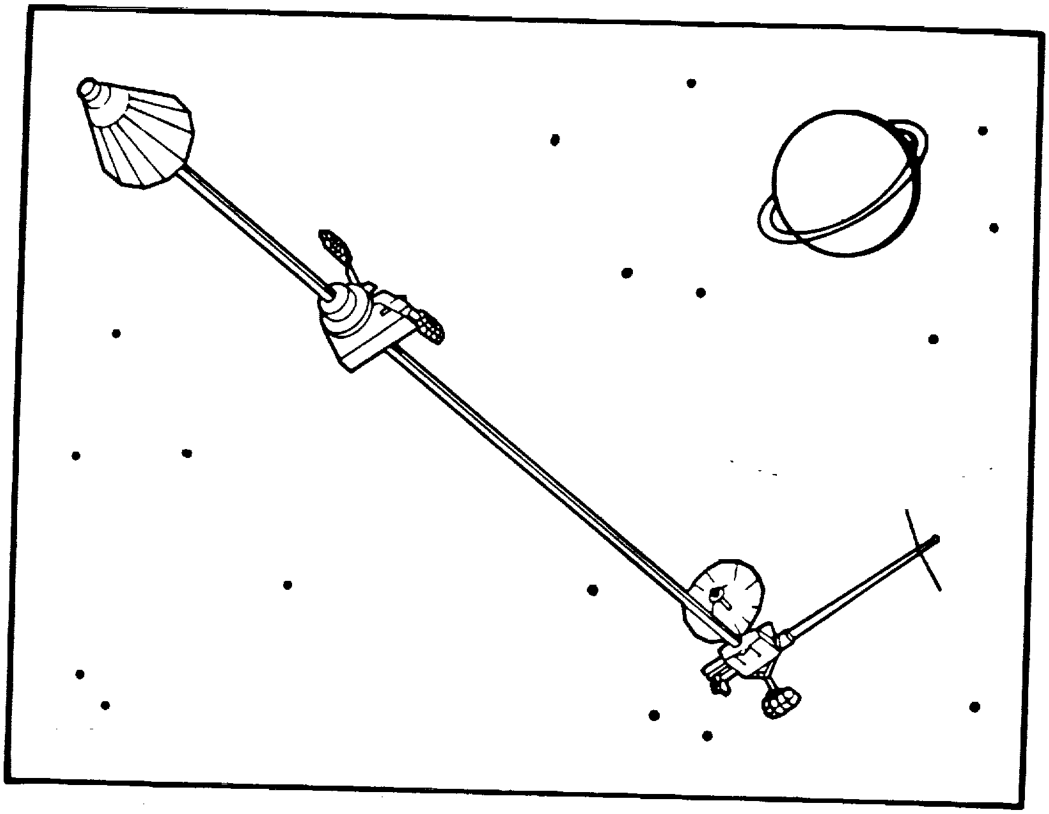


Figure 4-6. Conceptual Illustration of a Far Outer Planets Probes/Orbiter Mission

Table 4-5. Key Parameters for Far Outer Planets Probes/Orbiters Mission

Mission	Conduct scientific exploration of Uranus, Neptune, and Pluto with probes and orbiters.
Power Requirements	80-100 kW_e
Mission Life	8-11 years launches beginning 2010+
Orbit	Not applicable
Shielding	Protect instruments from radiation and heat
Spacecraft RMA	Reactor represents single point-of-failure Class A science mission; RMA critical

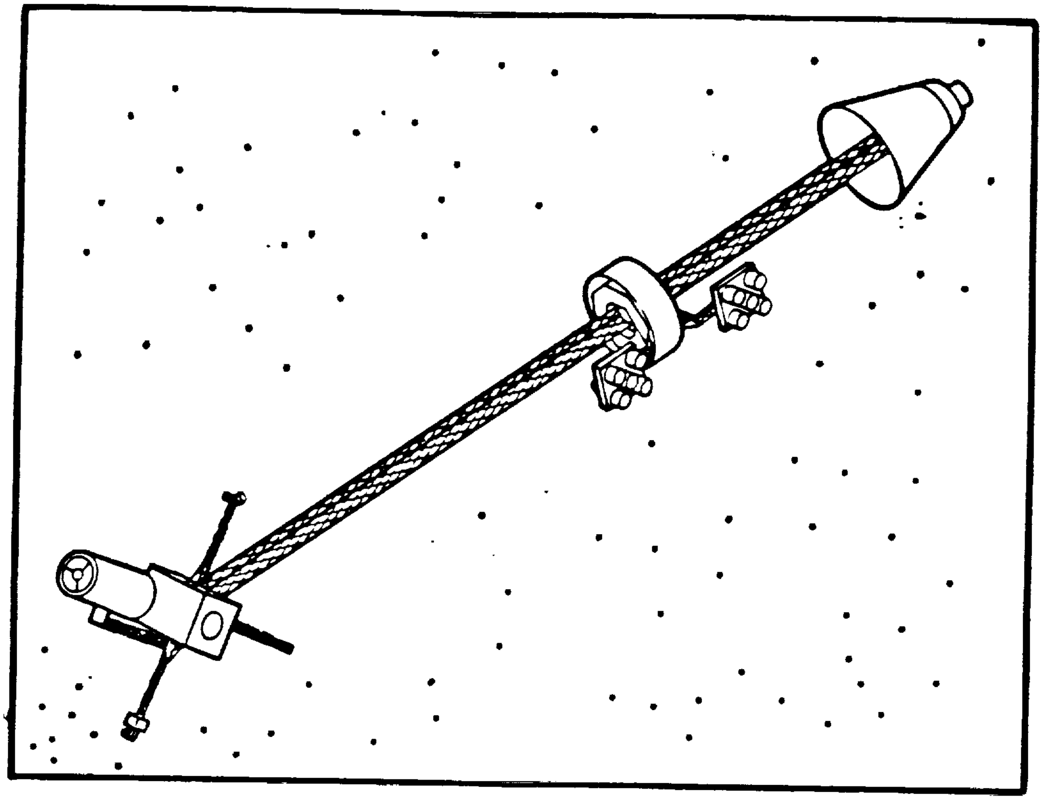


Figure 4-7. Conceptual Illustration of a Thousand Astronomical Unit (TAU) Explorer Mission

Table 4-6. Key Parameters for Thousand Astronomical Unit (TAU) Explorer Mission

Mission	Conduct science and imaging observations and perform astrometry at 1,000 AU from Earth.
Power Requirements	300-1000 kW_e
Mission Life	Indefinite life; reach 1,000 AU in 55 years launch 2010+; 10-year propulsion phase
Orbit	Not applicable
Shielding	Protect instruments from radiation and heat
Spacecraft RMA	Reactor represents single point-of-failure Class A science mission; RMA critical

Following the beginning of operations at the manned Lunar base, and the beginning of surface mining/processing operations, the development and operation of major observatories on the back side of the moon will become feasible. One such concept is the Large Array Lunar Observatory (LALO); this observatory will be utilized in the search for near-by extra-solar planetary systems. The LALO will consist of approximately 100-200 individual reflector/receivers arranged in a five hundred meter circular array. Each receiver will require power and refrigeration systems; for a 160 reflector array the total power requirement is approximately 130 kW_e. Table 4-7 provides several key parameters for the projected large Array Lunar Observatory. Figure 4-8 provides an illustration of the LALO on the Lunar surface.

The LALO will be an unmanned, long-term operational facility. Periodic maintenance, and replacement of the power system will thus be a requirement, but manned proximity operations will not. In the presently envisioned configuration, primary scientific objective of the LALO would be observations of extra-solar planetary systems within a distance of approximately 10 parsecs (33 light years) of the Solar System. This objective results in the large scale of the observatory, the large number of individual receivers, and the high levels of power required.

4.3 SPACE OPERATIONS

This section discusses selected space operations missions during the 1995-2050 timeframe; including most of the planned U.S. inner solar system space infrastructure. This category includes space vehicles and outposts where humans live and work. It also includes the Materials Processing Factory Platform, which is a component of the Space Station, but will be a commercial operation.

4.3.1 Overview

As the United States increases activities in space during the coming decades, new vehicles and bases will be required to support them. The Space Station represents the first logical step in building this infrastructure in space. A wide variety of activities will be conducted from the Space Station, including: (1) spacecraft servicing and staging, (2) astrophysics observations and Earth remote sensing, (3) space technology and engineering research, (4) life sciences research, and (5) commercial research and operations (e.g., materials processing laboratories and factories).

Stepping further away from Earth during the early portion of the 21st century, planetary bases, probably on the moon and Mars, will open up still broader frontiers. The scientific research, and resource exploration and production carried out at these bases will add still further to our knowledge and capabilities.

Table 4-7. Key Parameters for Large Array Lunar Observatory

Mission	Astrophysics observations and the detection of near-by (approximately 30 lightyears) extra-solar planetary systems
Power Requirements	130 kW_e
Mission	Indefinite Life Approximately 2015+
Orbit	Lunar Surface
Shielding	Protect observatory systems from radiation and excess heat; protect periodic manned maintenance crews
Spacecraft RMA	Observatory elements must be accessible for repairs and evolutionary modificaions

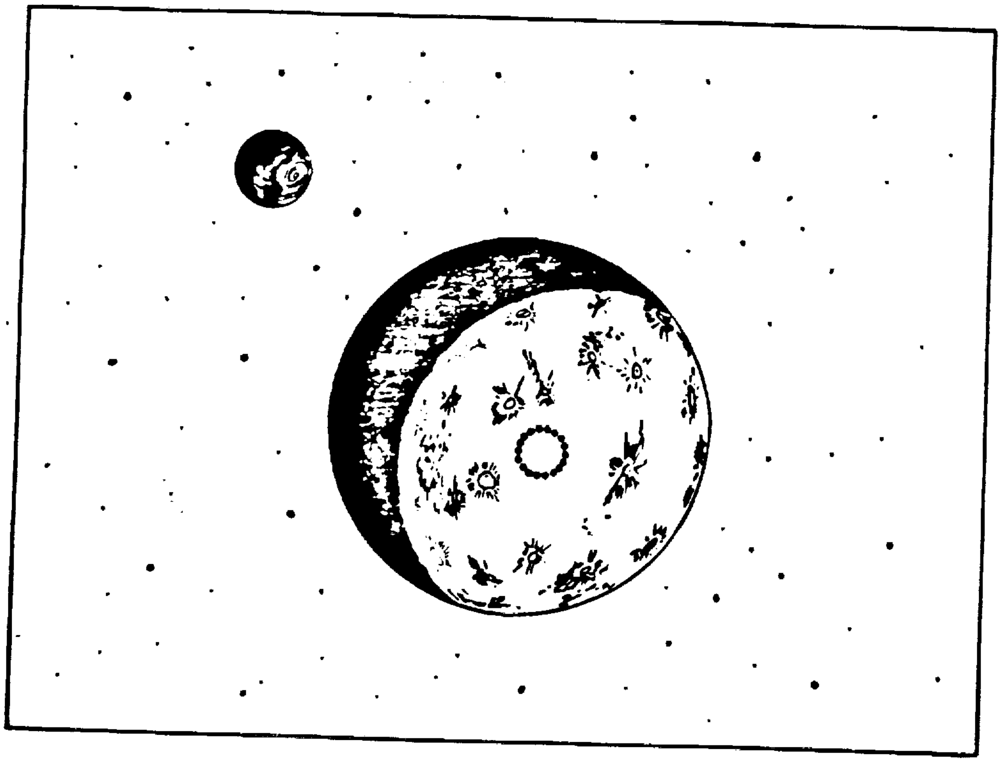


Figure 4-8. Conceptual Illustration of a Large Array Lunar Observatory

A variety of new space vehicles will be developed to support these space activities. Chemically propelled Orbital Maneuvering Vehicles (OMVs) and Orbital Transfer Vehicles (OTVs) will carry personnel and time-sensitive cargo between various Earth orbits. Unmanned nuclear electric OTV's will shuttle non-time sensitive payloads between low Earth orbits (LEO) and geosynchronous orbits (GEO) and the moon. As operations expand, still more advanced vehicles will be developed to carry people and cargo between the Earth-Moon system and Mars.

4.3.2 Space Station

4.3.2.1 Overview. The Space Station will be a permanently manned facility in low Earth orbit (500 km) designed both to satisfy the requirements of the near-term missions and to enable on-orbit evolution to accommodate increasingly complex and ambitious missions. The Space Station will support a variety of users and activities, including U.S. commercial missions, science and application activities, and technology research and development, as well as international participation by Europe, Japan, and Canada. Ultimately, the Space Station complex will consist of a core, permanently manned facility plus remote and co-orbiting free flyers and platforms; chemically propelled Orbital Maneuvering Vehicles (OMVs) and Orbit Transfer Vehicles (OTVs) based at the Station; extensive storage and servicing facilities, and one or more unmanned platforms in polar orbit.

The reference configuration of the core Space Station is the so-called "dual-keel, power tower." This configuration was developed during the 1985-1987 Definition Phase of the Space Station Program and represents the best basis for establishing the scope of Station-based space operations for the 1990s time frame.

In the present configuration, the Space Station will operate in a local vertical/local horizontal orientation, with the primary dual keels along the vertical direction (taking advantage of gravity gradient stabilization to reduce the burden on the attitude control system). Two solar array booms, each accommodating two photovoltaic arrays and one solar dynamic system, will produce an average power level of approximately 75 kW_e. Two U.S. modules - one habitation module and one laboratory module - are planned. Two other modules - one Japanese and one European - will be accommodated on the Initial Operational Capability (IOC) Station. Externally attached payloads, including science, technology, and commercial missions, will be physically located and provided with utilities (such as power, thermal/heat rejection, and data links) at one of several "payload attachment equipment" sites on the primary structure. The IOC reference configuration will accommodate solar-, stellar-, and anti-Earth-pointing, externally attached payloads on the "upper" boom, and Earth-pointing payloads on the "lower" boom of the Space Station. Other payloads, including many projected technology development missions, will be accommodated at various other attached payload locations on the Station's primary structure.

4.3.2.2 Operations. The Space Station will serve as the primary staging site in a developing U.S. space infrastructure, including activities in and beyond low Earth orbit. A variety of launch and resupply vehicles (primarily space shuttles) will link the Space Station to Earth, while OTVs and OMVs (manned and unmanned) will provide transportation between the various orbits and from one spacecraft to another.

The Space Shuttle will provide the basic logistics capability needed to launch food, water, and maintenance supplies to the Space Station. Crews will rotate duty on 90-day cycles. The Shuttle will also deliver equipment and materials required by the laboratories and commercial platforms, and will carry back the finished products and laboratory results. The Shuttle, and perhaps expendable launch vehicles (ELVs), will also launch satellites, spacecraft, and other equipment to be assembled and deployed by the Space Station crew.

The Space Station will provide its crew with life support, medical and recreation facilities, housing, and other needs. The crew, in turn, will repair, maintain, assemble, and deploy spacecraft, tend the companion free-flying platforms, and maintain satellites in orbit (or retrieve them for repair on board the station, if necessary). In addition, the crew will construct and deploy in orbit any assemblies too large or delicate to be launched assembled in a shuttle bay. They could also assemble spacecraft for science and exploration missions if the craft were not to be launched directly from Earth; then they could ferry the craft to high orbit, activate and launch it.

The Station will play a major role in the advancement of space technology and engineering. Some technologies will support the evolutionary development of many of the Space Station's eventual capabilities. For example, OTVs and OMVs to be implemented at the station will support assembly and repair of spacecraft in orbit. Other technologies will be developed on the Space Station for application in a variety of advanced space operations. Areas for future technology development will include advanced ion propulsion, space qualification of advanced electronics, large space structure controls and dynamics, fluid and thermal physics, materials, automation and robotics, and life support systems. In fact, research into long-term life in space will be particularly important, both for Growth Space Station operations and for future manned interplanetary voyages.

4.3.2.3 Space Station Scenario. The Space Station will grow gradually as technologies are developed and user needs expand. The first facility, the "permanently manned capability" (PMC) Space Station, will be constructed in space during 1993-1994. Table 4-8 provides preliminary power requirements for the Space Station PMC configuration. Following PMC, a steady build-up will occur, until the currently planned Initial Operating Capability (IOC) Space Station is achieved (approximately 1995). Table 4-9 provides preliminary power requirements for the Space Station IOC configuration.

Table 4-8. Space Station Permanently Manned Capability (PMC) Power Requirements

Elements	Power Requirements
Habitat Modules - 1 (crew of 4)	10.0 kW_e
Laboratory Modules - 1	15.0 kW_e
Servicing Facility & Systems	5.0 kW_e
Systems (GN&C, C&T, etc.)	10.0 kW_e
Approximate Total Power Requirement:	40.0 kW_e

Table 4-9. Space Station Initial Operational Capability (IOC) Power Requirements

Elements	Power Requirements
Habitat Modules - 1 (crew of 6)	15.0 kW_e
Laboratory Modules - 3	35.0 kW_e
Attached Payload Missions - 5+	10.0 kW_e
Servicing Facility & Systems	5.0 kW_e
Systems (GN&C, C&T, etc.)	10.0 kW_e
Approximate Total Power Requirement:	75.0 kW_e

The IOC Station will continue to evolve during that closing year of the decade to become the projected Growth Space Station. Two alternative scenarios for the Growth Space Station Complex have been considered in this study. In Option 1, it was assumed that all primary Space Station functions will be performed on the core Station platform, including materials processing production operations. Table 4-10 provides preliminary power requirements for the Growth Space Station under Option 1. An illustration of a nuclear-powered Growth Space Station is provided in Figure 4-9. Key parameters for (option 1) Growth Space Station are provided in Table 4-11.

In Option 2, it was assumed that materials processing production operations could, and would, be downloaded onto a specialized, coorbiting platform. Table 4-12 provides preliminary power requirements for the Growth Space Station under Option 2.

Table 4-10. Space Station - Growth Configuration Power Requirements; Option 1: Materials Processing Production Placed on the Core Station

Elements	Power Requirements
Habitat Modules - 2 (crew of 12)	2 x 15.0 kW_e
Laboratory Modules - 5	80.0 kW_e
Materials Processing Production Units	140.0 kW_e
Attached Payload Missions - 10+	20.0 kW_e
Servicing Facility & Systems	30.0 kW_e
Systems (GN&C, C&T, etc.)	30.0 kW_e
Approximate Total Power Requirement:	330.0 kW_e

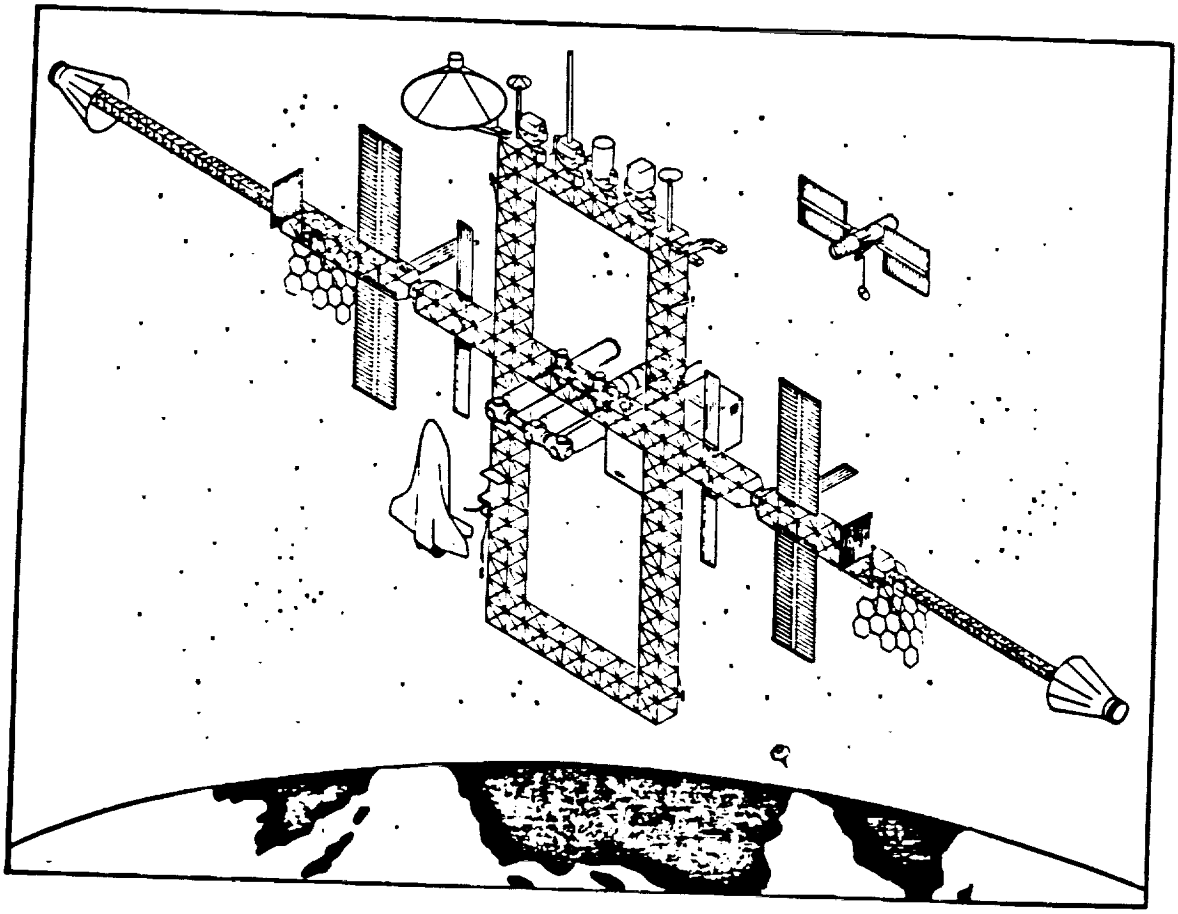


Figure 4-9. Conceptual Illustration of a Nuclear Powered Growth Space Station

Table 4-11. Key Parameters for Growth Space Station (with materials processing production)

Mission	Provide a permanently manned base for planetary staging operations, spacecraft assembly, materials processing research, and other development work. The Growth Space Station will include various satellites and platforms.
Power Requirements	330 kW_e
Mission Life	2000 - 2015+
Orbit	Low earth orbit of 500 km
Shielding	Protect crew, instruments, and experiments from radiation and heat; serious proximity operations concerns
Spacecraft RMA	Crew must be able to maintain the space station Spacecraft must be able to approach the base

Table 4-12. Space Station - Growth Configuration Power Requirements; Option 2: Materials Processing Production Placed on the MPFP

Elements	Power Requirements
Habitat Modules - 2 (crew of 12)	2 x 15.0 kW_e
Laboratory Modules - 5	80.0 kW_e
Attached Payload Missions - 10+	20.0 kW_e
Servicing Facility & Systems	30.0 kW_e
Systems (GN&C, C&T, etc.)	20.0 kW_e
Approximate Total Power Requirement:	180.0 kW_e

After some period of operations, the Growth Space Station will be replaced by more Advanced Space Station configuration. The Advanced Space Station(s) will continue the basic LEO operations of the initial Space Station complex, but with increased emphasis on very-long duration manned operations in support of manned and unmanned mission staging, and also servicing and maintenance support for the Earth-Moon space infrastructure. Table 4-13 provides preliminary power requirements for the Advanced Space Station concept. Those requirements are based upon the assumption that Option 2 - downloading of materials processing production units to a coorbiting platform - has been pursued.

Using the mission requirements listed in Space Station Mission Requirements Data Base (MRDB) and reasonable assumptions regarding the availability of the space shuttle fleet for Space Station user mission logistics flights, a JPL-developed simulation program, the Mission Forecast Program, was used to develop synthesized user requirements for electrical power for both the IOC and Growth Space Station Periods. Figure 4-10 presents the MFP-synthesized mission user requirements for electrical power aboard the Space Station during the 1990s and the early years of the next century (for Option 2).

As described above, the current IOC Space Station reference configuration does not incorporate the utilization of an SRPS for electrical power generation; the Space Station depends instead upon photovoltaic and solar dynamic engine solar arrays for power. Although the Growth Space Station may require power levels of approximately 300 kW_e, concerns remain regarding low Earth Orbit disposal of an SRPS under emergency conditions and also the issue of SRPS shielding. In the latter case, near-continuous crew extravehicular activity (EVA) and regular space shuttle proximity operations create a potentially unacceptable shield mass/configuration requirement for a reactor system. However, as discussed above, commercial materials processing missions may be placed aboard the Space Station or on coorbiting platforms. A Materials Processing Factory Platform (MPFP) could be an important commercial activity for the Growth Space Station. This concept is discussed in Section 4.3.3.

Table 4-13. Space Station Complex - Advanced Station Power Requirements (without on-board materials processing production units)

Elements	Power Requirements
Habitat Modules - 8 (crew of 48)	8 x 15.0 kW_e
Laboratory Modules - 7	180.0 kW_e
Attached Payload Missions - 15+	40.0 kW_e
Servicing Facility & Systems	80.0 kW_e
Systems (GN&C, C&T, etc.)	50.0 kW_e
Approximate Total Power Requirement:	470.0 kW_e

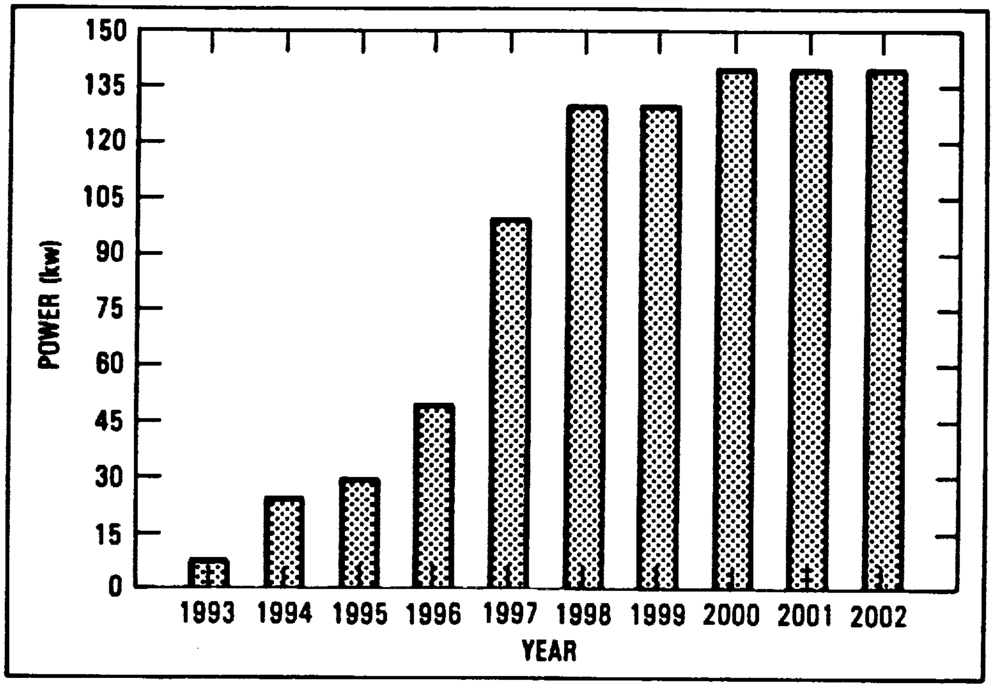


Figure 4-10. Core Space Station (IOC and Growth) Mission User Power Requirements (without materials processing production units)

4.3.2.4 Space Station Complex: Geosynchronous Orbit. In addition to the evolving system of manned and unmanned platforms that will constitute the Space Station complex in low earth orbit, a Space Station-derived, man-tended platform will be established at a geosynchronous Earth-orbit. This platform will serve as a way-station and supply/servicing depot for various Earth-Moon system operations. (Note: in alternative scenarios, the GEO Space Station could replace many of the functions projected for the L1 Libration Base; in this assessment it is assumed that one such point will be fully developed while the other serves only a limited role. The Libration Base was selected for the sake of this analysis.) The power requirements for a man-tended, depot-oriented platform are in the 10-40 kW_e range, hence no analysis of this element of the infrastructure is provided in this report.

4.3.3 Materials Processing Factory Platform

4.3.3.1 Overview. The Materials Processing Factory Platform (MPFP) concept would place a research and manufacturing facility coorbiting with the Growth Space Station. The MPFP would enable researchers and manufacturers to examine long-duration, ultralow acceleration materials processing (both basic research and production operations). By eliminating gravitational effects, the MPFP would allow the production of materials which cannot be cost-effectively made on Earth, as well as conduct research to improve terrestrial materials processing techniques and products as more is learned about the basic properties involved. Section 4.3.3.2 describes the MPFP. Section 4.3.3.3 discusses likely materials processing activities.

4.3.3.2 Platform Operations. The MPFP would be one of the many components of the Growth Space Station System infrastructure. The platform would be tended from the Space Station, but would be a separate structure; one reason for this separation is that most of the experiments and operations aboard the MPFP require microgravity conditions (10^{-3} to 10^{-5} g or less). Docking spacecraft and other common operations at the Space Station could disturb the crucial microgravity environment. Isolating potentially noxious materials or processes on a coorbiting platform protects the crew in the event of an accident.

The MPFP would coorbit with the Space Station in LEO (potentially "formation flying"), providing a microgravity environment with low cost, frequent access to station personnel. The MPFP would have multipurpose laboratory equipment as well as facilities for commercial production modules. Protecting proprietary data and products will be vital to the success of the MPFP. The current platform concept has high power and thermal requirements; these power needs include furnaces, positioning systems, and refrigeration.

4.3.3.3 Materials Processing in Space. Space-based materials processing appears to be especially promising for crystal growth products, glasses and fibers, and biological materials. Other areas of microgravity research may include chemical processes, separation sciences, containerless processing, and fluid studies.

The production of semiconductor and metallic materials can be vastly improved in space. The quality of metals and semiconductor crystals is significantly better when they are processed under microgravity conditions, and the absence of thermal convection provides for the production of larger, more uniform crystals at higher growth rates than are possible on Earth.

Several processes can be used to grow crystals. (Appendix A provides more information.) Two of the methods use a furnace, one to melt the material and the other to control the crystal growth temperature. Both processes require almost continuous power use. A third method uses vapor transport and a temperature gradient to form the pure crystalline product.

Microgravity conditions may prove advantageous to biological material processing. The usefulness of many biological materials depends on the degree to which they can be concentrated and purified. Under full gravity, thermal and buoyance-driven convective forces limit the purity of the separation products. Eliminating the convective forces can greatly enhance the sharpness of separation and can increase the concentration of the product.

Pharmaceutical separation could provide a near-term commercial product of space-based materials processing. Other biological products may include hormones, cells, and interferon.

Microgravity processing makes possible containerless processing and higher quality glasses. Molten glass can be supercooled farther under microgravity than on Earth, resulting in a lower level of crystalline structure and more ideal glassy properties. Space-processed glasses will probably be used for products requiring high purity, such as optical fibers. Optical glasses for lenses and mirrors may be another space product, since the low level of crystallization would provide higher quality image processing.

Containerless processing generates more ideal glassy properties and may produce unique glasses, impossible to duplicate on Earth. Under microgravity conditions, fluids tend to form large globules which float whole in space. Materials can be melted and resolidified without ever contacting the container walls. This decreases the opportunities for contamination and increases glass quality.

4.3.3.4 Materials Processing Factory Platform Scenario. Using the mission requirements stated in the Space Station MRDB and the MFP simulation program (see Section 4.3.2), mission user power requirements for a commercial MPFP in the Growth Space Station era were synthesized. The detailed results of that analysis appear in Figure 4-11. Table 4-14 provides preliminary power requirements for the Materials Processing Factory Platform. Figure 4-12 provides a conceptual illustration of the MPFP in LEO, while Table 4-15 summarized key parameters for the platform.

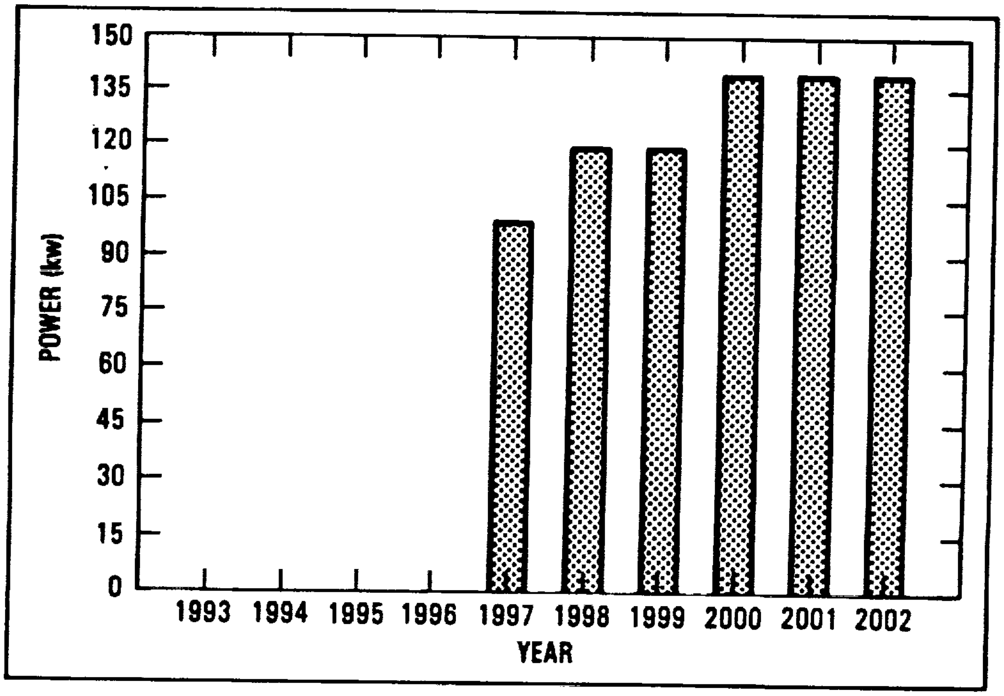


Figure 4-11. Materials Processing Factory Platform Mission User Power Requirements

Table 4-14. Materials Processing Factory Platform Power Requirements

Elements	Power Requirements
Full Scale Modules - 4	4 x 30.0 kW_e
Half-Scale Production Modules - 2	2 x 10.0 kW_e
Logistics Modules - 2	2 x 5.0 kW_e
Systems (GN&C, C&T, etc.)	10.0 k_{We}
Approximate Total Power Requirement:	160.0 k_{We}

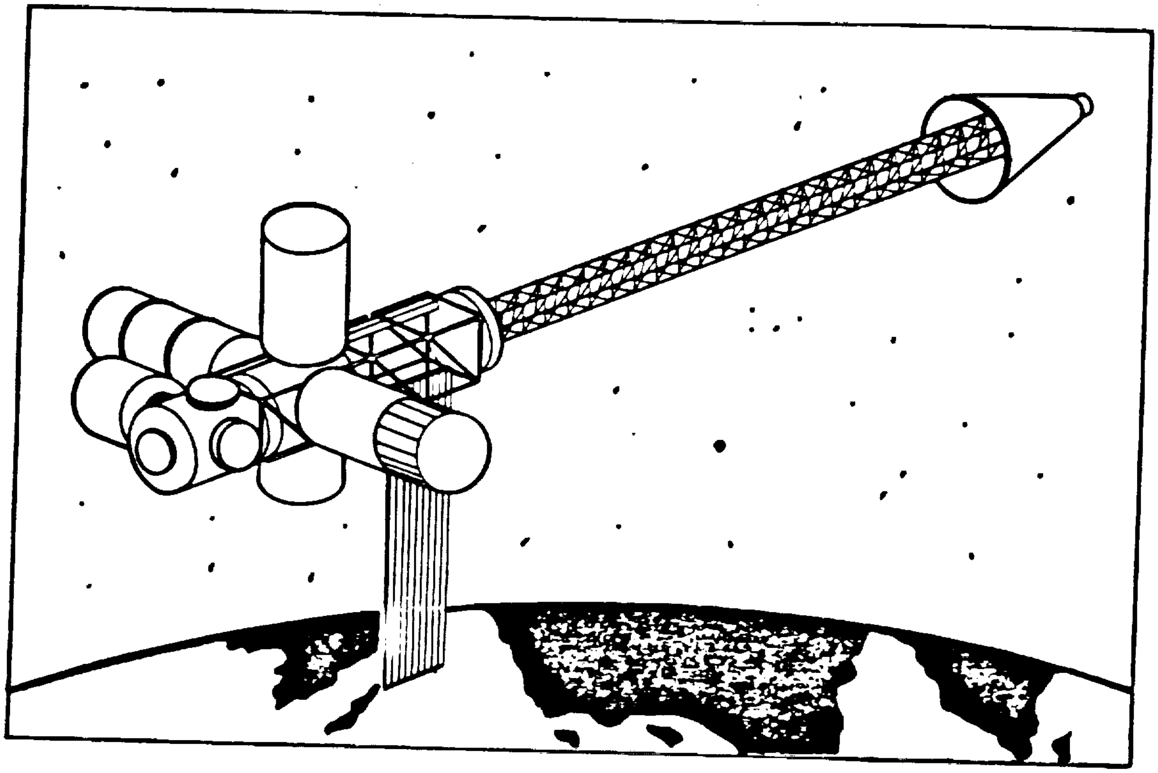


Figure 4-12. Conceptual Illustration for a Materials Processing Factory Platform

Table 4-15. Key Parameters for Materials Processing Factory Platform

Mission	Accommodate those Space Station missions involving commercial materials processing operations (assumed to be free-flying).
Power Requirements	160 kW_e
Mission Life	Varies; long-duration commercial operations 2000+
Orbit	Coorbit with Space Station
Shielding	Protect biological materials and crew from radiation and heat
Spacecraft RMA	Accessibility important (human-tended)

4.3.4 Lunar Settlement

4.3.4.1 Overview. Just as the space station will grow through stages, so will human settlements on the Moon. First will come the preparatory missions - probes, prospectors, and sample return missions to expand our present knowledge of the Moon. Camps will be established on the Moon at promising sites, along with a permanently occupied initial operational camp which will grow into the nominal operational base. The settlement's third and final stage will be the colony, or growth operations stage. The colony will attempt a closed-ecology life support system to the greatest feasible extent, using on-site materials to supply its needs.

4.3.4.2 Preparatory Stage. While the Apollo Program and other missions returned useful data from the Moon's surface, the data is highly incomplete. Sample data is limited for the near side, and nonexistent for both the far side and the potentially important polar regions. Photographic and chemical surveys of the Moon are incomplete for the far side and very limited for the polar regions. In order to remedy this situation, probes, prospectors, and sample return missions will survey the lunar surface and investigate locales of particular interest. The resulting data will be used to select sites for further investigation and for future bases and operations posts.

Following analysis of the data gathered by the unmanned missions, manned lunar explorations will continue, and camps will be established at interesting sites. These camps may be separated according to activities, as some research activities or operations may interfere with others. Seismologists, for example, will need to be far away from mining operations and spacecraft landing areas in order to minimize seismic noise produced by these activities. As research and exploration continue, some sites may be found to be more valuable than others, and the temporary camps located at these sites will be enlarged. Some of these initial outposts will become permanently occupied lunar camps.

4.3.4.3 Base Development Stages. As scientists and explorers remain on the Moon for longer periods, they will require larger, permanent bases. Such bases will have supply centers, research labs, recreational facilities, medical centers, spacecraft landing areas, and vehicle repair and refueling facilities. The bases will house support staff and will serve as the explorers' lunar home, to which they will return between visits to operations or research outposts.

The first lunar camp may be constructed from habitation modules similar to those used for the space station. These modules will include living and recreation areas, health maintenance facilities, and the necessary command/control stations. (Some modifications may be required so that these modules, which were originally designed for microgravity conditions aboard the space station, can operate properly under lunar gravity.)

Developing indigenous lunar resources will be necessary for extensive lunar exploration, settlement, exploration, and commercial enterprises. Using lunar materials will significantly reduce the base's transportation costs and dependence on supplies from Earth.

The lunar soil can provide many useful products and can itself be used for construction, such as in mixing concrete. Recent studies have shown that concrete made from lunar soil behaves like high-quality concrete made from Earth materials and is 5 percent stronger than ordinary concrete. Moreover, the lunar soil can provide shielding for Moon buildings and vehicles from solar flares and other radiation. Using lunar materials would avoid a substantial transportation cost; the amount of shielding needed to protect six astronauts from solar flares would fill some three shuttle payloads and would weigh at least 85 metric tons.

Several means, including a nuclear power system, have been suggested for meeting the power requirements of an inhabited lunar base, including a nuclear power system. One ELV or STS could transport the reactor subsystem of an SRPS from Earth. To transport shielding and other subsystems would take another two or three STS or ELV launches. Using lunar surface materials for shielding, however, might permit a single STS/ELV launch for the entire SRPS.

Mining lunar materials may well play a major role in the development of space operations. The tremendous cost of transporting materials from Earth would consume resources which could otherwise be applied to operations and to developing advanced technologies. Lunar materials may supply propellant for OTVs, oxygen for life support systems, metal for spacecraft production, and raw soil for radiation shielding.

The surface of the Moon is covered with a layer of fine powder, from tens to hundreds of meters thick. The lunar highlands, about 80 percent of the Moon, are rich in calcium and aluminum. The flat, low plains of the Moon's near side have abundant titanium, magnesium, and iron, while many of the lunar rocks and soils contain silicon. The permanently shadowed craters at the lunar poles may hold deposits of water ice and and carbonaceous materials.

The lunar rocks and soil could be fused to produce glass and ceramic products, using existing terrestrial technology. The metals, ceramics, and glasses could be used for buildings, machines, and communications lines. The silicon could be manufactured into solar cell panels. The iron and aluminum could be used for electrical conductors and along with titanium, for structural members in construction.

4.3.4.4 Lunar Bases Scenario: Lunar Surface. Human settlements on the Moon will grow through several stages, expanding from an initial camp to a lunar colony. The base could grow in many different ways. The following scenario presents one such way, describing the gradual increase in crew, power requirements, structures, and activities as the base grows.

Lunar Initial Operational Camp - The initial operational camp (see Table 4-16) will have a staff of six people and would require some 60 kW$_e$ of power. The camp will consist of one habitat module, and a logistics module. The logistics module will serve as a ferry, carrying humans and cargo between the Moon and the space station. The logistics module will be attached to the lunar camp modules on arrival and draw power from the modules for life support, pressurization, and operations while it remains at the base. The camp will also have the necessary operations hardware, including a fuel depot and communications equipment. A breakdown of key parameters is shown in Table 4-17. A preliminary scenario involving production of oxygen from lunar materials has been assumed, with pilot plant operations producing approximately 5 tons/year for the stated power requirement.

Table 4-16. Lunar Initial Camp Power Requirements

Elements	Power Requirements
Habitat modules - 1 (crew of 6)	1 x 15.0 kW_e
Laboratory modules - 1	15.0 kW_e
Logistics modules	2.5 kW_e
Operations hardware (comm., fuel depot)	2.5 kW_e
Lunar Materials Processing Equipment	25.0 kW_e
Approximate Total Power Requirement:	60.0 kW_e

Table 4-17. Key Parameters for Lunar Initial Camp

Mission	Human settlement on the lunar surface will provide a base for exploration, mining, surface materials processing, and research.
Power Requirements	60 kW_e
Mission Life	3 years Approximately 2000-2003
Orbit	Not applicable
Shielding	Protect crew, instruments, and experiments from radiation and excess heat
Spacecraft	Base must be accessible to orbital and lunar craft
RMA	Crew must be able to make repairs

Lunar Nominal Base - After about three years, the initial operational camp will grow into the nominal base The base will have twelve crew members, two habitat and laboratory modules, and two logistics modules and require 200 kW_e of power.

The materials processing plants would use most of the power at the nominal operations base. They would extract elements from the lunar soil for use by the base and its vehicles. The processing plants would be an early step in reducing the base's dependency on Earth.

The base will also have a lunar materials handling equipment for lunar soil processing. This equipment might package lunar surface materials and export them for use as radiation shielding on Earth-orbiting satellites and other spacecraft. A breakdown of lunar base power requirements is given in Table 4-18. A preliminary scenario involving concurrent extraction of oxygen and other minerals from lunar materials has been assumed, with processing operations producing approximately 30 tons of oxygen/year and 30 tons of other minerals/year for the stated power requirement. A conceptual illustration of the Lunar Nominal Base is provided in Figure 4-13; key parameters for the base are summarized in Table 4-19.

Lunar Operational Base - After about four years, the base will have grown to six habitat modules and 24 crew members and use some 310 kW_e per year. There will be two laboratory modules, four logistics modules, four lunar materials handling plants, and six lunar materials processing plants. The lunar operational base would actively mine lunar materials. It would produce not

Table 4-18. Lunar Nominal Base Power Requirements

Elements	Power Requirements
Habitat modules - 2 (crew of 12)	2 x 15.0 kW_e
Laboratory modules - 2	2 x 15.0 kW_e
Logistics modules - 2	2 x 2.5 kW_e
Operations hardware (comm., fuel depot)	5.0 kW_e
Lunar materials handling equipment	10.0 kW_e
Lunar materials processing equipment	120.0 kW_e
Approximate Total Power Requirement:	200.0 kW_e

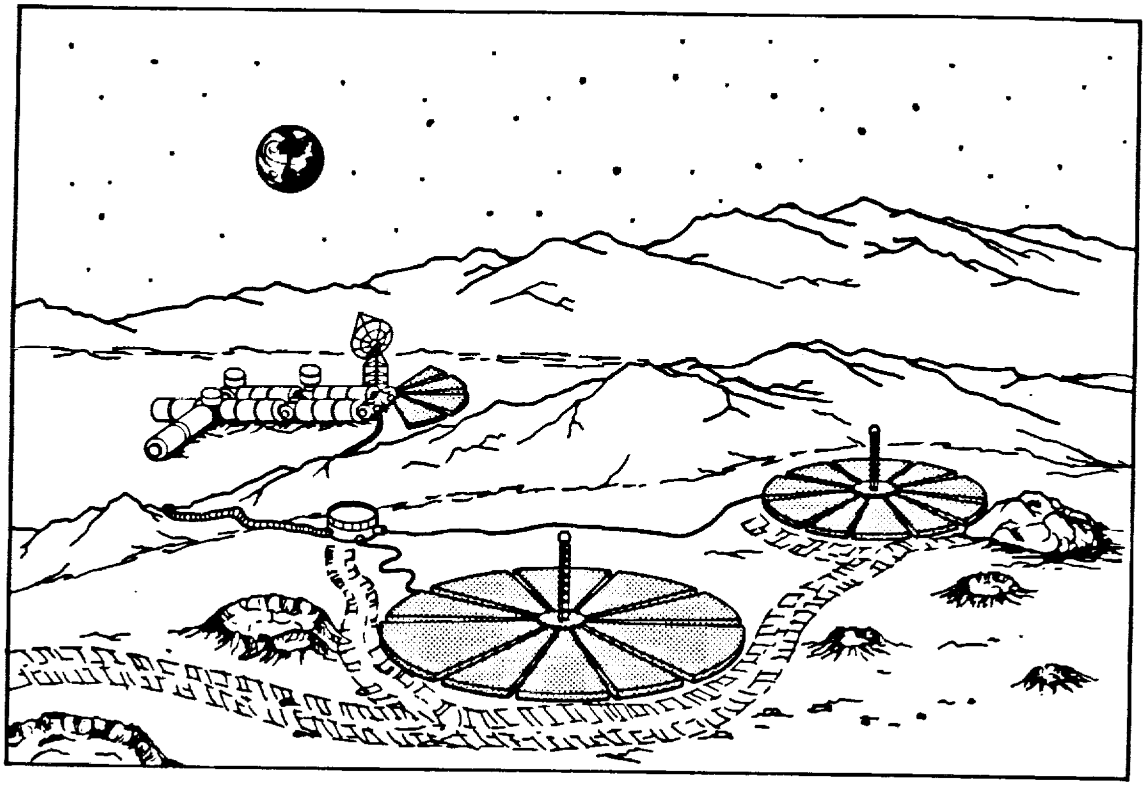


Figure 4-13. Conceptual Illustration of a Lunar Nominal Base

Table 4-19. Key Parameters for Lunar Nominal Base

Mission	Human settlement on the lunar surface will provide a base for exploration, mining, surface materials processing, and research.
Power Requirements	200 kW_e
Mission Life	4 years Approximately 2003-2007
Orbit	Not applicable
Shielding	Protect crew, instruments, and experiments from radiation and excess heat
Spacecraft RMA	Base must be accessible to orbital and lunar craft Crew must be able to make repairs

only ore and other raw materials for export, but also would have begun to produce manufactured products. The lunar operational base will be an important first step onto the "Bridge Between Worlds" (as described by the National Commission on Space), opening the solar system to human exploration and settlement. The Moon is an accessible, relatively short flight from Earth. The lunar base will provide a "concept test" for planetary colonies, determining people's needs for long-duration planetary settlements. The technology used on the Moon will build on the experience gained at Antarctica and on the Space Station. In turn, the lunar technology could be improved and exported, to a colony on Mars, to the solar system, and beyond. A breakdown of power requirements is given in Table 4-20. A scenario involving concurrent extraction of oxygen and other minerals from lunar surface materials has been assumed, yielding materials processing operations that would produce approximately 90 tons of oxygen/year and 90 tons of other minerals for the stated power requirement. A summary of key parameters is provided in Table 4-21.

Lunar Growth Colony - During the course of operations (perhaps following the first twenty years), the lunar operational base will evolve into a self-sustaining Lunar colony. The colony will consists of a complex of ten habitat modules, four laboratory modules, eight logistics modules, and sixteen lunar materials processing and handling plants. The lunar growth colony continues and builds upon the role of the lunar operational base in the development of manned inner solar system infrastructure; the colony incorporates an electromagnetic launch system which boosts processed lunar materials to the libration point base for use in construction/shield-mass applications. A breakdown of power requirements is provided in Table 4-22. By the 2035 timeframe, an oxygen (in addition to other minerals) production capability of approximately 200 tons/year has been assumed, yielding the stated power requirements. Table 4-23 provides several key parameters for the projected lunar growth colony.

Table 4-20. Lunar Operational Base Power Requirements

Elements	Power Requirements
Habitat modules - 6 (crew of 24)	6 x 15.0 kW_e
Laboratory modules - 2	2 x 15.0 kW_e
Logistics modules - 4	4 x 2.5 kW_e
Operations hardware (comm., fuel depot)	10.0 kW_e
Lunar materials handling equipment	30 kW_e
Lunar materials processing equipment	360 kW_e
Approximate Total Power Requirement:	500.0 kW_e

Table 4-21. Key Parameters for Lunar Operational Base

Mission	Human settlement on the lunar surface will provide a base for exploration, mining, surface materials processing, and research.
Power Requirements	500 kW_e
Mission Life	Approximately 20 years 2010 - 2030
Orbit	Not applicable
Shielding	Protect crew, instruments, and experiments from radiation and excess heat
Spacecraft RMA	Base must be accessible to orbital and lunar craft Crew must be able to make repairs

Table 4-22. Lunar Growth Colony Power Requirements

Elements	Power Requirements
Habitat Modules - 10 (crew of 48)	10 x 15.0 kW_e
Laboratory Modules - 4	4 x 15.0 kW_e
Logistics Modules - 8	8 x 2.5 kW_e
Operational Hardware (comm., fuel depot)	20.0 kW_e
Lunar materials handling equipment	50.0 kW_e
Lunar materials processing equipment	800.0 kW_e
Approximate Total Power Requirement:	1100.0 kW_e

Table 4-23. Key Parameters for Lunar Growth Colony

Mission	Human settlement on the lunar surface will provide a base for exploration, mining, surface materials processing, and research.
Power Requirements	1100 kW_e
Mission Life	Indefinite Approximately 2030+
Orbit	Not applicable
Shielding	Protect crew, instruments, and experiments from radiation and excess heat
Spacecraft RMA	Base must be accessible to orbital and lunar craft Crew must be able to make repairs

4.3.4.5 Lunar Bases Scenario: Libration Base. Concurrently with the development of settlements on the surface of the Moon, an advanced space station/base will be established at the "L1" Earth-Moon libration point. This base - which will be constructed in large measure from materials mined/ transported from the Moon - will consist of a complex of three large habitat modules, one laboratory module, two logistics modules, and a variety of advanced spacecraft assembly and servicing facilities. The base is part of the developing manned inner solar system infrastructure, and supports the settlement of Mars and the utilization of Lunar materials throughout the infrastructure. A preliminary breakdown of power requirements for the Libration Base is provided in Table 4-24. Table 4-25 provides several key parameters for the projected Earth-Moon Libration Base.

4.3.5 Mars Settlement

4.3.5.1 Overview. Human settlements on Mars will also progress through stages and will take advantage of lessons learned by the lunar colony. The initial operational camp will be the first settlement established on the Mars surface. The camps will grow into the nominal operational base, and finally will reach the colony, or growth operations, stage.

4.3.5.2 Preparatory Stage. Previous missions have provided some data about the nature and composition of Mars. The database includes global photomaps of Mars and a series of very high-resolution, contiguous images taken by Viking to investigate potential sites for sample return landers. In addition, the two Viking spacecraft performed chemical and biological experiments on the Mars surface.

Table 4-24. Libration Point Base Power Requirements

Elements	Power Requirements
Habitat Modules - 3 (crew of 36)	3 x 20.0 kW_e
Laboratory Modules - 1	1 x 15.0 kW_e
Logistics Modules - 2	2 x 2.5 kW_e
Attached Payload Missions - 5+	10.0 kW_e
Servicing Facility & Systems	50.0 kW_e
Systems (GN&C, C&T, etc.)	20.0 kW_e
Approximate Total Power Requirement:	160.0 kW_e

Table 4-25. Key Parameters for Libration Base

Mission	Space station/base at the L1 Earth-Moon Libration Point; staging point for transportation between LEO/GEO operations and Earth-Mars transportation, as well as limited scientific research operations.
Power Requirements	160 kW_e
Mission Life	Indefinite Life Approximately 2030+
Orbit	Lunar
Shielding	Protect crew, instruments, and experiments from radiation and excess heat
Spacecraft RMA	Base must be accessible to orbital and lunar craft Crew must be able to make repairs

Future missions will add more data. A Soviet spacecraft will approach Mars' moons, Phobos and Deimos, in 1989, and will carry out chemical analyses of those moons. The Mars Surface Sample Return mission, planned for launch around 2000, will bring back a sample of Martian soil. Other sample return missions would collect materials from the Martian moons as well. Robotic hard landers would analyze surface and subsurface soils for water and other materials important to the establishment of Mars settlements.

The data provided by these missions will aid in selecting sites rich in useful raw materials and in scientific interest. Research efforts could then be concentrated at the most promising sites, and human settlements located near the indigenous resources.

4.3.5.3 Base Development Stage. Since Mars is so much farther from Earth than the Moon, the first Mars settlers will arrive in a group and build the first centrally located base. Such a base will support humans in exploration, research and daily life, with facilities similar to those at the lunar colony.

The first Mars camp will be constructed from habitation modules similar to those used for the Space Station. The camp will be established about 2005, around the middle of the lunar colony's nominal operational base phase. The Martian colony will be able to improve on the habitation modules, construction techniques, etc., first used at the lunar base.

Developing Martian resources will be even more vital for the Mars base than for the lunar colony, because of its increased distance from Earth. Scientists expect to find carbon, nitrogen, and hydrogen on Phobos. They expect that the polar caps consist of carbon dioxide and water ice. The atmosphere may supply carbon dioxide, oxygen, hydrogen, as well as traces of nitrogen and argon.

As on the Moon, native materials such as the ones mentioned above could be used by the Mars base. For example, the oxygen and hydrogen could be used in the base's life support system or for rocket propellant. As in the moon base, raw Martian soil could be used for shielding the base against solar flares and other radiation.

4.3.5.4 Mars Bases Scenario: Phobos Base. Concurrently with the development of the first settlements on the surface of Mars, a base will be established on the surface of Mars' moon, Phobos.

Evidence gathered during Viking mission operations indicates that Phobos, with a mean density of 2 g/cm^3, a low albedo, and a spectral reflectance similar to that of Ceres, may well be composed of a water-rich, carbonaceous chondrite-like material. (Similar information on Mars' second moon, Deimos, is inconclusive.) Thus, Phobos represents an excellent site for a multipurpose, manned base. The Mars/Phobos base will strongly support the development of the manned inner solar system infrastructure and the settlement of Mars; it could support mining and fuel production and storage, as well as spaceport functions.

The projected base will consist of a complex of two habitat modules, one laboratory module, four logistics modules, a mining system, and one associated materials handling plant. An initial breakdown of power requirements for the base is provided in Table 4-26. Table 4-27 provides several key parameters for the projected Mars/Phobos base.

In addition to the various ambitious civil space missions that are discussed in this report, an additional mission which may contribute to the development of a U.S. inner Solar System infrastructure is Asteroid Mining. Asteroid mining (whether within the main belt or targeted on specific near-Earth asteroids) could yield substantial mineral and propellant resources; however, this mission application is not discussed further in this report. The physical characteristics of Phobos and Deimos - i.e., low-density, water-rich material - suggests that they may well be captured asteroids rather than proper satellites of Mars. Hence, requirements for asteroid mining applications would be generally similar to those specified for Mars/Phobos settlement/mining operations. (One possible exception would be mass driver operations - if the entire asteroid were to be moved into a more accessible orbit prior to exploitation.)

4.3.5.5 Mars Bases Scenario: Mars Surface. Human settlements on Mars will progress in stages, but could develop in many different ways. The following growth scenario describes the gradual increase in crew, activities, structures, and power requirements.

Table 4-26. Mars/Phobos Base Power Requirements

Elements	Power Requirements
Habitat Modules - 2 (crew of 8)	2 x 10.0 kW_e
Laboratory Modules - 1	1 x 15.0 kW_e
Logistics Modules - 4	4 x 2.5 kW_e
Operational Hardware (comm., fuel depot)	20.0 kW_e
Mining Systems - 1	35.0 kW_e
Phobos materials handling plants - 1	50.0 kW_e
Approximate Total Power Requirement:	150.0 kW_e

Table 4-27. Key Parameters for Mars/Phobos Base

Mission	Human settlement on Mars' Moon Phobos; providing a base for exploration, mining, surface materials processing, and various research activities on Phobos, as well as staging for settlement on the surface of Mars.
Power Requirements	150 kW_e
Mission Life	Indefinite Life Approximately 2010+
Orbit	Not applicable
Shielding	Protect crew, instruments, and experiments from radiation and excess heat
Spacecraft RMA	Base must be accessible to orbital and lunar craft Crew must be able to make repairs

Mars Initial Camp - The initial operational camp (see Table 4-29) will be staffed by four people and require 30 kW_e of power. As on the Moon, the camp will consist of a habitation module, laboratory module, logistics module, and necessary operational hardware. Table 4-28 is a breakdown of camp power requirements; Table 4-29 provides a summary of key parameters.

Mars Nominal Base - After about five years, the initial operational camp will grow into the nominal operational base (see Table 4-30, 4-31 and Figure 4-13). This base will have twelve crew members and require 120 kW_e for its two habitation modules, two laboratory modules, two logistics modules, two Mars materials processing plants, and operational hardware. Table 4-30 is a breakdown of camp power requirements.

Mars Operational Base - After about five years, the base will have grown to six habitation modules and 24 crew members. It will use about 290 kW_e to run the two laboratory modules, four logistics modules, six materials processing plants, operations hardware, and living quarters. The materials processing plants, as on the Moon, will extract useful resources from the soil or atmosphere for use by the base. Table 4-32 is a breakdown of colony power requirements; Table 4-33 provides a summary of key parameters.

Table 4-28. Mars Initial Camp Power Requirements

Elements	Power Requirements
Habitat modules - 1 (crew of 4)	10.0 kW_e
Laboratory modules - 1	15.0 kW_e
Logistics modules - 1	2.5 kW_e
Operations hardware (comm., fuel depot)	2.5 kW_e
Approximate Total Power Requirement:	30.0 kW_e

Table 4-29. Key Parameters for Mars Initial Camp

Mission	Human settlement on the Martian surface will provide a base for exploration, mining, surface materials processing, and research
Power Requirements	30 kW_e
Mission Life	5 years Approximately 2010-2015
Orbit	Not applicable
Shielding	Protect crew, instruments, and experiments from radiation and excess heat
Spacecraft	Base must be accessible to orbital and surface craft
RMA	Crew must be able to make repairs

Table 4-30. Mars Nominal Base Base Power Requirements

Elements	Power Requirements
Habitat modules - 2 (crew of 12)	2 x 10.0 kW_e
Laboratory modules - 2	2 x 15.0 kW_e
Logistics modules - 2	2 x 2.5 kW_e
Operations hardware (comm., fuel depot)	5.0 kW_e
Mars materials processing plants - 2	2 x 30.0 kW_e
Approximate Total Power Requirement:	120.0 kW_e

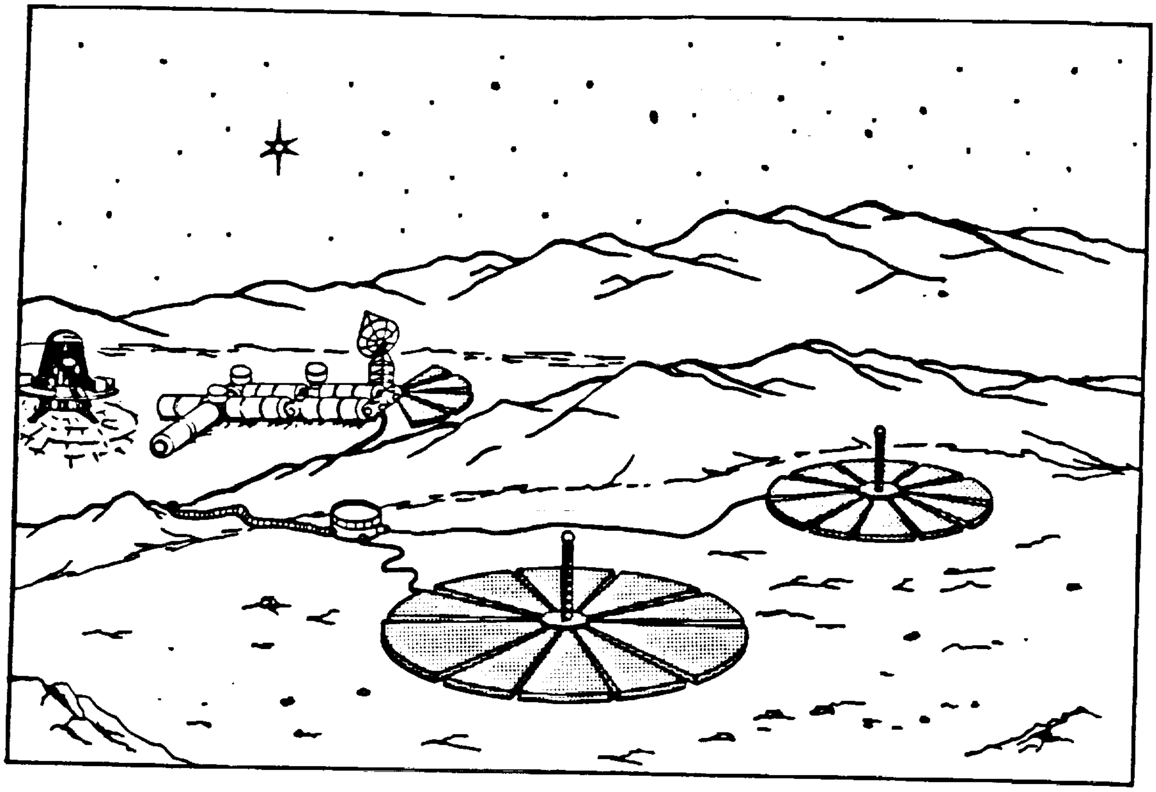


Figure 4-14. Conceptual Illustration of a Mars Nominal Base

Table 4-31. Key Parameters for Mars Nominal Base

Mission	Human settlement on the Martian surface will provide a base for exploration, mining, surface materials processing, and research
Power Requirements	120 kW_e
Mission Life	10 years Approximately 2015-2025
Orbit	Not applicable
Shielding	Protect crew, instruments, and experiments from radiation and excess heat
Spacecraft RMA	Base must be accessible to orbital and surface craft Crew must be able to make repairs

Table 4-32. Mars Operational Base Power Requirement

Elements	Power Requirements
Habitat modules - 6 (crew of 24)	6 x 10.0 kW_e
Laboratory modules - 2	2 x 15.0 kW_e
Logistics modules - 4	4 x 2.5 kW_e
Operations hardware (comm., fuel depot)	10.0 kW_e
Mars materials processing plants - 6	6 x 30.0 kW_e
Approximate Total Power Requirement:	290.0 kW_e

Table 4-33. Key Parameters for Mars Operational Base

Mission	Human settlement on the Martian surface will provide a base for exploration, mining, surface materials processing, and research.
Power Requirements	290 kW_e
Mission Life	15 years Approximately 2025+
Orbit	Not applicable
Shielding	Protect crew, instruments, and experiments from radiation and excess heat
Spacecraft RMA	Base must be accessible to orbital and surface craft Crew must be able to make repairs

Mars Growth Colony - During the course of operations (perhaps following the first fifteen years), the Mrs operational base will evolve into a self-sustaining Martian colony. The colony will consist of a complex of twelve habitat modules, four laboratory modules, eight logistics modules, and fifteen materials processing and handling plants. The Mars growth colony continues and builds upon the role of the Mars operational base in the development of manned inner solar systems infrastructure. A breakdown of power requirements is provided in Table 4-34. Table 4-35 provides several key parameters for the projected Mars growth colony.

Table 4-34. Mars Growth Colony Power Requirements

Elements	Power Requirements
Habitat Modules - 12 (crew of 48)	12 x 15.0 kW_e
Laboratory Modules - 4	4 x 15.0 kW_e
Logistics Modules - 8	8 x 2.5 kW_e
Operational Hardware (comm., fuel depot)	20.0 kW_e
Mars materials processing plants - 15	15 x 30.0 kW_e
Approximate Total Power Requirement:	730.0 kW_e

Table 4-35. Key Parameters for Mars Growth Colony

Mission	Human settlement on the Martian surface; providing a base for exploration, mining, surface material processing, and various research activities.
Power Requirements	730 kW_e
Mission Life	Indefinite Approximately 2040+
Orbit	Not applicable
Shielding	Protect crew, instruments, and experiments from radiation and excess heat
Spacecraft RMA	Base must be accessible to orbital and lunar craft Crew must be able to make repairs

4.3.6 Transportation Vehicles

4.3.6.1 Overview. As human exploration and settlement extend out into the solar system, vehicles will be needed to transport cargo and people between spaceports, planetary bodies, and the Earth. The overall space transportation system will consist of many components, including the space shuttles, Space Station, Orbital Maneuvering Vehicle (OMV), Orbital Transfer Vehicle (OTV), and Interplanetary Transport Vehicles (ITV), both manned (M-ITV), and unmanned, cargo-carrying (C-ITV). Together, they will allow commercial space operations; the launch and servicing of satellites, orbiting platforms, exploratory spacecraft, and interplanetary vehicles; and the staging of missions supporting planetary base operations.

4.3.6.2 Orbital Transfer Vehicle. The Orbital Transfer Vehicle (see Figure 4-15 and Table 4-36) will form an integral part of the overall space transportation system, enabling maximum system efficiency and lowest user transportation costs. Reuseable, chemical propulsion OTVs will be based at the Space Station, where the latter's crew will maintain, refuel, check out, launch, and recapture them. The OTVs will provide the crew of the Space Station with access to a wide range of Earth orbits; they will be used to place payloads in given orbits, to retrieve satellites for repair, and to stage spacecraft for launch to the solar system and beyond.

While a chemical propulsion system may be used initially, an advanced OTV that could be developed in the 2000s would use electric propulsion. The OTV will require a high-performance propulsion system which is capable of multistart, high-performance, low-thrust operation and in-space maintenance. Nuclear electric propulsion could provide power for the OTV, as assessed in Section 5.

The NEP Orbital Transfer Vehicle itself will have an indefinite lifetime, but the thrusters will have a lifetime of only 1,000 to 5,000 hours, depending on the propulsion means selected. (The baseline lifetime of arcjets is 1,000 hours, and of ion thrusters, 5,000 hours.) Each unmanned OTV would make several trips during its lifetime, and would take from 120 to 360 days to travel from LEO to GEO (again the actual time depends on the propulsion system).

4.3.6.3 Manned-Interplanetary Transport Vehicles. The Manned-Interplanetary Transport Vehicle (M-ITV) will ferry cargo and passengers between Earth orbit and human outposts in space. One kind of M-ITV (see Figure 4-16 and Table 4-37) will carry passengers and cargo to the Mars base.

The National Commission on Space has proposed cycling spaceships between the Earth and Mars. The ITV would be in a stable orbit between these planets, met at either end by transfer vehicles. Personnel going to Mars would board a transfer vehicle at an Earth spaceport. This craft would then accelerate to match the ITV's velocity and dock with the spaceship. The crew would then store their vehicle in a hanger for the 5- to 7-month voyage. The ITV would provide them with food, life support and other necessities, along with sufficiently spacious quarters for the long voyage. Artificial gravity would be provided by rotation (acceleration level/rotation rate variable).

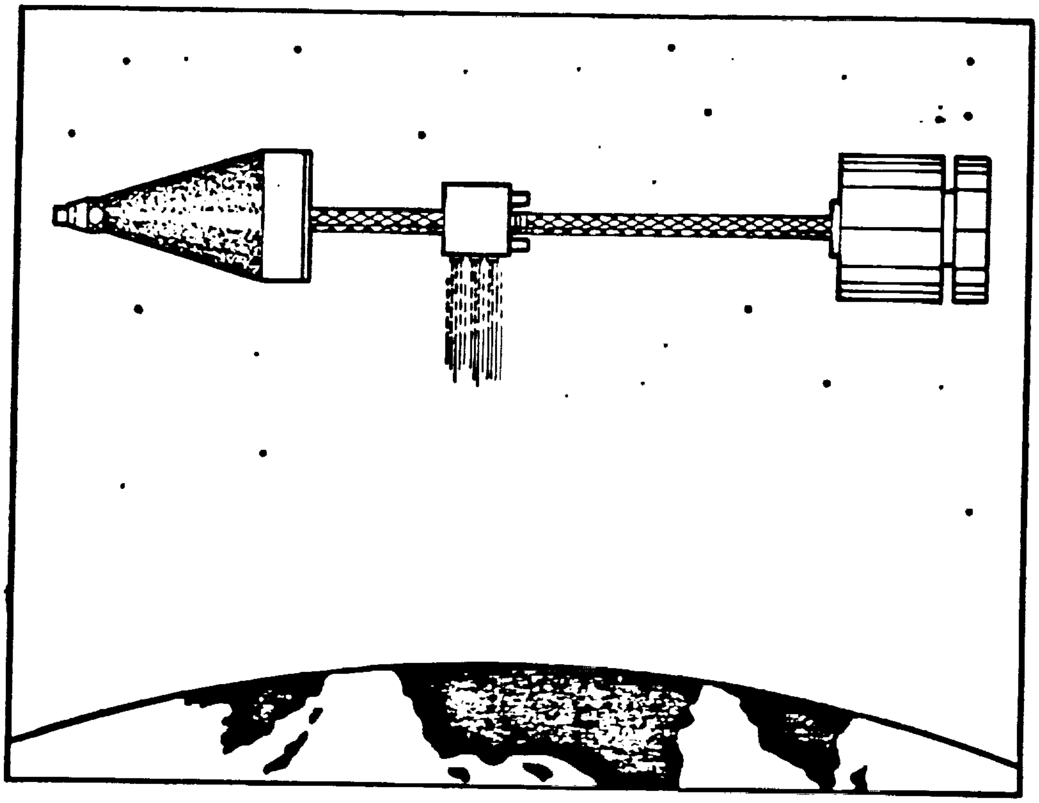


Figure 4-15. Conceptual Illustration of an Orbital Transfer Vehicle (NEP)

Table 4-36. Key Parameters for Orbital Transfer Vehicle (NEP)

Mission	Ferry material among spacecraft satellites, and spaceports
Power Requirements	100-300 kW_e
Mission Life	Indefinite vehicle life Thruster life of 1,000-5,000 hours Mission begins approximately 2000+
Orbit	Varies with the application
Shielding	Protect sensitive cargo and instruments from radiation and excess heat
Spacecraft RMA	Must be serviceable in orbit

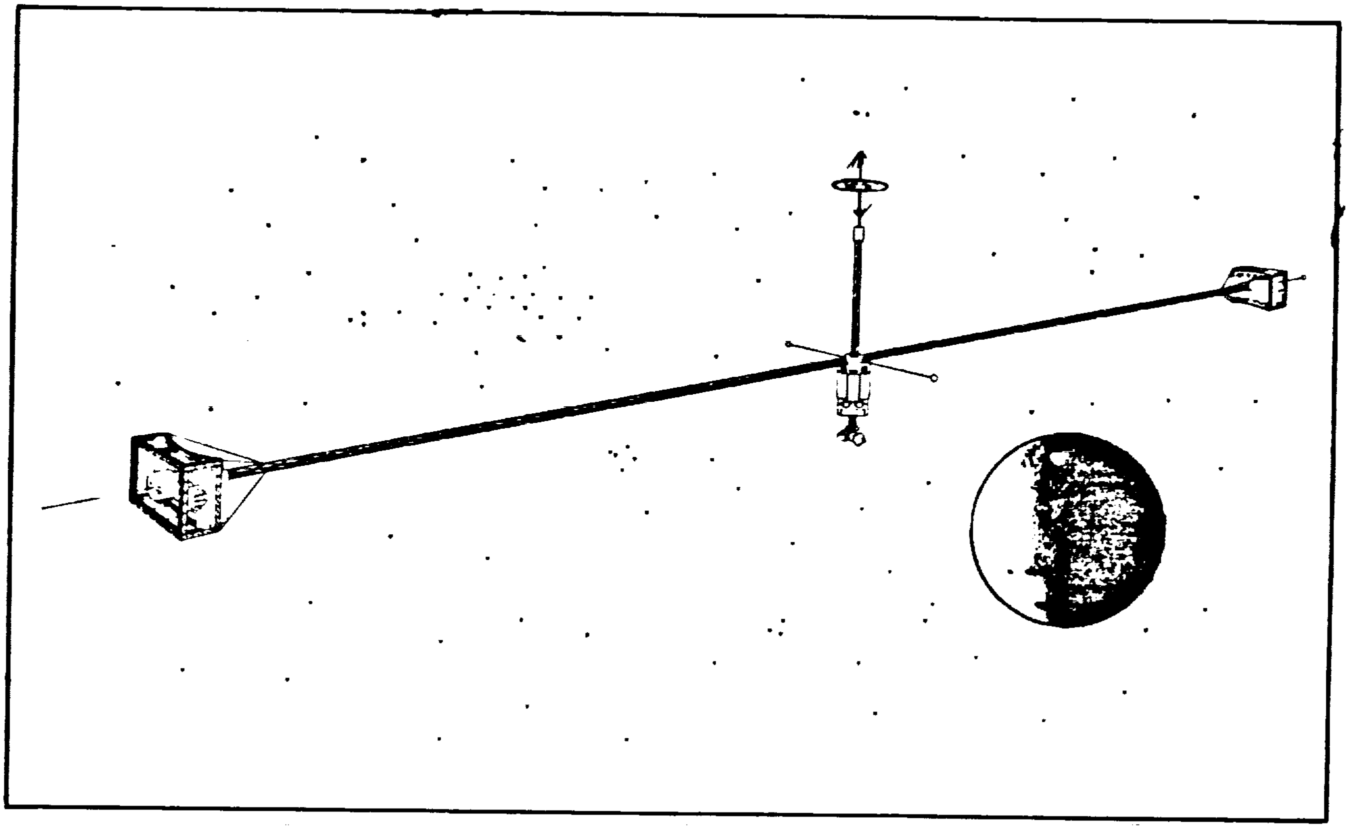


Figure 4-16. Conceptual Illustration of a Manned Interplanetary Transport Vehicle

Table 4-37. Key Parameters for a Manned Interplanetary Transport Vehicle Mission

Mission	Transport cargo and personnel between Earth and the planetary bases
Power Requirements	300 kW_e
Mission Life	Indefinite, beginning approximately 2010+
Orbit	Varies with the application
Shielding	Protect crew and passengers, sensitive cargo, and instruments from radiation and excess heat
Spacecraft RMA	Reliability especially important for powering life support systems

The crew would use transfer vehicles for transit to the Mars/Phobos Spaceport or to Mars. They would leave the M-ITV, aerobrake on the Martian atmosphere, and either orbit to Phobos or descend directly to the Mars' surface for a stay of 1 to 4 years at Mars.

This cycling spaceship would provide the backbone of the Earth-Mars transportation system. As the Martian base expands, the capabilities of the spaceship would grow to meet the base's transportation needs. The cycling approach allows transportation with less propellant than would be used for direct travel, since the cycling ship doesn't have to accelerate or decelerate on arrival.

4.3.6.4 Unmanned/Cargo Interplanetary Transport Vehicle (C-ITV). Following the establishment of a manned base/spaceport on Phobos, and the beginning of water mining/processing operations, a substantial shipping operation will develop between the Mars' moon and the Earth-Moon system; hardware and modules for the growing Martian colony will be shipped outbound, while water (and possible mineral resources) are shipped inbound. A large, unmanned, cargo-carrying interplanetary transport vehicle (C-ITV) analogous to a contemporary oil-carrying super tanker is envisioned for this activity. (Table 4-38 provides several key parameters for the projected cargo-carrying interplanetary transport vehicle.) The C-ITV will employ a large, multiple-reactor power system producing 7 MW_e to power magneto-plasma-dynamic (MPD) thrusters. In the assumed scenario, the MPD thrusters generate a specific impulse of 5000 seconds, operating at an overall efficiency of 50%. The C-ITV would transport a maximum cargo of approximately 330 metric tons, requiring a total round-trip time of about 3 years.

Table 4-38. Key Parameters for Cargo-Interplanetary Transport Vehicle

Mission	Transportation of equipment and materials (principally processed water) between the Mars/Phobos spaceport and the Earth-Moon system
Power Requirements	7000 kW_e
Mission	Indefinite Life Approximately 2025+
Orbit	Not applicable
Shielding	Protect spacecraft systems and cargo from radiation and excess heat
Spacecraft RMA	Spacecraft must be accessible to orbital craft Robotic systems must be able to make repairs

4.4 COMMERCIAL UTILIZATION

This section describes selected enterprises which use the unique space environment for commercial production or services. The missions selected for discussion are the Geosynchronous Communications Platform and the Air/Ocean Traffic Control missions.

4.4.1 Overview

Space offers a new spectrum of opportunities for scientific research, technology development, manufacturing, and services. Many communications and broadcasting firms have already launched satellites and use them in their daily operations. Commercial enterprises in space will probably continue to expand their present space operations, but may also extend to research and development work in Earth orbit or to launch services for satellites, cargo, and personnel.

Of course, one important prospect for future commercial utilization of space lies in the area of materials processing. In-space research in the fundamental processes of crystal growth and chemistry will add enormously to the capabilities of U.S. ground-based industry. Moreover, the outlook is good for commercial manufacturing on-orbit in both semiconductor and biological materials. This area is discussed in Section 4.3 on the Space Station.

4.4.2 Geosynchronous Communications Platform

One natural extension of present operations would be a geosynchronous communications platform (see Figure 4-17 and Table 4-39). Many single-mission communications satellites are already in Earth orbit, and by the 1990s, the geostationary arc will have become already crowded with individual satellites. As a result, only those missions with high commercial appeal and rapid initial cost recovery will be able to reserve a place in geosynchronous orbit (GEO).

A geosynchronous communications platform would help to relieve this congestion by providing multiple services from a single GEO position. Several missions could be placed on the platform, sharing common functions and equipment. For example, the platform would provide a large number of antennas and transponders, as well as signal processing equipment, power supply, and attitude control systems. In order to operate the multiple missions, the platform would require 15 to 150 kW_e. This sharing equipment among several missions might provide cost savings over the traditional, single function approach.

Some of the missions supported by the platform could include direct broadcast services, land mobile satellite services, video conferencing, and electronic mail. COMSAT General Corporation expects land mobile satellite services to be in high demand in 1990 and beyond. Video conferencing will become more important as picture quality improves. As communications technology increases in sophistication, other functions could be included on the platform to meet the demand for these services.

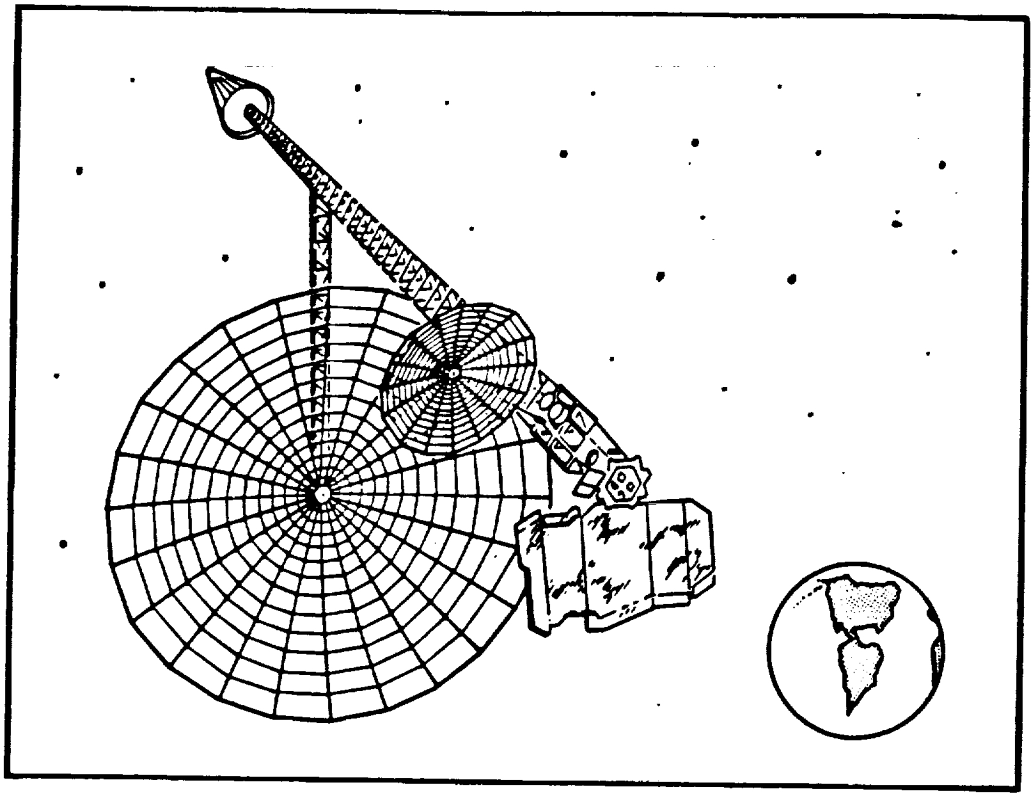


Figure 4-17. Conceptual Illustration of a Geosynchronous Communications Platform Mission

Table 4-39. Key Parameters for Geosynchronous Communications Platform Mission

Mission	Several communications missions aboard a single orbiting platform, sharing common power supply, attitude control systems, and structure
Power Requirements	15-150 kW_e
Mission Life	7-10 years each, beginning 2000+
Orbit	Geosynchronous orbit
Shielding	Protect electronic components from radiation
Spacecraft RMA	Accessibility important; must be able to maintain the platform and perform component change-out

4.4.3 Air/Ocean Traffic Control Radar

Another extension of existing technology would be a space-based air traffic control radar system (see Figure 4-18 and Table 4-40). Twenty-five to 30 percent of the North Atlantic and some 75 percent of the North Pacific would be covered by this system, with systems of other nations covering the remaining area, under international agreement. The radar would provide positive air traffic control, allowing continuous tracking of aircraft. Some of the benefits of the system are:

- improved air safety, since aircraft are more accurately monitored
- improved fuel efficiency, since planes are allowed to fly at the most efficient altitudes
- reduced departure and arrival delays
- timely changes in flight plans due to weather.

The air traffic control radar would be placed aboard a platform in low Earth orbit. The radar system would require 40 to 200 kW_e, depending on the desired resolution, number and range of targets, antenna size, and other factors.

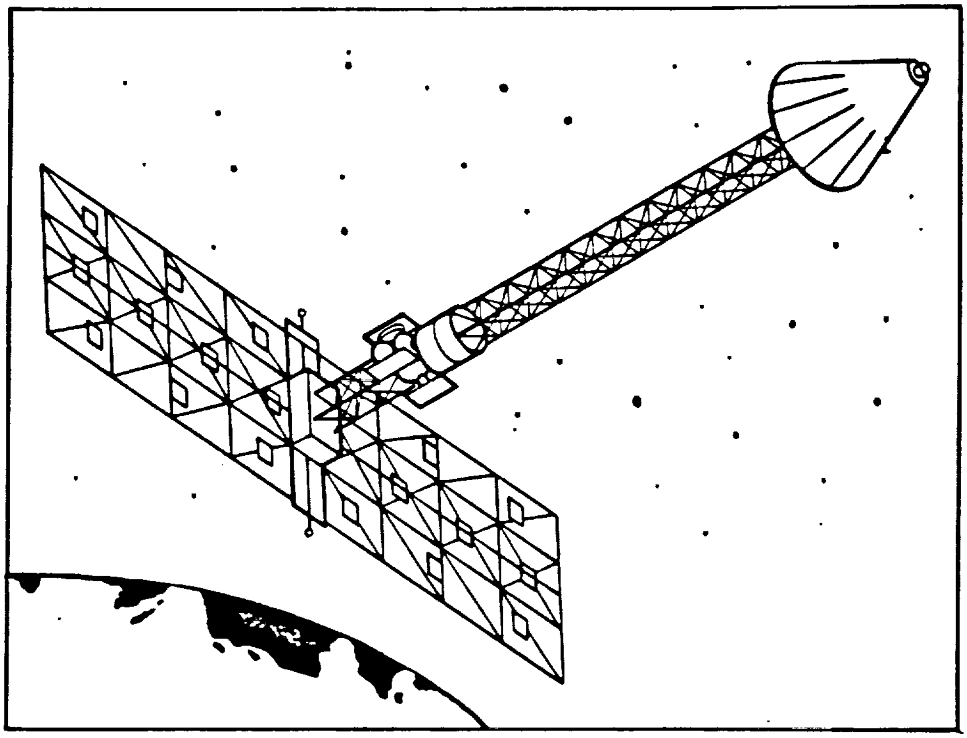


Figure 4-18. Conceptual Illustration of an Air/Ocean Traffic Control Radar Mission

Table 4-40. Key Parameters for an Air/Ocean Traffic Control Radar Mission

Mission	Radar platform in low Earth orbit which will track aircraft/ships over the oceans
Power Requirements	40-200 kW_e
Mission Life	7-10 years each, beginning 2005+
Orbit	Low Earth orbit (700-4,000 km)
Shielding	Protect electronic components from radiation
Spacecraft RMA	Accessibility important; must be able to maintain the platform and perform component change-out

SECTION 5

POWER SYSTEM APPLICATIONS ASSESSMENT

5.1 INTRODUCTION

This section assesses the suitability of space nuclear power to individual civil space mission applications. In this study, the suitability of space nuclear power to a particular civil mission application is not based on whether a competing technology (such as photvoltaics) is better or worse. Instead, the assessment is based on whether or not the mission requirements are met and if the mission itself is enhanced by the application of the current space reactor technology, the SP-100 SRPS.

A ranking system is developed to qualitatively describe the suitability of space nuclear power to civil space missions based on strawman implementations of the SP-100 SRPS using current flight demonstration technology. The strawman implementations are based on the configurational trades and considerations given in Section 3. The assessments are based on the issues that arise from the strawman configurations. In those instances where the mission requirements are not met or are marginally met by current space reactor technology, attempts are made to quantify the shortcomings in such a way as to provide a rational basis to accept or dismiss the potential application.

5.2 DEFINITIONS

It is often necessary when performing application assessments to assign qualitative judgmental labels in order to rate the suitability of the application. Such is the case in this study, where strawman SP-100 implementations are rated for their suitability to civil space mission applications. A classification of IDEAL, GOOD, or POOR is used here to rate the overall suitability of the current space nuclear power technology to a particular civil mission application. A rating of IDEAL is assessed where the mission requirements are either met or bettered by the implementation of space nuclear power. A rating of GOOD is assessed where the mission requirements are only just met or slightly exceed the currently projected capabilities of the SP-100 SRPS. In order to be rated GOOD, however, it must be possible to meet all mission requirements even if special operating procedures must be adopted. If special operating procedures cannot correct for deficiencies in the implementation, the implementation must be assessed as POOR.

5.3 ASSESSMENT CRITERIA

While there are dozens of individual mission traits, there are only a few parameters which are of importance to all missions. This section identifies those global parameters and discusses them in detail in order to provide the necessary background required to interpret the individual mission assessments. These discussions include a detailed rationale for the selection of electric propulsion. Selection of power levels based on available reactor power, power system mass and orbital delivery considerations, and power system reliability and lifetime are also addressed.

5.3.1 Rationale for Nuclear Electric Propulsion

For the purposes of this study, nuclear electric propulsion (NEP) was selected for all major space vehicles with requirements for propulsion. The selection of NEP was based on the analysis of three currently feasible modes of propulsion maneuvering, including NEP. The comparisons are based on the assumptions of a fixed payload and single launch constraint and on an analysis of total flight time. The impact of varying assumptions and constraints is greatest on the Far Outer Planets/Orbiters.

5.3.1.1 Gravity Assist and Aerobraking. Gravity assist and aerobraking, while not modes of propulsion in themselves, are important enough in their significance to warrant discussion. The technique of gravity assist can be used in mission cases to enhance the spacecraft propulsion capability and reduce the flight times to the outer planets. The gravitational attraction between a large mass (a planet) and the spacecraft accelerates the craft toward the planet. With the correct trajectory, the spacecraft will not be captured into orbit by the planet, but will instead travel in a new direction with increased velocity. This assumes that the planetary positions are such that the spacecraft will approach the target planet at the same time the spacecraft approaches the target planet's orbit.

Once the spacecraft has reached its designated planet, it can utilize the upper atmospheric layers of the planet to slow itself and fall into a capture orbit around the planet. This maneuver is called aerobraking. Aerobraking requires that the spacecraft be equipped with a heat-resistive shield to provide a braking surface and to protect the spacecraft from the resulting heat. It also requires that the planet being visited have an atmosphere substantial enough to significantly brake the motion of the spacecraft in a single pass. The shield may be fixed or deployable, and more than likely it would be jettisoned after use. The shield would be quite large and is expected to be a major percentage of the payload mass.

The alternative to aerobraking is to plan the spacecraft trajectory such that the spacecraft will travel in a long, slow spiral around the planet due to gravitational forces, eventually stabilizing in a capture orbit with the assistance of a propulsion system.

Both gravity assist and aerobraking are maneuvers implemented to conserve and limit the amount of spacecraft propellant required over the course of the mission. Aerobraking significantly reduces the capture time at end-of-flight, while gravity assist adds time at the beginning of flight by limiting the launch windows. In the case of far outer planets missions, Jupiter will be used to supply the gravity assist. Jupiter is in a position to provide gravity assist every twelve years. The limited availability of Jupiter restricts the launch windows for any mission which must rely on this method for a majority of its acceleration. (The Voyager mission relied on an alignment of Jupiter, Saturn, Uranus, and Neptune that occurs only once every 180 years.)

Acceleration must therefore come from the spacecraft propulsion system if the need for gravity assist is to be relaxed.

5.3.1.2 Chemical Propulsion. Chemical propulsion is the scheme with the greatest historical experience. Once a chemically propelled spacecraft has been inserted into low earth orbit by an ELV or STS, a large disposable chemical booster (such as a Centaur G) is required to transport it into free space beyond Earth's gravity. Spacecraft chemical propulsion systems are notoriously inefficient compared to the weight of the propellant they must carry. This is characterized by their low specific impulse, I_{sp}, which is a measure of performance based on the thrust produced by an equivalent system with a propellant weight flow of unity.

Measured in seconds, the I_{sp} of chemical propulsion systems is typically on the order of 300 seconds. If a competing system produced the same effective thrust but with a higher specific impulse, then the competing system would be more efficient in the use of same mass of propellant. A competing system with lower thrust but a higher I_{sp} may be more efficient if it can sustain the lesser thrust long enough to achieve the same result with a savings of propellant mass.

5.3.1.3 Electrical Propulsion. Electric propulsion is a broad category that actually covers three basic types of thrusters: electrothermal, electromagnetic, and electrostatic. Electrothermal thrusters, such as arcjets and resistojets, heat and expand a propellant using either an electric arc or resistive heating element. Electromagnetic (plasma) thrusters use both electric and magnetic fields to accelerate propellants that are highly ionized. Electrostatic thrusters use electrodes to charge or ionize the propellant and electric fields only to accelerate the particles and produce thrust. Of the three types of electric thrusters listed, the electrostatic thrusters (in the form of ion engines) appear to be the most promising and will form the basis of the evaluation of electric propulsion for civil nuclear powered space missions.

Ion thrusters are characterized by their moderate thrust and high I_{sp}. For a 30-cm mercury ion thruster, thrusts of 0.3 to 0.6 N, with an I_{sp} of 3,000 seconds or more, are easily attained. The I_{sp} of ion thrusters is increased by simply increasing the input power. This points out the most important aspect of electric propulsion: the energy producing the thrust is not stored in the propellant as it is in chemical propulsion, but rather comes from a power source. This permits electric propulsion to more efficiently utilize the same mass of fuel. Given the same mass limitations as electric propulsion, the chemical propulsion systems typically cannot carry enough propellant to enable more direct far outer planet trajectories that minimize the use of time-consuming gravity assist techniques.

The electric energy used by the thrusters can be either solar- or nuclear-generated; however, it is important to note in the case of the distances of the far outer planets from the Sun that the available solar energy drops off significantly. In fact, the available solar energy at the distance of Saturn is only one percent of the solar energy found at the distance of the Earth. Since the I_{sp} of the electric thrusters is directly related to the input power from the power source, it is conceivable that the solar-driven electric propulsion may not be able to provide reasonable maneuver response at its destination. Also, the large solar panels required would prohibit the time-saving aerobrake orbit capture.

Table 5-1 shows the approximate minimum mission flight times for Saturn, Uranus, and Neptune for various types of propulsion systems.

5.3.2 Power Levels

The available electric power output of the SP-100 SRPS currently lies in the range of 100 to 1000 kW_e. Outputs of slightly less than 100 kW_e are possible if the reactor is throttled back or if the number of thermoelectric ele- ments is reduced. It is important to note that either of these two procedures would result in an increase in the specific mass of the power system.

The availability of higher power levels may prove to be absolutely necessary when it is considered that future advanced space missions will use either electric propulsion for expedient mission travel and data gathering or be manned and require substantial power for and safety margin for life support systems. Additionally, electric propulsion becomes more efficient and attractive as the available power increases. Table 5-2 shows the various flight times for an unmanned science mission to Neptune for different available electric power levels. Reducing flight times on long-duration missions will reduce the costs of extended ground operations in support of those missions. The fact that the electric propulsion subsystem will no longer require the high electrical power output of the SRPS once it has reached its destination means that more power will become available to the payload. This increased power to the payload will enable more advanced instruments, higher data rate communications, and new scientific endeavors such as very high resolution radar mapping and advanced telerobotic exploration.

Table 5-1. Flight Times to Far Outer Planets with Different Propulsion Systems

Mission	Flight Time, yrs Nuclear Electric Propulsion	Solar Electric Propulsion	Chemical Propulsion
Saturn	5	6	7
Uranus	8	11	12
Neptune	11	16	17

Available Electric Power: 100 kW_e
Payload: 1,500 kg
Single Shuttle Launch Constraint
Chemical Booster for Solar and Chemical
NEP Spiral Escape
Solar and Chemical Utilize Gravity Assist

Table 5-2. Flight Time to Neptune Versus Power Level

Power Level, kW_e	Flight Time, yrs
100	11.0
200	9.3
300	8.5
400	8.0
500	7.8

I_{sp} = 5000 seconds
30-cm ion propulsion is assumed

5.3.3 Power System Mass and Orbital Delivery

The increased power levels and ambitious scientific payloads made possible by space nuclear power are not without their drawbacks. One such drawback is the prsently limited launch mass capability of the Space Shuttle and currently available expendable launch vehicles. While the development of launch vehicles with greater lift capacity is certainly independent of the development of space nuclear power, the development and implementation of space nuclear power is not independent of the ability to place the mission into space. Launch capability therefore must be considered as a factor in the implementation of space nuclear power and the SP-100 SRPS. This section discusses present and future launch vehicles and capabilities in terms of the payload mass, payload envelope, and the costs associated wih launching ambitious space missions.

5.3.3.1 Baseline STS-Station Scenario. The total mass of the SP-100 SRPS is completely dependent on the mission application. For some applications the total mass may be too large for any current launch vehicle. This necessitates the on-orbit assembly of some of the more ambitius SRPS missions. On-orbit assembly will most inevitably include Space Station services. The current baseline space shuttle launch scenario for Space Station operations is 6 to 8 STS flights per year; with 4 STS flights required for Station crew changeover and operations logistics, and 2 to 4 STS flights provided for user mission hardware and logistics. The currently projected STS lift capacity for users, including shuttle-Station docking equipment, is approximately 12,231 kg to the nominal Station orbit. This available launched mass is reduced by the requirement to launch and return the OMV during the first three years of normal operations; it would be further reduced if a standardized payload logistics module were also required. These factors do not come into play for the launch of unpressurized payloads, such as a spacecraft-SRPS mission.

There are several missions either currently tabulated in the Space Station Mission Requirements Data Base (MRDB) - or discussed in this report - whose launch mass requirements (as currently projected) exceed the constrained capabilities of the space shuttle to the Space Station. These missions involve commercial materials processing modules, astrophysics observatories, large space antenna missions, tethered platform systems, as well as large, Earth-orbiting or planetary manned spacecraft reactor applications requiring substantial shielding beyond the SP-100 baseline. The launch of these missions using the projected shuttle-Station baseline transport system would entail breaking the mission into two or more constituent elements, launching the pieces separately, and assembling them at the Station. Of course,this approach greatly increases the associated launch costs for the missions (although not linearly, because the STS carrying individual pieces may be shared with other users). In addition, carrying a single mission into orbit in several pieces necessitates potentially extensive and costly on-orbit crew activity at the Station for assembly and testing.

These requirements would be substantially reduced if alternative launch vehicles providing greater lift capacities were available by the 1995-plus time frame.

5.3.3.2 Launch Vehicle Cost/Capability Comparison. A comparison of the cost and capabilities of the several alternative launch vehicle systems (manned and unmanned) that could be available for operations to the Space Station is provided in Table 5-3. (This data is rough and based on only a preliminary survey; it is specifically directed at a 28.5° inclination, 463 km, circular orbit.)

In general, the launch performance of the shuttle to the Space Station is severely constrained because of the requirement that a shuttle-Station docking adaptor be carried on the shuttle. It is difficult to fairly assess the cost/capability of the various launchers because of the differing levels of embedded subsidies that are incorporated in some of the launch costs provided. However, the cheapest launch vehicle (dollars/kg) in the assessment, and the vehicle providing the greatest single lift capability, is clearly the Jarvis; at approximately $4,125/kg for Jarvis vs. approximately $8,200/kg for the shuttle-Station transport system - where the shuttle is constrained by considerable overhead weight. Aside from cost, a medium-lift launch vehicle such as Jarvis is not expected to enhance the ability to place the most ambitious missions in space. Power system masses clearly call for the development of heavy-lift launch vehicles.

Several heavy-lift launch vehicles are currently under study within the aerospace industry which would, if available, still further facilitate the implementation of SRPS missions. For example, a United Technologies Corporation concept for a shuttle-derived expendable launch vehicle would provide a 63,000 kg/launch capability to 28.5° LEO orbits by the 1995-plus time frame. While a heavy-lift launch vehicle is expected, assessments are made based on present launch capabilities (STS or Titan).

5.3.3.3 Scenario Modifications. Several simple, alternative modifications to the baseline shuttle launch scenario can be made which significantly alter

Table 5-3. Launch Vehicle Data Base (see Notes 1, 2)

Expendable Launch Vehicles

Vehicle	Vehicle Availability	Launched Mass (kg)	Envelope (D x L,[3] meters)	Cost ($, M)	Cost/kg ($)
Delta 3920/PAM	existing	3,080	2.2 x 2.3	50	16,234
Atlas G/ Centaur D-1A	existing	5,663	3.0 x 8.5	80	14,127
Titan IV	existing	14,496	4.6 x 20.0	225	15,522
"Jarvis" MLV	projected	36,360	8.5 x TBD	150	4,125
Heavy Lift Vehicle	projected	63,636	TBD	TBD	TBD
Ariane 4 (ESA)	existing	10,872	N/A	55	5,059
Ariane 5 (ESA)	projected	14,949	4.6 x TBD	TBD	TBD
H-2 (Japan)	projected	11,778	TBD	TBD	TBD
Manned Launch Vehicles					
Shuttle-Station (see Note 4)	existing	12,231	4.6 x 20.0	100	8,176
Space Shuttle	existing	29,445	4.6 x 20.0	100	3,396
Ariane 5 (ESA) + Hermes	projected	4,530	TBD	TBD	TBD

Note 1. Scenario - Launch to 463 km/circular (average Station orbit)

Note 2. All quantities provided are approximate.

Note 3. Diameter x Length

Note 4. The performance of the space shuttle to Space Station is limited in this assessment by the requirement to carry a shuttle-Station docking adaptor.

the character of SRPS mission launch and staging assessments that are provided in the text (see Section 5). Detailed analysis of those modifications is beyond the scope of the present study; however, the following observations can be made immediately: (1) the addition of a "Jarvis-class" medium lift expendable launch vehicle to the baseline shuttle launch vehicle scenario would provide a significant cost reduction for SRPS missions, (2) the addition of Titan IV/Ariane 4-class vehicles provides no real improvement for this type of mission because of the requirements for high mass launch capability, (3) the addition of heavy launch vehicles, perhaps in the 63,000-kg range, may well be enabling for low-cost implementation of ambitious (very massive) SRPS civil missions during the 1995-plus time frame.

5.3.4 Power System Reliability and Lifetime

Advanced science missions demand the highest reliability from their subsystems. To date, no verification of the reliability of an SP-100 SRPS has been performed. The specified full-power life of 7 years with 95 percent probability of success is given as a growth parameter that will be achieved as more SP-100 systems are flown. Before life critical missions or scientifically ambitious (and expensive) missions are undertaken, it is advisable that either historical data be accumulated or back-up power be available. The historical data is easily accumulated from less ambitious missions in near-Earth operations without impacting the mission schedule.

If a 7-year life at 95 percent is assumed, the applicability of the SP-100 to longer-range missions is in question. While it can be assumed that end-of-life replacement is possible for near-orbit and surface-deployed reactors, any long-term continuous power deep space probes must be able to complete their mission before the reactor reaches the end of its life.

If a mission will undergo long periods of time where the power requirements are minimal, it may be possible to turn down (throttle down) the reactor output and place the reactor in a standby state. The standby state will serve to lengthen reactor lifetime by reducing the fuel burnup, or allowing operation at lower reactor outlet temperatures.

5.4 SCIENCE AND EXPLORATION

Science and exploration missions have a basic core of characteristics and stringent requirements. All are unmanned and categorized as "Class A" missions, which demand the lowest possible designable probability of failure. Reliability is one of the critical issues that define Class A missions. Once launched, these spacecraft are out of reach until the end of their mission. These missions may end either at their destination or upon return to the place of their origin.

It is useful here to divide the missions according to where the spacecraft end their useful lives. There are significant differences between two spacecraft following the same mission if one of the spacecraft is to return to Earth orbit. Duration of the mission and the disposal of the spacecraft are two such differences. In turn, these differences will place differing requirements on the spacecraft power system.

5.4.1 Sample Return Missions

An example of a mission that has the additional requirement of returning to Earth orbit is the sample return mission. Three such missions are currently being planned: the Asteroid, Comet and Mars Sample Return missions. The goal of these missions is to conduct scientific experiments and measurements at the destination and to return samples to Earth for additional scientific analysis that is difficult if not impossible to conduct onboard the spacecraft.

5.4.1.1 Asteroid Sample Return. The Asteroid Sample Return mission summarized in Table 4-1 will rendezvous with several asteroids, survey them, and with the assistance of a reusable lander collect core samples for return to Earth. Based on nuclear electric propulsion, it is anticipated that this round trip mission will take from five to nine years to complete. The mission is unmanned, therefore the radiation requirements are much less strict and minimum shielding can be utilized. Estimated power requirements currently indicate a need for 80-100 kW_e to support the propulsion and scientific systems.

The reference design specified in Section 3 is adequate for this application. The spacecraft may be assembled in orbit and tested under low power conditions before its unmanned full power up (radiation requirements and the minimum shielding dictate unmanned reactor activation). On the return phase of the mission, the reactor may either be turned off as it nears the sample retrieval point or the reactor may be jettisoned in a safe orbit. In the former case OTV support may be required for reactor disposal to SNDO after sample retrieval. It is anticipated that OMV support will be required in either case for the retrieval of the samples.

The lifetime and RMA of the reactor power system remain a pressing issue. The present seven year life of the SRPS may affect a long term mission of nine years. It is possible that by placing the reactor in a standby state during relatively inactive mission phases that the life can be extended somewhat. This standby phase is not yet a demonstrated feature of the SRPS, nor is it known that this dormancy will significantly improve SRPS life without risk to SRPS reliability.

Table 5-4 lists the parameters of the strawman implementation for the Asteroid Sample Return mission.

5.4.1.2 Comet Nucleus Sample Return. The Comet Nucleus Sample Return mission summarized in Table 4-2 is essentially the same as the Asteroid Sample Return mission. Instead of a series of asteroids, however, a short period comet will be visited. The samples of the comet nucleus will be taken by a lander for return to Earth, and a long term monitoring station will be left

Table 5-4. Strawman SRPS Implementation for Asteroid Sample Return Mission

Estimated Power Requirement	80-100 kW_e
System Configuration	Reference mission configuration
Radiators	Conical configuration
Shielding	Shadow shield, not man-rated; untended power-up required
Power System Mass	2,900 kg
Reactor Disposal Options	
OTV/chemical booster to SNDO on return	
Reactor jettisoned in safe orbit	
OMV required to retrieve samples	
Required RMA	Class A science mission requiring high reliability; reliability may be affected if reactor throttling is employed.
Lifetime Required	Mission designed for 5-9 years; longer term missions extended two years beyond rated life of power system
Assessment	Good

behind on the comet surface. The power requirement for the mission is 80-100 kW_e, and the anticipated mission duration is twelve to eighteen years, which is beyond the lifetime capabilities of a single SRPS. This mission is a possible candidate for a dual reactor power system if throttling will not significantly extend the reactor life.

The mission will be unmanned, therefore the reference mission configuration defined in Section 3 is applicable here if additional protection is provided against damage from dust and particulate matter that surrounds the comet nucleus.

Table 5-5 summarizes the parameters of the strawman implementation for the Comet Nucleus Sample Return mission.

Table 5-5. Strawman SRPS Implementation for Comet Sample Return Mission

Estimated Power Requirement	80-100 kW_e
System Configuration	Reference mission configuration
Radiators	Conical configuration
Shielding	Shadow shield, not man-rated; untended power-up required
Power System Mass	2,900 kg (for a single reactor, mass slightly higher if additional protection against dust is required)
Reactor Disposal Options	
OTV/chemical booster to SNDO on return	
Reactor jettisoned in safe orbit	
OMV required to retrieve samples	
Required RMA	Class A science mission requiring high reliability; reliability may be affected if reactor throttling is employed.
Lifetime Required	Mission designed for 12-18 years. Possible candidate for dual reactors.
Assessment	Poor to Good, depending on final reactor life

5.4.1.3 Mars Surface Sample Return. The Mars Surface Sample Return mission summarized in Table 4-3 is identical in purpose to the other sample return missions. In addition to in-situ studies, the lander craft will return a sample to the spacecraft for return to LEO for recovery. The mission is expected to last four to five years. A power level of 80-100 kW_e is required to accomplish the mission. This is well within the reactor lifespan and the reference mission configuration detailed in Section 3 is well suited to this application.

Table 5-6 summarizes the parameters of the strawman implementation for the Mars Surface Sample Return mission.

Table 5-6. Strawman SRPS Implementation for Mars Sample Return Mission

Estimated Power Requirement	80-100 kW_e
System Configuration	Reference mission configuration
Radiators	Conical configuration
Shielding	Shadow shield, not man-rated; untended power-up required
Power System Mass	2,900 kg
Reactor Disposal Options	
OTV/chemical booster to SNDO on return	
Reactor jettisoned in safe orbit	
OMV required to retrieve samples	
Required RMA	Class A science mission requiring high reliability; reliability may be affected if reactor throttling is employed.
Lifetime Required	Mission designed for 4-5 years. This is well within the projected lifetime of the SRPS.
Assessment	Ideal

5.4.2 Observations and Exploration Missions

Unlike the sample return missions, the observation and exploration missions listed here are one-way missions; none will be returning to their points of origin. Non-returning missions have a greater exploration radius than a returning counterpart. Like the returning missions, exploration missions are Class A missions and reliability is a critical concern.

5.4.2.1 Saturn Ring Rendezvous. The Saturn Ring Rendezvous mission summarized in Table 4-4 is designed to support scientific observation/radar/probe investigations of the planet Saturn, its rings, and the moon Titan. The mission is anticipated to require a seven to ten year transit time, with the scientific investigation phase requiring up to an additional two years. The mission, which lasts 9 to 13 years, will require 80-100 kW_e for propulsion and for operating its scientific payload.

Table 5-7 summarizes the parameters of the strawman implementation for the Saturn Ring Rendezvous mission.

Table 5-7. Strawman SRPS Implementation for Saturn Ring Rendezvous

Estimated Power Requirement	80-100 kW_e
System Configuration	Reference mission configuration
Radiators	Conical configuration
Shielding	Shadow shield, not man-rated; untended power-up required
Power System Mass	2,900 kg
Reactor Disposal Options	None required
Required RMA	Class A science mission requiring high reliability; reliability may be affected if reactor throttling is employed.
Lifetime Required	Mission duration is nine to thirteen years. This is up to six years greater than the anticipated single SRPS lifetime.
Assessment	Poor to good, depending on final reactor life

5.4.2.2 Far Outer Planets Probes/Orbiters. The purpose of the Far Outer Planets Probe/Orbiter missions summarized in Table 4-5 to continue the scientific exploration of the outer reaches of the solar system such as that done by the Voyager missions. Unlike Voyager, however, these probes and orbiters will not necessarily be fly-by missions. The new missions will allow detailed long-term investigations of the outer planets, including their moons, ring structures and possibly atmospheres and surfaces.

Approximately eight to eleven years must be allowed for transit to the outer planets Uranus, Neptune, and Pluto. This is one to four years longer than the present anticipated full-power life of the nuclear reactor power system and does not include the time during which the probe is conducting its exploration of the destination planet. Like the Saturn Ring Rendezvous mission, it is believed that a reactor providing 80-100 kW_e will be sufficient to cover the mission power requirements.

Table 5-8 summarizes the strawman implementation parameters for the Far Outer Planets Probe/Orbiter missions.

Table 5-8. Strawman SRPS Implementation for Far Outer Planets Probes/Orbiters

Estimated Power Requirement	100 kW_e
System Configuration	Reference mission configuration
Radiators	Conical configuration
Shielding	Shadow shield, not man-rated; untended power-up required
Power System Mass	2,900 kg
Reactor Disposal Options	None required
Required RMA	Class A science mission requiring high reliability; reliability may be affected if reactor throttling is employed.
Lifetime Required	Mission typically requires 8 to 11 years. This is outside the 7 year life of the reactor power system.
Assessment	Poor to Good, depending on final reactor life

5.4.3 Extra-Solar Spacecraft -- TAU

The Thousand Astronomical Unit (TAU) Extra-Solar mission summarized in Table 4-6 is very unique in its goals and objectives. The TAU mission will attempt to relay data from a point in space much further away than has ever been explored. Well outside of the solar system, the TAU spacecraft will provide an extremely long baseline from which scientists will be able to perform detailed measurements of the universe.

Fifty-five years will be required for travel to the 1000 AU destination. Since this is very much beyond the expected life of a single reactor power system, twin reactors will be employed. The first reactor life will only allow the propulsion phase of the mission to extend to the edge of the solar system. The second reactor is brought on-line when the spacecraft reaches its destination.

Table 5-9 summarizes the strawman implementation parameters for the TAU mission.

Table 5-9. Strawman SRPS Implementation for the Extra-Solar Mission - TAU

Estimated Power Requirement	300 - 1000 kW_e
System Configuration	Reference mission configuration
Radiators	Conical configuration
Shielding	Shadow shield, not man-rated; untended power-up required
Power System Mass	7-27,000 kg (2 reactors)
Reactor Disposal Options	None required
Required RMA	Class A science mission requiring high reliability
Lifetime Required	The life of the spacecraft is undefined. The goal of 1,000 AU is achievable in 55 years. The length of time the reactor is required to support propulsion is 10 years. A second reactor kept dormant during flight will be required in order to provide power at the destination.
Assessment	Good; two reactors required

5.4.4 Large Space Observatories

Following the initiation of permanent manned operations on the Moon, lunar-based extremely large observatories will become feasible and cost-effective. These observatories will be unmanned and based on the back side of the moon, operating primarily during the Lunar night. Nuclear reactor systems will represent the most effective means of power supply for this mission class.

The Large Array Lunar Observatory (LALO) is depicted in Figure 4-8 and its requirements are summarized in Table 4-7. The parameters of the strawman SRPS implementation for the LALO concept are summarized in Table 5-10.

Table 5-10. Strawman SRPS Implementation for Large Array Lunar Observatory

Estimated Power Requirement	130 kW_e
System Configuration	
Radiators	Daisy configuration
Shielding	Reactor is buried and surface materials are used to provide fully man-rated 4-pi shielding
Power System Mass	2,900 kg
Reactor Disposal Options	In-situ burial of reactor at end-of-life
Required RMA	High reliability preferred; reactor replacement recommended in the event of failure
Lifetime Required	7 year reactor life sufficient, with multiple replacement for 20+ yr. mission
Assessment	Ideal

5.5 SPACE OPERATIONS

There civil missions categorized as space operations represent on-going activities which are designed not only to further the colonization of space but also to expand the beneficial commercial utilization of space. The space operation mission scenarios typically have the most unique of the mission requirements.

5.5.1 Space Station

The Space Station mission is a long-term mission providing a permanently manned facility to act as the center of space activity in LEO. At first, the Space station will serve primarily as a space research center, supporting research and development activities for a variety of users; these activities will include acting as a launch point for ambitious science and exploration missions. As time goes on, the Space Station will evolve into an active node in the "bridge between worlds," supporting the transfer of materiel and personnel between the Earth and the Planetary outposts and colonies.

The Space Station mission is conveniently divisible into two areas. First is the Station operations mission, whose scope covers the core facility and related core facility activities. Second are the remote, co-orbiting platforms and free flyers performing specialized tasks that the Space Station supports. Since there are numerous free flyers and platforms that will eventually be deployed co-orbiting with the Station, the Materials Processing Factory Platform was chosen as an example for discussion.

5.5.1.1 Station Operations. At present, the IOC Space Station will not use a space nuclear reactor as a power source. However, the discussion here will assume that the use of an SP-100 SRPS in the Growth Station timeframe is a possibility.

The Growth Space Station illustrated in Figure 4-9 and described in Table 4-11 is a permanently manned facility. As such, Station operations will entail stringent limitations on total crew radiation exposure. Radiation dosages during operations, whether from the natural background or from a reactor source, will add cumulatively, until Station personnel reach a pre-determined upper biological exposure safety bound and are cycled back to Earth. Minimizing the dose rate will help to extend personnel stay times and minimize costs associated with crew launch and training.

A Space Station application reactor system should therefore incorporate an optimized shield/distance configuration for crew radiation dosage minimization without unacceptable adverse effects n projected Station operations. In addition, the permanent character of the Space Station necessitates that easy mechanisms for reactor disposal at end-of-life be devised. A variety of alternative reactor deployment schemes can be considered; these include a centrally mounted reactor, boom-mounted reactor, and a tethered reactor system.

The centrally mounted reactor requires massive 4-pi shielding for acceptable radiation levels, as well as large, high-temperature, waste heat dissipation sytems in close proximity to planned extensive manned and unmanned operations. Also, ultimate disposal of a massively shielded, centrally-located reactor represents a major challenge. A tether-mounted reactor system would entail low shield-mass requirements, however a counterbalance tethered mass would be required to maintain ultra-low accelerations at the manned laboratory modules; this mass largely offsets shielding savings. Moreover, a nuclear reactor system tethered from the upper and lower booms of the Space Station may unacceptably impact observational science missions (astro-physics, solar physics, and Earth-Observation sciences) at those sites.

Rather than mount a single large reactor in the line of flight of the Space Station, for this assessment, a twin-reactor, boom-mounted SRPS application on the Growth Space Station has therefore been assumed. Figure 4-9 provides a conceptual illustration of this application scenario. In this scenario, dual reactors are symmetrically mounted as extensions on the already assembled Space Station power array truss structures perpendicular to the line of flight. Nonetheless, a number of concerns remain.

The Growth Space Station, as currently planned, will accommodate a greatly augmented amount of manned and unmanned, vehicular and space-cuited proximity operations traffic. While reactor shielding could in theory be increased to any level, a lesser shield mass would reult in significantly reduced launch costs. In order to conserve mass, shadow, 2-pi, or 4-pi preferential shielding could be used instead of 4-pi, fully man-rated shielding. A realistic shield mass would, however, necessitate potentially strict limitations on projected proximity operations and unanticipated complications in near-Station vehicular navigation and maneuvering. In particular, utilization of shadow shielding could significantly reduce total Station vicinity working volumes; advanced Station missions rely on extended

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EVA operations over a wide volume of surrounding space (for example, one mission involves the construction of a 100-meter-diameter radiometer at the Station). Finally, the twin-boom placement, although eliminating potential center of gravity problems, would still restrict manned and vehicular traffic in the areas around the reactors because of the ambient thermal environment near the reactor radiators.

There are other factors as well that affect the decision to deploy a space nuclear reactor as part of the Growth Space Station. One such factor is the reactor lifetime. At present, the Space Station is projected to permit gradual evolution over an indefinite period of time. At present, the SRPS is designed for a seven-to-ten year normal operational life. Most probably the reactor would require replacement during the course of Growth Space Station operations. Also, several safety issues remain to be addressed. First the Station will require a back-up source of power in case of a reactor emergency. The projected dual-reactor configuration, added to the baseline IOC Space Station power systems, would answer that issue. Factors involving salvage and vehicular economics for reactor disposal from LEO have not yet fully been addressed.

For the reasons discussed above, the application of an SP-100 SRPS to the Growth Space Station is rated as POOR; although each limitation noted may be surmountable taken individually, together they represent an uncertain implementation scheme that could unacceptably impact on the cost-effective accomplishment of Growth Space Station objectives. This assessment is summarized in Table 5-11.

5.5.1.2 Materials Processing Factory Platform. While the Space Station itself may not be able to utilize an SP-100 SRPS, it is possible that one or more of its co-orbiting platforms and free flyers may benefit from the application of an SRPS. The case in point is the Materials Processing Factory Platform (MPFP) depicted in Figure 4-12 and summarized in Table 4-15.

The MPFP is an independent structure that is tended by Space Station operations. It is located some distance from the Station so that it remains undisturbed by the everyday Station activities. Being located some distance away also would allow reactor operation that would not disturb the Station environment.

The MPFP has very high power and thermal requirements. The reactor could therefore serve a two-fold purpose, as both a supply of electrical power and of clean heat for the material furnaces. The available electric power could also be used to support a small amount of electric propulsion for station-keeping purposes. Table 5-12 summarizes the strawman implementation of the SP-100 SRPS for the MPFP.

5.5.2 Planetary Bases

By far the most ambitious of all space missions is the establishment of manned scientific and exploration facilities on the surfaces of other bodies in the solar system. Based on the technology tried and proven during the implementation of the Space Station, two such bases will evolve: one on the Earth's moon and a second on the surface of Mars.

Table 5-11. Strawman SRPS Implementation for Growth Space Station Operations (on-board materials processing)

Estimated Power Requirement	330 kW_e
System Configuration	Reference mission configuration
Radiators	Conical configuration
Shielding	Man-rated 4-Pi preferential
Power System Mass	50,500 kg (two 200-kW_e reactors)
Reactor Disposal Options	
OTV/Chemical booster to SNDO	
Emergency reactor jettison capability required	
Required RMA	High RMA requirements; back-up power provided by dual reactor configuration; reactor replacement will be necessary during Station life
Lifetime Required	Mission currently designed to last 14+ years
Assessment	Poor: possible radiation hazard to station crew, high temperature hazard

Both of these bases will require power for life support systems, scientific endeavors, and for surface materials processing. Both bases will require a twin reactor configuration to provide the optimal back-up power capability. The reactors will be remotely deployed in order to minimize any hazards and permit substantial traffic around the surface facilities.

Surface materials will be used for shielding; the reactor will be buried and the surrounding soil will act as a 4-pi shield configuration. The radiators will be a daisy configuration, supported by a structure composed of surface rock and possibly locally produced concrete. The use of local materials greatly reduces the amount of materials that must be lifted into Earth orbit earlier in the supply sequence. This significantly reduces the weight of the power system and makes its application more attractive.

Table 5-12. Strawman SRPS Implementation for Materials Processing Factory Platform

Estimated Power Requirement	160 kW_e
System Configuration	Reference mission configuration
Radiators	Conical configuration
Shielding	2-Pi man-rated
Power System Mass	26,500 kg
Reactor Disposal Options	
OTV/Chemical booster to SNDO	
Emergency reactor jettison capability required	
Required RMA	Backup power source recommended for life support systems; reactor replacement during platform life may be required
Lifetime Required	Mission currently designed to last 20+ years
Assessment	Good: low personnel radiation hazard since platform is typically unattended

As the bases grow into colonies, more reactors can be added to meet the power requirements. As reactors are expended, they can be buried in-situ.

5.5.2.1 Lunar Base. The Lunar Nominal Base is depicted in Figure 4-13 and its requirements are summarized in Table 4-19. The parameters of the strawman SRPS implementation are summarized in Table 5-13.

Table 5-13. Strawman SRPS Implementation for Lunar Nominal Base

Estimated Power Requirement	200 kW_e
System Configuration	
Radiators	Daisy configuration
Shielding	Reactor is buried and surface materials are used to provide fully man-rated 4-pi shielding
Power System Mass	5,800 kg
Reactor Disposal Options	In-situ burial of reactor at end-of-life
Required RMA	High reliability required; back-up power source for life and other critical systems required, twin reactors to meet this requirement
Lifetime Required	Mission currently designed to last 20+ years
Assessment	Good

5.5.2.2 Libration Base. The Earth-Moon system Libration Base (at the L1 libration point) is a permanently manned Space Station/base, constructed in large measure from lunar materials. The key parameters for the Libration Base are summarized in Table 4-25. It is assumed in this assessment that lunar materials are available for use in constructing reactor system shielding; hence the deployment scheme envisioned is a simple boom with 4-pi shielding.

The parameters of the strawman implementation are provided in Table 5-14.

Table 5-14. Strawman SRPS Implementation for the Libration Base

Estimated Power Requirement	160 kW_e
System Configuration	
Radiators	Conical
Shielding	Single reactors are boom-deployed with 4-pi lunar material shielding
Power System Mass	2,900 kg (single reactor, excluding lunar shielding material)
Reactor Disposal Options	OTV/chemical booster/early jettison to SNDO required for reactors
Required RMA	High reliability required; reactor replacement required; dual 80-100 kW_e reactors recommended for back-up power configuration
Lifetime Required	Mission currently designed to last 20+ years
Assessment	Good

5.5.2.3 Mars/Phobos Base. The Mars/Phobos Base is a permanently manned Space Station/base, constructed on Mar's moon Phobos. It is assumed in this assessment that the reactor can be buried, as in the Lunar application scenario. The key parameters for the Mars/Phobos Base are summarized in Table 4-27.

The parameters of the strawman implementation are provided in Table 5-15.

Table 5-15. Strawman SRPS Implementation for the Mars/Phobos Base

Estimated Power Requirement	150 kW_e
System Configuration	
Radiators	Daisy configuration
Shielding	Single reactors are buried with Phobos material, 4-pi shielding
Power System Mass	2,900 kg (single 150 kW_e reactor)
Reactor Disposal Options	Buried in situ
Required RMA	High reliability required; reactor replacement recommended in the event of failure
Lifetime Required	Mission currently designed to last 20+ years, reactor replacement possible
Assessment	Ideal

5.5.2.4 Mars Base. The Mars Nominal Base is depicted in Figure 4-14 and its requirements are summarized in Table 4-31. The Mars base power system has an additional requirement of having to survive martian sandstorms. The reactor itself is buried and is safe from surface hazards. The heat radiators are immune to damage from the dust and can be secured using surface materials. It is believed that solar panels could not hold up under the long-term dust threat.

The parameters of the strawman SRPS implementation are summarized in Table 5-16.

Table 5-16. Strawman SRPS Implementation for Mars Nominal Base

Estimated Power Requirement	120 kW_e
System Configuration	
Radiators	Daisy configuration
Shielding	Reactor is buried and surface materials are used to provide fully man-rated 4-pi shielding
Power System Mass	5,800 kg
Reactor Disposal Options	In-situ burial of reactor at end-of-life
Required RMA	High reliability required; back-up power source for life and other critical systems required, twin reactors recommended to meet this requirement
Lifetime Required	Mission currently designed to last 20+ years
Assessment	Good

5.5.3 Transportation

The transportation vehicles discussed here are intended to form crucial links in the "bridge between worlds" that will enable the colonization of the Moon and Mars.

5.5.3.1 Orbital Transfer Vehicle. The NEP Orbital Transfer Vehicle (OTV) depicted in Figure 4-15 is an electrically propelled space tug that will ferry articles and materials from LEO to higher orbits and possibly even to the Moon. Because it is electrically propelled and utilizes instrument-rated shielding, it is therefore limited to moving large, delicate structures, and for use as a routine cargo bearer in a regularly scheduled supply line. The NEP OTV mission is summarized in Table 4-36.

The projected nuclear-electric OTV will operate in a fully-unmanned mode; with transfer of cargo (for example, from the Space Station to the OTV) performed by the telerobotic orbital maneuvering vehicle (OMV), or other similar systems. As a consequence, the nuclear OTV will require only shadow 2-pi. The great majority of the electrical output of the SRPS will be used for nuclear electric propulsion, with some power going to the cargo bays for environmental control.

The strawman SRPS implementation is summarized in Table 5-17.

Table 5-17. Strawman SRPS Implementation for Nuclear OTV

Estimated Power Requirement	100-300 kW_e
System Configuration	
Radiators	Conical configuration
Shielding	Varies with application (shadow 2-pi)
Power System Mass	2,900-10,000 kg
Reactor Disposal Options	OTV/chemical booster to SNDO required
	Emergency jettison capability to SNDO must be provided
Required RMA	Reactor RMA a concern; power-down capability required for EVA and repair operations
Lifetime Required	Mission life 7-10 years, within lifetime of the reactor
Assessment	Good

5.5.3.2 Manned Interplanetary Transport Vehicle. The Manned Interplanetary Transport Vehicle (M-ITV) shown in Figure 4-16 and Table 4-37 is not like the NEP OTV in that it is a cycling spaceship that will provide a service route between the Earth and Mars. It will carry passengers as well as supplies to the Mars colony. The electrical power output of the SRPS primarily supports the life support systems, with some electrical power going to the electrical propulsion system. Back-up power will be needed for the critical systems. The reactor will have a 4-pi man-rated shield in order to allow power-on EVA and approach. Lunar material might be utilized for shielding.

Table 5-18 summarizes the SRPS strawman implementation.

Table 5-18. Strawman SRPS Implementation for Manned ITV

Estimated Power Requirement	300 kW_e
System Configuration	
Radiators	Daisy configuration
Shielding	4-pi preferential, man-rated
Power System Mass	20-40,000 kg
Reactor Disposal Options	OTV/chemical booster/early jettison to SNDO required for reactor
Required RMA	Back-up power required for life support and other critical systems; dual 150-200 kW_e reactors recommended
	Reactor replacement during life of ITV may be required
Lifetime Required	Has indefinite mission life
Assessment	Good

5.5.3.3 Cargo-Carrying Interplanetary Transport Vehicle. The requirements of the Cargo-Carrying Interplanetary Transport Vehicle (C-ITV) are summarized in Table 4-38. The parameters for the strawman SRPS implementation for the C-ITV concept are summarized in Table 5-19. Strawman implementation differs from all others in this report in the following respects: (1) advanced thermal-to-electric conversion technologies have been assumed in this case, (3) multiple reactors have been assumed to meet the basic power requirement for the mission, and (2) a specific mass of 15 kg/kW_e for a 1000 kW_e class SRPS has been assumed as the baseline system for this assessment. Current SP-100 SRPS conversion technologies would result in an unacceptably high power system mass (approximately 200,000 kg) for the C-ITV application. As a consequence of these assumptions, the C-ITV assessment is not comparable to the other assessment in this section.

The projected C-ITV will operate in a fully-unmanned mode; with transfer of cargo (for example, from the Mars/Phobos base to te C-ITV) performed by a chemically propelled, telerobotic orbital transfer vehicle, or other similar systems. As a consequence, the nuclear-powered C-ITV will require only shadow shielding. The great majority of the electrical output of the SRPS will be used for nuclear electric propulsion, with some power going to the cargo bays for environmental control. Lunar material might be utilized for shielding.

Table 5-19. Strawman SRPS Implementation for Cargo-ITV

Estimated Power Requirement	7000 kW_e
System Configuration	
Radiators	Daisy configuration
Shielding	Multiple reactors are boom-deployed with limited man-tending shadow shielding
Power System Mass	105,000 kg
Reactor Disposal Options	OTV/chemical booster/early jettison to SNDO required for reactors
Required RMA	High reliability required; reactor replacement recommended in the event of failure
Lifetime Required	7 year reactor life sufficient, with multiple replacement for total mission
Assessment	Good, based on advanced power conversion

5.6 COMMERCIAL

Civil missions classed as commercial are those activities which are either controlled by or for the benefit of private industry. Two missions were chosen for study in this category: the Geosynchronous Communications Platform and the Air/Ocean Traffic Control Radar. The Materials Processing Factory Platform could well fall under this category; however, because of its close connections with the Space Station, it is discussed in Section 5.5.1, Space Operations.

5.6.1 Geosynchronous Communications Platform

The Geosynchronous Communications Platform is a commercial effort to ease the overcrowding in the geostationary orbit by providing a geosynchronous platform with shared services, such as power and attitude control, to a multitude of users.

The power requirements will vary with the number and type of users incorporated into the platform. Since the platform is unmanned, it does not require man-rated shielding. However, should a user payload require servicing, the payload must be serviced using telerobotic services, or the entire platform must be powered down to allow manned EVA.

The strawman SRPS implementation parameters for the Geosynchronous Communications Platform are summarized in Table 5-20.

Table 5-20. Strawman SRPS Implementation for Geosynchronous Communications Platform

Estimated Power Requirement	15-150 kW_e
System Configuration	
Radiators	Conical configuration
Shielding	Shadow shield, not man-rated
Power System Mass	6,000 kg @ 150 KW_e
Reactor Disposal Options	OTV/chemical booster to non-GEO SNDO required
Required RMA	Reactor RMA a concern; power-down capability required for EVA and repair operations
Lifetime Required	Mission life 7-10 years, within lifetime of the reactor
Assessment	Good

5.6.2 Air/Ocean Traffic Control Radar

The Air/Ocean Traffic Control (ATC) Radar (Figure 4-18, Table 4-40) is a single user mission that requires power to operate and station-keep a very large radar array designed to efficiently track air and ocean traffic. The power requirements vary widely with the type of technology employed and coverage desired.

Like the Geosynchronous Communications Platform, the ATC Radar does not require man-rated shielding. The same servicing requirements also apply. Safety issues are addressed by using chemical escape rockets to lift the reactor into a non-GEO orbit.

The parameters of the strawman SRPS implementation for the Air/Ocean Traffic Control Radar are summarized in Table 5-21.

Table 5-21. Strawman SRPS Implementation for ATC Radar

Estimated Power Requirement	40-200 kW_e
System Configuration	
Radiators	Conical configuration
Shielding	Shadow shield, not man-rated
Power System Mass	7,000 kg @ 200 KW_e
Reactor Disposal Options	OTV/chemical booster to non-GEO SNDO required
Required RMA	Reactor replacement during life of OTV may be required
Lifetime Required	Indefinite OTV life
Assessment	Good

SECTION 6

CONCLUSIONS

In its recent deliberations, the National Commission on Space identified a wide variety of ambitious U.S. civil space objectives. These missions run the gamut from unmanned science and exploration, to manned space operations, to private commercial operations in space. They range from low Earth orbit to beyond the farthest reaches of the solar system. In every case, the availability of electrical power at levels far greater than those that have hitherto have been required seems essential to successfully accomplishing mission objectives. During the next 10 to 30 years, the following power sources will be available for space applications: (1) electrochemical (fuel cells; used only for short-term, LEO power or systems), (2) solar-photovoltaic (PV arrays; used for Earth-orbiting and inner planet missions), (3) solar dynamic generators (reflector/heat engine systems; used where conversion efficiency or other performance, superior to PV arrays, is required), (4) radioisotope generators (small nuclear power systems; used for long-duration, low-power level missions where solar power systems do not apply), and (5) space reactor power systems (medium-to-large amounts of nuclear power; used for long-duration, high power level missions).

At the present time, the SP-100 type of SRPS represents the U.S. baseline capability for space nuclear power. A summary assessment of the applicability of the SP-100 type of SRPS to an array of projected, ambitious civil missions is provided in Table 6-1. In general, an SP-100 type of SRPS can be applied with considerable efficiency to most of the assessed missions; exceptions include: (1) the permanently manned Space Station, where safety issues remain due to planned extensive EVA and vehicular proximity operations; the safety issue for the Space Station has been addressed in this assessment by considering a scenario in which high power level, commercial materials processing activities are down-loaded to a coorbiting factory platform; and (2) Far Outer Planets/TAU Explorer missions, where very long mission durations exceed the present design RMA capability of the SP-100 type of technology; this issue could be addressed by the use of a multiple, smaller SP-100 type of reactor system to achieve comparable long-term power levels with enhanced reliability.

The availability of space nuclear power represents an integral assumption in current U.S. planning for the next 60 years of space exploration, utilization, and settlement; Figure 6-1 graphically illustrates the broad scope of challenging applications. Detailed case studies are now needed to determine where and when the application of space nuclear power represents the most cost-effective -- if not enabling -- power system alternative.

Table 6-1. Mission Requirements Summary and Applications Assessment

CIVIL MISSION APPLICATIONS OF SPACE NUCLEAR POWER	MISSION REQUIREMENTS SUMMARY						REACTOR APPLICATION SCENARIO							ASSESSMENT	
	POWER LEVEL (kWe)	EARTH ORBIT (km)	SHIELDING REQ'TS SOURCES	MISSION RMA	MISSION DURATION (years)	ADDITIONAL REQUIREMENTS	RADIATOR CONCEPT	SHIELDING NEEDED	SYSTEM MASS WITHOUT P/L (kg)	SYSTEM MASS WITHOUT P/L REQUIREMENTS	END-OF-LIFE DISPOSAL	SP-100 TYPE APPLICATION ASSESSMENT	ISSUES	ADDITIONAL REMARKS
SCIENCE AND EXPLORATION														
• Asteroid Sample Return	80-100	N/A	Instruments and samples	Critical; Class A	5-7	Multisite; deep coring	Conical	Shadow, not man-rated	2,900	1 STS/ELV; untended power-up	SHBO	Good	Reactor life, RMA, and disposal	SP-100 reference config. applies
• Comet Sample Return	80-100	N/A	Instruments and samples	Critical; Class A	12-18	Multisite; deep coring	Conical	Shadow, not man-rated	2,900	1 STS/ELV; untended power-up	SHBO	Poor to Good	Reactor disposal; critical RMA	SP-100 reference config. applies
• Mars Sample Return	80-100	N/A	Instruments and samples	Critical; Class A	4-5	Multisite; deep coring	Conical	Shadow, not man-rated	2,900	1 STS/ELV; untended power-up	SHBO	Ideal	Reactor disposal; critical RMA	SP-100 reference config. applies
• Saturn Ring Rendezvous/Explorer	80-100	N/A	Instruments	Critical; Class A	8-11	Electric propulsion	Conical	Shadow, not man-rated	2,900	1 STS/ELV; untended power-up	Saturn orbit	Poor to Good	Reactor life; critical RMA	SP-100 reference config. applies
• Far Outer Planets Probes/Explorers	80-100	N/A	Instruments	Critical; Class A	8-11	Electric propulsion	Conical	Shadow, not man-rated	2,900	1 STS/ELV; untended power-up	Planetary orbit	Poor to Good	Reactor life; critical RMA	SP-100 reference config. applies
• Thousand Astronomical Unit (TAU) Explorer	300-1000	N/A	Instruments	Critical; Class A	55 +	Electric propulsion	Conical	Shadow, not man-rated	7,000-37,000	1-3 STS/ELV; untended power-up	Out of the solar system	Good	Reactor life; critical RMA	SP-100 reference multiple reactors
• Large Array Lunar Observatory	130	N/A	Instruments; maint. crew	Accessible; maintainable	Indefinite	---	Belay	4-pi, fully man-rated	2,900	1 STS/ELV; untended power-up	Burial	Ideal	Reactor life	Local material used for shielding
SPACE OPERATIONS														
• Space Station Complex - Growth Station	300	500	Systems, crew, & expts.	Accessible; maintainable	14 +	Safe; manned proximity ops	Conical	4-pi, preferential man-rated	50,000	3-4 STS/ELV; tended power-up	SHBO	Poor	Reactor replacement req'd	Personnel hazard; dual-reactors; hi-temp hazard
• Materials Processing Factory Platform(s)	160	500	Non-tending & bio-materials	Accessible; maintainable	20 +	Few-drag; continuous op	Conical	2-pi man-rated	26,500	2-3 STS/ELV; tended power-up	SHBO	Good	Reactor replacement req'd	Backup power req'd hi-temp hazard
• Nuclear Orbital Transfer Vehicle(s)	100-300	Varies	Systems & cargo	Accessible	Indefinite	Electric propulsion	Conical	Varies	2,900 10,000	1-2 STS/ELV; tended power-up	SHBO	Good	Reactor life	Indefinite mission life
• Lunar Settlement - Nominal Base	200	N/A	Systems, crew, & experiments	Accessible; maintainable	20 +	Growth capability	Belay	4-pi, fully man-rated	5,800	1 STS/ELV; tended power-up	Burial	Good	Reactor replacement req'd	Remote/twin-reactor
• Libration Point Base	160	Lunar	Systems & crew	Accessible; maintainable	20 +	Safe; manned proximity ops	Conical	4-pi, fully man-rated	2,900	1 STS/ELV; tended power-up	SHBO	Good	Reactor replacement req'd	Personnel hazard; backup power req'd; hi-temp hazard
• Manned-Interplanetary Transport Vehicle	300	N/A	Systems, crew, & cargo	Accessible	Indefinite	Electric propulsion	Belay	4-pi, preferential man-rated	20,000-40,000	3-4 STS/ELV; tended power-up	SHBO	Good	Reactor life	Indefinite mission life
• Cargo-ITV	7000	N/A	Systems & cargo	Accessible	Indefinite	Electric propulsion	Belay	Shadow	105,000	6-8 STS/ELV; tended power-up	SHBO	Good	Reactor life	Indefinite mission life, multiple reactors, advanced power conversion
• Mars/Phobos Base	150	Mars	Systems, crew, & experiments	Accessible maintainable	Indefinite	Growth capability	Belay	4-pi, fully man-rated	2,900	1 STS/ELV tended power-up	Burial	Ideal	Reactor life	Backup power req'd;
• Mars Settlement - Nominal Base	120	N/A	Systems, crew, & experiments	Accessible; maintainable	20 +	Growth capability	Belay	4-pi, fully man-rated	5,800	1 STS/ELV; tended power-up	Burial	Good	Reactor replacement req'd	Remote/twin-reactor
COMMERCIAL UTILIZATION														
• Geosynch. Communications Platform	15-150	GEO	Systems	Maintainable	7-10	Unmanned	Conical	Shadow, not man-rated	6,000	1 STS/ELV; untended power-up	SHBO	Good	Reactor RMA a concern	Power-down req'd for EVA/repair
• Air/Traffic Control Radar	40-200	LEO	Systems	Maintainable	7-10	Unmanned	Conical	Shadow, not man-rated	7,000	1 STS/ELV; untended power-up	SHBO	Good	LEO safety reactor RMA	Power-down req'd for EVA/repair

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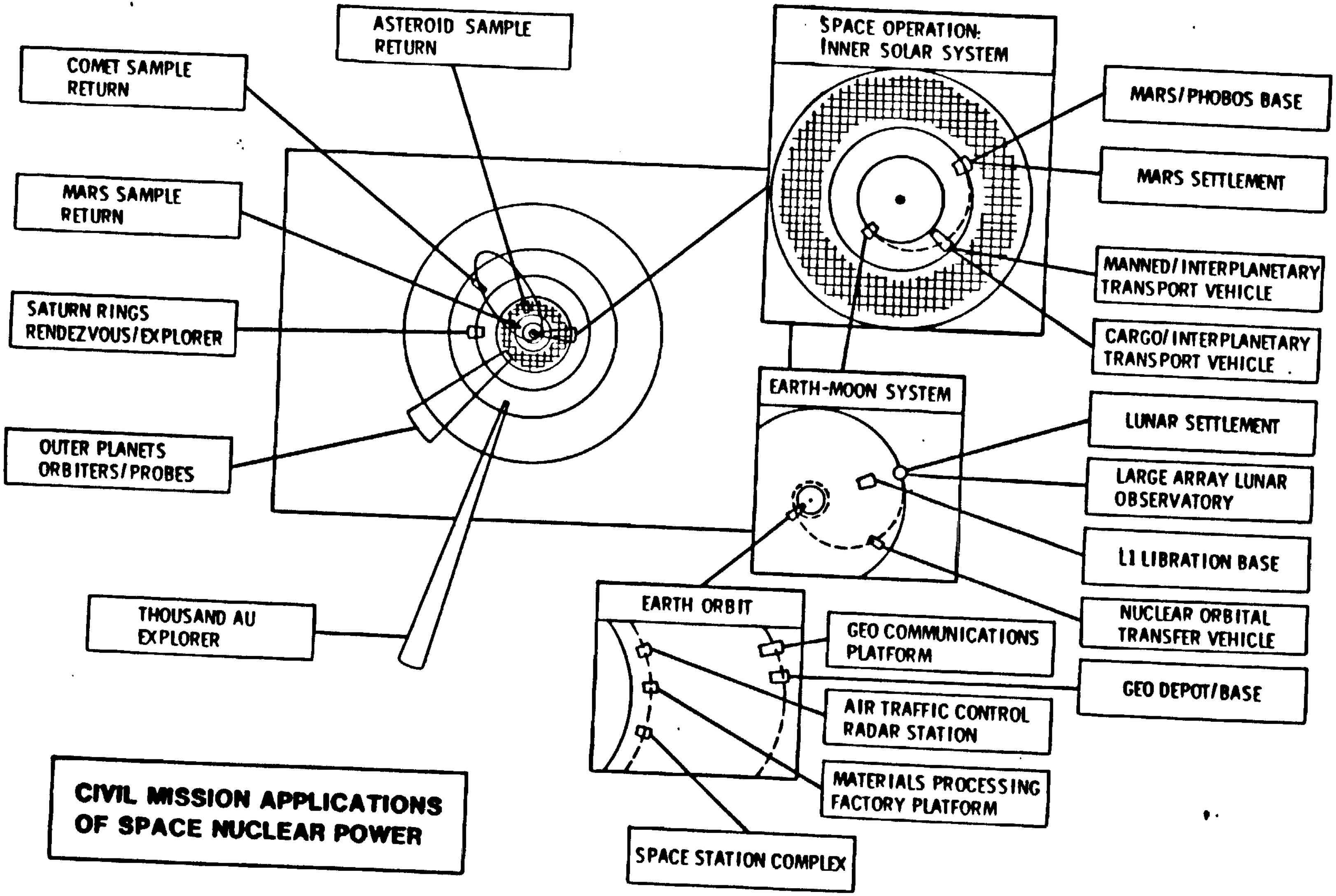

Figure 6-1. Civil Mission Applications of Space Nuclear Power

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SECTION 7

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APPENDIX A

PRINCIPAL U.S. SPACE NUCLEAR REACTOR PROGRAMS (PRE-SP-100)

Table A-1. Principal U.S. Space Nuclear Reactor Programs (pre-SP-100)

Power plant	Purpose	Power level	Operating temp, K	Period	Reactor type	Fuel	Converter	Development level
Rover	Propulsion	365-5000 MWt	2,450	1955-1973	Epithermal	UC		Twenty reactors tested. Demonstrated all components of flight engine 2 h. Ready for flight engine development
Fluidized bed	Propulsion	1000 MWt	3,000	1958-1973	Thermal	UC-ZrC		Cold flow, bed dynamics experiments successful
Gaseous core reactors	Propulsion & electricity	4600 MWt	10,000 1,500	1959-1978	Fast	Uranium plasma, UF_6	Brayton	Successful critical assembly of UF6
SNAP-2	Electricity	3 kWe	920	1957-1963	Thermal	Uranium zirconium hydride	Mercury Rankine	Development level. Tested two reactors with longest test reactor operated 10,500 h. Percursor for SNAP-8 and 10A
SNAP-10A	Electricity	0.5 kWe	810	1960-1966	Thermal	Uranium zirconium hydride	Thermoelectric	Flight tested reactor 43 days. Tested reactor with thermoelectrics in 417-day ground test
SNAP-8	Electricity	30-60 kWe	975	1960-1970	Thermal	Uranium zirconium hydride	Mercury Rankine	Tested two reactors. Demonstrated 1 year operation. Non-nuclear components operated 10,000 h and breadboard 8700 h
Advanced hydride reactors	Electricity	5 kWe	920	1970-1973	Thermal	Uranium zirconium	Thermoelectric Brayton	PbTe thermoelectrics tested to 42,000 h
Medium power reactor experiment	Electricity	140 kWe	1,365	1961-1966	Fast	UO_2	Potassium Rankine	Stainless steel loop tested up to 2500 h. Fuel tested 14,000 h
SNAP-50/SPUR	Electricity	300-1200 kWe	1,365	1962-1965	Fast	UN, UC	Potassium Rankine	Fuels test to 6000 h
Advanced metal-cooled reactor	Electricity	300 kWe	1,480	1965-1973	Fast	Uranium nitride	Brayton and Potassium Rankine	Non-nuclear potassium Rankine cycle components demonstrated to 10,000 h. Ready for breadboard loop
710 gas reactor	Electricity & propulsion	200 kWe	1,445	1962-1968	Fast	UO_2	Brayton	Fuel element tested to 7000 h
In-core thermionic reactor	Electricity	5-20 kWe	2,000	1959-1973	Fast or thermal driver	UO_2 Uc-ZrC	In-core thermionics	Integral fuel element, thermionic diode demonstrated 1 year operation
Nuclear electric propulsion	Electricity	400 kWe	1,675	1974-1981	Fast	UO_2	Out-of-core thermionics	Limited testing of thermionic elements
SPAR	Electricity	100 kWe	1,500	1979-1982	Fast	UO_2	Thermoelectric	Limited testing of core heat pipes and advanced thermoelectric materials

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APPENDIX B

THE MATERIALS PROCESSING FACTORY PLATFORM

APPENDIX B

THE MATERIALS PROCESSING FACTORY PLATFORM*

The Materials Processing Factory Platform will support a variety of missions. The three main uses of the platform will probably be crystal growth, biological materials processing, and glasses and fibers production. Special processing techniques are used in each area.

B.1 CRYSTAL GROWTH

Semiconductor crystal growth missions use electroepitaxial crystal growth (ECG), chemical vapor transport growth (VCG), and directional solidification (DSCG). The ECG and VCG methods will be for growing gallium arsenide crystals, which are used for semiconductor products. The DSCG method can be used to produce both semiconductors and metals.

The ECG method uses an electric current to grow the crystals. A saturated solution of a few percent gallium arsenide in gallium is brought into contact with a monocrystalline seed crystal and a polycrystalline source crystal. An electric current is established normal to the seed-solution interface, causing the arsenic ions to migrate toward the seed crystal and to crystallize with the solvent on the surface of the seed. The process is carried out in a furnace to maintain precise control of the crystal growth temperature, around 800-900°C.

The electrical power required for electroepitaxial growth of gallium arsenide depends on both the temperature and thickness of the crystal. At a furnace temperature of 875°C, the energy required to grow 1-cm thick gallium arsenide crystals in five days is about 66 kWh/kg. In addition to the power required for the growth current, 40 kWh/kg is required to maintain the furnace temperature for five days. The power load is then 66 kWh/kg of uninterruptible DC electric power at 28 Vdc, plus 40 kWh/kg of interruptible power for additional heating.

The VCG method involves transport of the crystalline elements from a source to a growth crystal in the vapor phase. A polycrystalline source of material is heated in the presence of a gaseous transport agent. A chemical reaction between the source and the transport agent results in exclusively gaseous products, which are removed from the source. The growth crystal is located at the other end of the growth ampoule, and is maintained at a lower temperature than the source material. The gaseous products are transported down the temperature gradient to the growth crystal, where they undergo the reverse chemical process and condense into the original chemical product, in monocrystalline form.

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*Source: S. W. Silverman et. al., "Applicability of 100 kW_e-Class Station Mission: Final Report" (see Reference Section for complete bibliographic information)

DSCG techniques can be applied to both semiconductors and metals. The material to be crystallized is melted in a crucible within a furnace. The furnace's temperature profile encompasses temperatures above and below the melting point. Crystal growth occurs at the cooler end of the crucible. The crucible is either stationary or it is slowly pulled out of the furnace and down the thermal gradient. In either configuration, crystal growth proceeds as a result of heat transfer from the melt.

B.2 BIOLOGICAL MATERIALS PROCESSING

Continuous flow electrophoresis (CFE) and isoelectric focusing would be used for processing such biological products as hormones, cells, pharmaceuticals, and interferon. The major power requirement is for the DC power maintaining the electric field in the apparatus. Other power consumers are the refrigeration units and fluid pumping.

In CFE, a liquid buffer solution is located between two electrodes. A potential difference between the electrodes establishes an electric field in the solution. Those components of the material being separated which have the highest electric mobility move the fastest to one electrode. After some time in the field, the various components of the material are separated. The continuous processing, larger volume, longer time in the electric field, and lack of convection in space allow much higher materials throughput, higher yield from a given quantity of sample material, finer separations, and greater purity of product material than can be achieved on Earth.

Isoelectric focusing works similarly to CFE. The buffer solution establishes a pH gradient when the electric field is imposed. Since the mobility of the material to be separated varies with the pH of the buffer, the sample material moves in the direction of the gradient to a particular value of the pH, the isoelectric point. The products are well-focused within the pH gradient and then collected, as in CFE. Since the pH environment of isoelectric focusing is extreme, it is not suitable for processing of living cells.

B.3 GLASSES AND FIBERS

The main component of a space facility for processing glass in space will be the furnace. The furnace will function both as a programmable power supply for heating and as a positioning control system for holding the melt in place. The material sample would probably be heated by absorption of some sort of electromagnetic radiation, most likely in the microwave or infrared range. Electron beam impingement and solar concentrators might also be used to heat the sample. Although the melting temperature of most of the candidate glasses is very high, the actual heating power load may be quite low, since containerless processing eliminates conductive and convective heat losses. Heat losses can be further minimized by using infrared reflecting walls.

Several means can be used to position the heated samples in space. For example, they can be attached to a sting which holds them in place by surface tension, but this method may result in heterogeneous nucleation and conductive heat loss to the sting. Or, if the samples can be allowed to come into contact with a cover gas, they can be held in place by acoustic pressure driven by loudspeakers in the walls of the chamber. In addition, truly containerless processing in a vacuum can be achieved by positioning the sample with either electromagnetic or electrostatic forces.

Some of these processing techniques have already been tested in space aboard the space shuttle. As research progresses, both on the ground and in orbit, all these techniques will be refined and adjusted to the space environment in preparation for the launch of the MPFP.