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Civilian Uses of Nuclear Reactors in Space

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The potential for civilian mission applications of space nuclear reactor power systems is addressed in this paper. A wide range of possible civilian missions, including human and unmanned solar system exploration, are identified, along with earth-orbit applications. These missions would require versatile, high-capacity space power systems whose attributes can best be provided by nuclear technology. The long mission durations, the high power levels required to fulfill many of the challenging mission objectives, and in some instances the lack of solar energy render the use of nuclear power sources as either mission-enabling or very advantageous.

CIVILIAN SPACE MISSIONS

Since the 1960s, NASA has used nuclear power sources in the form of radioisotope thermal generators (RTGs) for many successful scientific and exploration missions. RTGs are proven, highly reliable power sources that are indispensable to NASA's long-duration, deep-space missions. RTGs successfully powered the Viking missions to Mars, the Apollo Lunar Surface Experiment Packages (ALSEPs), and continue to provide power to the Voyager and Pioneer spacecraft as they head toward the outer reaches of the solar system some 10 and 16 years after launch.

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However, several recent studies have identified future civilian space missions for which RTGs and other contemporary power sources will be inadequate and which will require high-power nuclear reactor systems. These missions' planning studies were characterized by a long-term view of US space ventures in the 21st Century and provided the basis for the National Space Policy of 1988, which established the long-range civil space goals for the United States.

This paper addresses potential NASA space missions that are facilitated or significantly enhanced by the use of nuclear power sources. The source data for this forecast builds upon the earlier studies,[1,2,3,4] and the most recent efforts performed by NASA's Office of Exploration.[5]

Figure 1 outlines NASA's current scientific and operational planning interests; it attempts to classify the broad range of civilian space applications of nuclear power by mission and function.

The outer solar system applications might be in unmanned probes to investigate planetary bodies far beyond Mars. These include Saturn, Uranus, Neptune, and Pluto, as well as asteroids and comets.

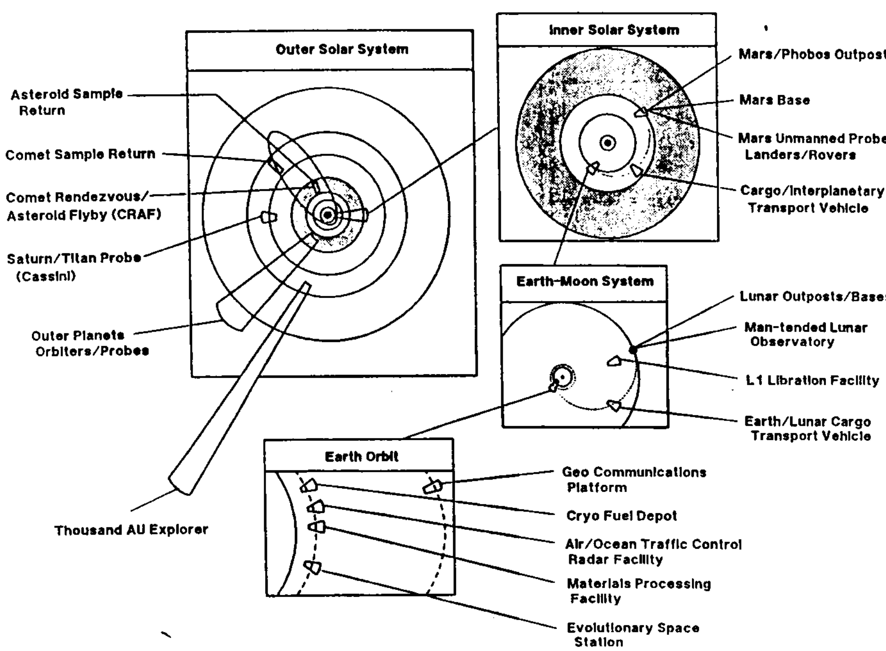

Figure 1: Civilian Mission Applications of Nuclear Power

Source: NASA

Assignments depicted for the inner solar system focus primarily on unmanned and human exploration of Mars and its moons. These might involve unmanned precursor probes, landers, and surface rovers, as well as moves toward human expeditions, outposts, and bases. Also included in this category are electrically propelled cargo transport vehicles.

Nuclear powered operations in the earth-moon category include lunar landers and surface rovers, permanent human outposts and bases on the lunar surface, human-tended lunar observatories, and, possibly, cargo transport vehicles using advanced propulsion systems. Examples of potential earth-orbit applications are shown.

We consider in detail three general categories: human exploration of the solar system, interplanetary nuclear-electric propulsion with emphasis on unmanned exploration missions, and earth-oriented applications.

HUMAN EXPLORATION

NASA's Office of Exploration (OEXP) was formed in June 1987 to study and compare alternative scenarios for human exploration of the solar system with initial emphasis on lunar and martian exploration.

In 1988 OEXP examined an initial set of four case studies:

- Human expedition to Phobos
- Human expedition to Mars
- Lunar observatory
- Lunar outpost to martian outpost.

An important element of these case studies was the determination of electrical power system requirements and characteristics, as well as identification of alternative power systems that could meet those requirements.

A number of missions were identified where the availability of high levels of power is essential for their accomplishment. These activities included sustained human planetary surface operations, interplanetary electric propulsion for cargo transportation, cryogenic fuel storage and transfer operations, and space-station-support operations for on-orbit assembly, checkout, training, and mission vehicles staging.

Planetary Surface Operations

Reliable, long-life electrical power sources (similarly to utility-type power stations on earth) installed on the surface of the moon, Phobos, or Mars would be essential for human exploration and the exploitation of natural resources. Power would also be required for manned and unmanned rover vehicle operations.

Four categories of human planetary bases have been defined so far: their power requirements are exhibited in table 1. In table 2, the planetary surface mission objectives and activities of interest for each of these bases are listed.

The power levels required to support the human outpost and human base operations for extended space science research and development and production of in-situ resources are estimated to range from hundreds of kilowatts to megawatts of electric power.

The primary minerals available from the lunar surface contain oxygen, silica, and the metals iron, magnesium, titanium, and aluminum. The lunar regolith (the unconsolidated residual or transported material that overlies the solid surface rock) also contains a high concentration of glass from micrometeorite bombardment.

To exploit these resources, the raw material must first be collected

Table 1: Planetary Surface Stationary Power Requirements

	Power level *kW*	**Power life**	**Source**
Human-tended lunar observatory	< 100	years *sustained*	Solar/reactor
Initial human sortie mission	< 100	< 60 days	Solar
Human outpost	100–600	years *sustained*	Reactor
Human base *with resource processing*	2–20 MW	years *sustained*	Reactor

and then processed. Refinement might involve hydrogen reduction, carbothermal reduction, hydrofluoric acid leach, magma electrolysis, or vapor phase reduction; all these processes require heat. The amount of thermal energy needed to treat these minerals depends largely on the their specific heats and melting points. From the cases examined, these are necessarily high energy-intensive activities. Available power (thermal or electrical) clearly limits the extent of such human enterprises.

For continuous, long-duration surface operations at sites with extended night periods, high-capacity nuclear reactor power systems can play a pivotal role, and thus, we believe, they constitute a mission-enabling technology.

A reactor power system does not have the mass penalty that would be associated with an extensive energy storage system, being independent of local day/night cycle duration or variations. For the high power levels of interest, the mass advantages of nuclear reactor power systems compared with advanced solar photovoltaic systems (including the electrochemical

Table 2: Planetary Surface Operations

Human-tended lunar observatory	**Initial human sortie mission**	**Human outpost**	**Human base** *with resource processing*
Very low frequency array	Habitat *2–4 crew*	Habitat *15 crew*	Habitat *24 crew*
Optical very large array	Laboratory	Additional labs	Research facilities
Stellar monitoring telescopes	Science experiments	Extended science	Sustained science
Moon-earth radio interferometer	LOX* pilot plant production	In-situ resources	Increased LOX
Solar observatory	Site preparation	CELSS† research	Metals production
Radio telemetry for SETI‡	Rovers/trailers	Surface surveys	Manufacturing
Local geological traverses in unpressurized rover	Lander/ascent vehicle		Ceramics production
Geophysical stations			Food production
			Product export

* Liquid oxygen
† Controlled ecological life support system
‡ Search for extraterrestrial life

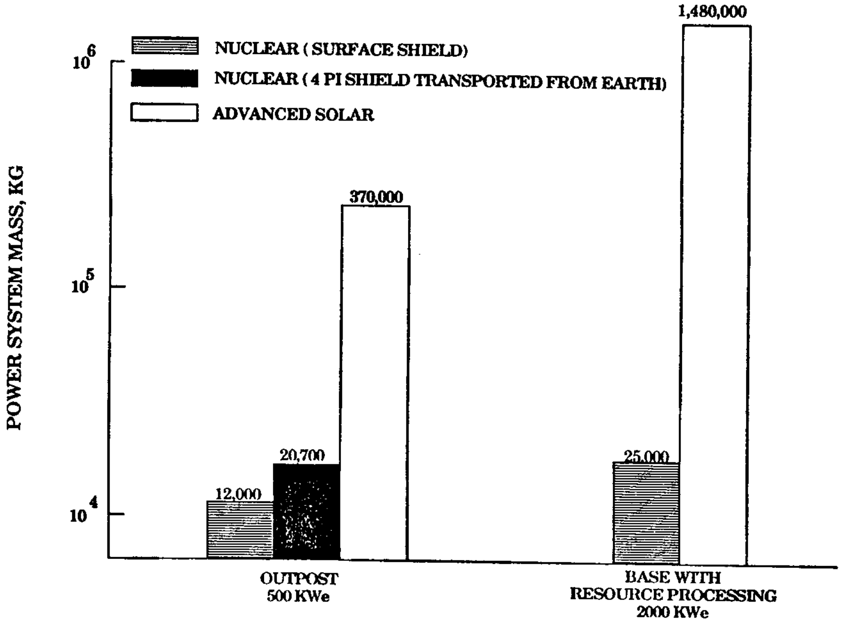

Figure 2: Mass Comparison of Lunar Surface Power Systems

Source: NASA

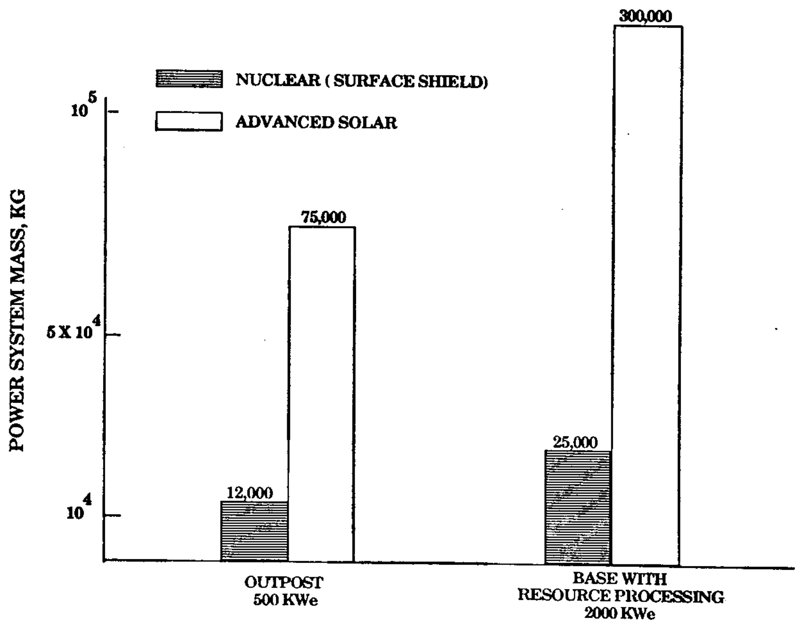

Figure 3: Mass Comparison of Martian Surface Power Systems

Source: NASA

energy storage system) are shown in figure 2 for two reactor shielding cases, i.e., a 4-π man-rated radiation shield (completely surrounding the reactor) transported from earth to the moon, and a similarly rated shield that uses lunar soil as the shielding material and eliminates this transportation requirement.

The nuclear reactor power system used for comparison consists of a SP-100 type reactor coupled with a free-piston Stirling power conversion system. The mass estimates for the advanced solar power generation and storage system assume advanced photovoltaic arrays with 20-percent efficient gallium arsenide solar cells (with a mass specific power of 300 watts per kilogram) together with a very high performance hydrogen/oxygen regenerative fuel cell (RFC) storage system with a round-trip storage efficiency of 70 percent and an assumed mass specific energy of 500 Whrs/kg.

The reactor system has a substantial mass advantage when compared with even a very advanced solar-energy system concept. This is primarily because of the large mass of the energy storage system a solar power source would need. Consider, for example, the lunar outpost. The bulk of the energy storage system would comprise the RFC reactants and their associated tankage and plumbing—approximately 370,000 kilograms split about equally between the two system elements.

A similar overall power-system mass comparison is shown in figure 3 for sustained operations at a martian outpost and base. For this case the solar system mass disadvantage is less than for the lunar case because the martian night is only about 12 hours. Nevertheless, the mass difference is still significant for any large-scale surface operations.

The mass difference in these two cases becomes more dramatic when one considers the associated required mass delivery to the low earth or staging orbit. For every kilogram of mass delivered to the lunar surface, approximately five kilograms needs must be put into low earth orbit (LEO). Most of this mass is the propellant required to transport the payload from LEO to the lunar surface. The analogous ratio for Mars is approximately 6.5.

This is illustrated in figure 4, where the mass savings to LEO of a lunar or martian nuclear power system compared with a solar power system are shown graphically for both the outpost and base applications. These mass savings to LEO can be translated to cost savings in terms of

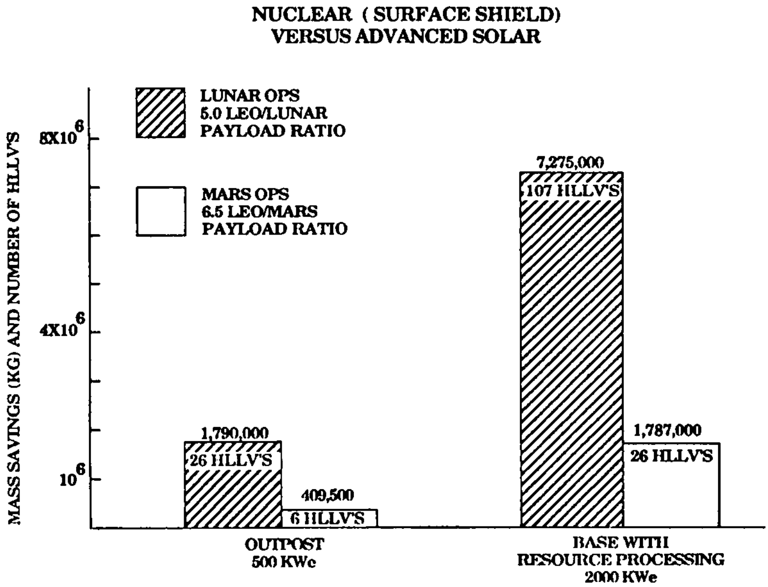

Figure 4: Mass Savings in LEO for Lunar and Mars Operations

Source: NASA

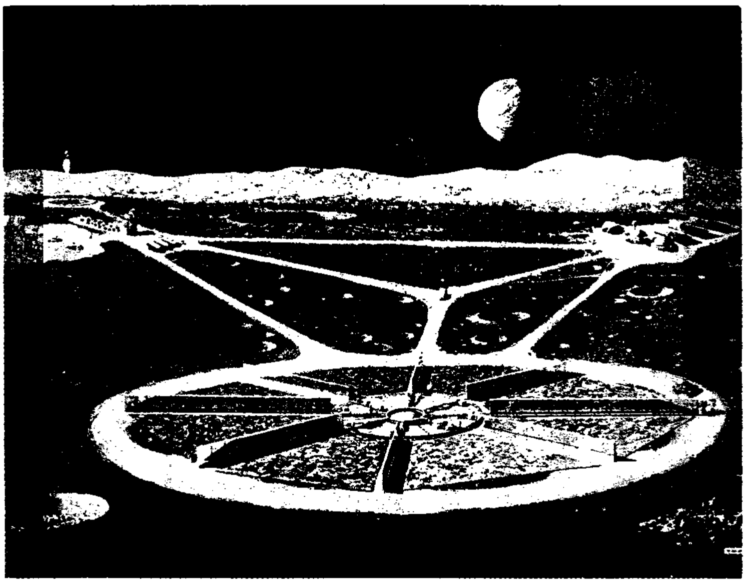

Figure 5: Nuclear Power Plant Installation—Lunar Outpost

Source: NASA

the number of launches of heavy lift launch vehicles (HLLVs), assuming in this case, a 68-tonne (150,000-lb) HLLV payload capability to LEO.

Figure 5 illustrates how a nuclear utility power system might look for a lunar base. The power system installation, capable of 825 kilowatts of electrical-power generation for seven years, is depicted in the foreground. A 2.5-megawatt-thermal SP-100 type reactor is coupled to eight free--piston Stirling power converters. For this case, two power converters are held in reserve, with the remaining power converters planned to operate nominally at 91.7 percent of rated capacity. The reactor is shown located at the center in an excavated cylindrical hole that provides some gamma and neutron radiation shielding for the installation. Eight vertical radiator panels extend radially from the power converters, and a thermal reflective shield is placed between the panels to help reduce the local lunar surface temperature to 222 K during power system operation. The radiator surface design temperature is 525 K, and the assumed thermal-to-electric efficiency for this conceptual power system design is 33 percent.

LEO Logistics Support Operations

The human exploration scenarios being examined by the Office of Exploration necessarily involve delivery and storage of very large amounts of cryogenic propellant in LEO. These scenarios have assumed the need for a cryogenic fuel depot in LEO to serve as an orbiting gas station for lunar or martian transportation vehicles.

Possible methods of transporting liquid hydrogen and oxygen propellants from the earth's surface to the cryogenic fuel depot include conveying them directly via heavy lift launch vehicles, or transporting water to the fuel depot, electrolyzing the water in LEO and then liquefying the resultant oxygen and hydrogen in orbit. Since water is easier to handle and store than cryogens, the latter method may result in simplified tank designs, launch logistics, and payload handling, but all at the expense of higher in-orbit fuel depot power requirements. The required power level could be of the order of hundreds of kilowatts based on preliminary studies.

Three of the four exploration case studies examined by NASA require mission vehicles so massive that assembly in space appears to offer the only viable operational approach. This gives rise to the need for a LEO transportation node that can serve as an assembly, checkout, training, and staging base for the mission vehicles. These functions can be accommodated at an evolutionary space station, or at separate facilities that would be established in LEO. If power levels approaching the megawatt range were determined to be required to support these operations, a compact, high-performance nuclear reactor power source could be a likely candidate for this application.

INTERPLANETARY NUCLEAR-ELECTRIC PROPULSION

Two other future applications, in which nuclear reactor power systems can play a very significant operational role, are associated with interplanetary electric propulsion systems.

The first, application of nuclear-electric propulsion cargo vehicles for large-scale economical logistical support of human exploration of the moon and Mars will require propellent exhaust velocities on the order of 30,000–100,000 meters per second. These velocities are ten or more times higher than that of the highest energy chemical propulsion systems.

Use of electric propulsion cargo vehicles for interplanetary transfer of equipment and materiel are an integral part of the lunar-outpost-to-martian-outpost case studies. In fact, the use of such vehicles was found to be necessary, because advanced chemical-propulsion cargo vehicles would have required delivery of unacceptably large amounts of propellant to LEO. The electrical power levels required to drive the necessary thrusters—in the megawatts range—and the low specific mass requirements can be furnished in space only by high performance nuclear reactor power systems.

Compact high-capacity power capability of reactor systems can enable unmanned deep-space exploration missions of high scientific interest. The basic advantage of nuclear power sources for these applications is that they are independent of available solar energy. Figure 6 illustrates the dramatic fall-off in available solar energy flux beyond the inner planets as distance from the sun increases.

With the thruster performance possible from reactor systems, spacecraft mission trip times to the outer planets can be significantly reduced by application of nuclear-electric propulsion (NEP), which will require lower spacecraft mass than alternative propulsion systems for a given

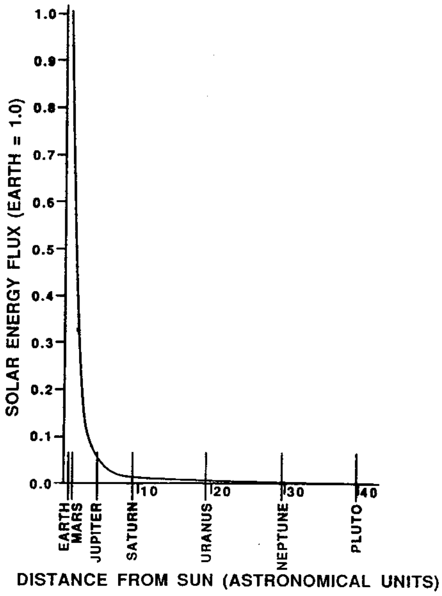

Figure 6: Solar Energy Flux as a Function of Distance from the Sun

Source: NASA

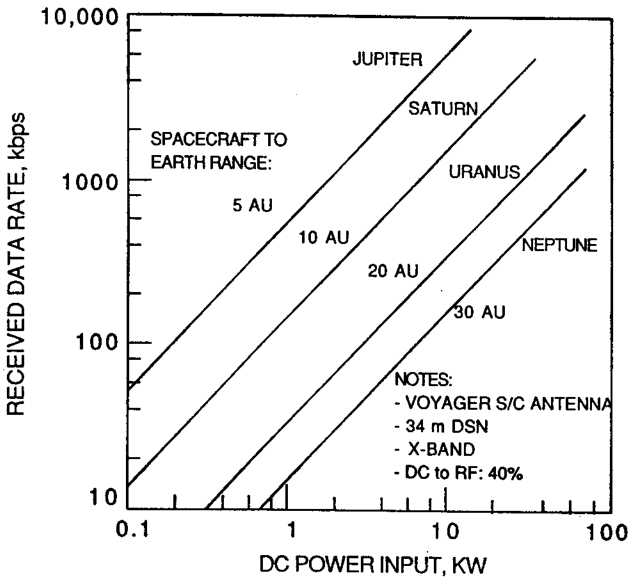

Figure 7: Enhanced Data Rates with Increased Power

Source: NASA

power and mission payload. The earth-to-orbit transportation system delivers the mission vehicle, including the space propulsion system, into LEO; the NEP system is then employed via a "slow" (low thrust) spiraling-out earth escape trajectory that finally attains the desired outer space destination.

The approximate minimum mission flight times to Saturn, Uranus, and Neptune are shown in table 3 for various types of propulsion systems. These are based on the assumptions of a fixed mission payload and single launch constraint and show significant trip-time savings using nuclear-electric propulsion.

Shorter flight times can also provide significant cost savings in both tracking and communications functions. By increasing the power level available for the NEP system, flight times can be further reduced, as shown in table 4 for a mission to Neptune.

Other benefits to be gained from higher power levels, which could be significant in mission planning and operations, are shown in figure 7. Greater available spacecraft power levels could enhance the communica-

Table 3: Flight Times to Far Outer Planets with Different Propulsion Systems *years*

	Nuclear-electric propulsion	Solar-electric propulsion	Chemical propulsion
Saturn	5	6	7
Uranus	8	11	12
Neptune	11	16	17

ASSUMPTIONS
Available electric power: 100 kilowatts electric
Payload : 1,500 kilograms
NEP spiral escape
Single shuttle launch constraint
Chemical booster for solar and chemical propulsion
Solar and chemical propulsion utilize gravity assist

Table 4: How Flight Time to Neptune Would Vary with Power Level

Power level *kWe*	100	200	300	400	500
Flight time *years*	11.0	9.3	8.5	8.0	7.8

Assume exhaust velocity = 50,000 meters per second tions link. If transmission power is increased, the required size and number of the receiving antennas could be reduced. Further, data return rates of spacecraft have been increasing historically, and since greater transmitted power improves the signal-to-noise ratio of the link, then much higher rates are feasible.

Another potential benefit from higher spacecraft power availability is enhanced overall scientific return from the missions. Future missions utilizing the higher spacecraft power levels could consider increasing the scientific return by allowing the incorporation of such features as imaging radar capable of resolving small ground features from a distant planet's orbit. This and other examples are noted in table 5.

Finally, the additional flexibility afforded by NEP could have a significant benefit in reducing launch-window constraints. Current perform-

Table 5: How Science Capability Increases with Power Level

		kWe
Radar		
Altimeter/ranging	Tracking from 10,000 kilometers	0.1–1.0
sounder	Deep subsurface mapping	0.5–5.0
Planetary mapper	Distant mapping	1–200
Synthetic Aperture	Increased resolution/detail	0.5–1.0
Laser		
Bombardment	Remote, detail surface spectroscopy, debris and cloud penetration/detection	0.1–1.0
Radio		
Occultation	Increased RF signal depth into planetary atmosphere: ♦Jupiter 0–40 kilometers ♦Saturn 10–60 kilometers ♦Uranus 30–40 kilometers	≥20
Transmission	Increased science data rates, maintain current Deep Space Network sensitivity, relaxed pointing, size, and testing	
	♦1,000 kbps - Jupiter	2
	♦1,000 kbps - Neptune	80
Low temperature	Additional cryogenic cooling for more/larger sensors and transmitters	1 per 10 watts cooling

ance-limited chemical space propulsion systems often require gravity-assisted maneuvers around the earth or planetary bodies to reach the outer planets. These maneuvers impose severe launch-window constraints in many cases. With comparable trip times, a nuclear-electric propulsion system could provide a more direct trajectory, resulting in much more frequent earth launch opportunities.

A number of potential NASA unmanned exploration missions have been identified where nuclear reactor power systems can be either enhancing or essential for mission success. One sampling of these missions and the effects of available power levels are illustrated in table 6. The power requirements are presented in terms of three power and space propulsion scenarios. The first scenario represents the current baseline power requirements for the proposed missions. These power levels are generally low and correspond to the capability of current state-of-the-art power systems. The second scenario corresponds to much higher power levels, and indicates those missions whose science return could be significantly enhanced by use of a nuclear reactor power system. The third scenario indicates those missions that could be enhanced or enabled with nuclear-electric propulsion (NEP). The ambitious Thousand Astronomical

Table 6: Summary of Power Level Impact Scenarios

	scenario		
	I	II	III
Comet-Rendezvous and Asteroid Flyby	♦		♦
Cassini *Saturn orbiter and Titan probe*	♦	♦	♦
Mars rover and sample return	♦		
Mainbelt asteroid	♦	♦	♦
Mars aeronomy observer	♦	♦	
Solar probe	♦		
Asteroid sample return	♦	♦	♦
Outer planet probes	♦	♦	♦
Icarus lander	♦		
TAU*			
Comet nucleus sample return	♦	♦	♦

SCENARIO KEY
I: 0.1–10 kilowatts electric science, chemical propulsion
II: 10–100 kilowatts electric advanced science, chemical propulsion
III: 100–120 kilowatts electric advanced science and NEP

* dual 1-2-megawatt-electric reactors may be needed to achieve reliable power for the extremely long mission life

Unit (TAU) Explorer is representative of an mission endeavor of high scientific interest that can only be undertaken with a long-life NEP system.

Much of the advantage of using an electric propulsion system results from operating it from LEO to earth escape. In terms of initial mass in LEO, the performance benefit is approximately two to one—twice as much of the mass placed in LEO with an NEP system is useful payload compared with a chemical propulsion system. Specifically, the NEP's high specific impulse can boost approximately 88 percent of the initial vehicle mass out of earth orbit, whereas a high-thrust chemical propulsion system with an exhaust velocity of 4,700 meters per second can boost only about 44 percent of its initial mass out of earth orbit.

EARTH-ORIENTED APPLICATIONS

Earth-oriented applications of significant interest for the 21st century that could conceivably use nuclear reactor power systems include air and ocean traffic control, microgravity materials processing, and communications.

Air and Ocean Traffic Control

The US Federal Aviation Administration (FAA) does not currently have the ability to track noncommunicating aircraft after they have passed more than 180 miles from either of the North American coastlines.

Space-based radar satellite systems, most likely operating at 1,000–3,000-kilometer orbits in the Van Allen radiation belt, could offer significant advantages for future civilian air and ocean traffic control operations. Preliminary analyses[6] of space-based radar systems for aircraft traffic control have yielded potential power requirements in the range of 50 to 200 kilowatts electric, depending on such specific factors as mission characterization, resolution, orbit altitude, number of targets, range of coverage, and antenna size. At these mid-altitudes, photovoltaic systems encounter the problem of sustaining acceptable efficiencies due to the damaging radiation environment. Low (200–400-kilometer) orbit operations appear to be impractical because of the number of radar platforms that would be needed to provide for continuous coverage of the target zones.

Microgravity Processing
The microgravity conditions of space are believed to be very conducive to the production of high-quality electronic materials (crystals); metals, glasses, and ceramics; and biological materials (protein crystals); and to the development of advanced chemical processing techniques.

Communications
Space platforms will likely play a substantial role in the development of high-data-rate communications—including direct broadcast video, closed-circuit teleconferencing, electronic mail transmission, and mobile communications.

These various applications for the 21st century and their power implications are now being studied. It is too soon, however, to determine whether and the extent to which space-based nuclear power could contribute significantly to their implementation.

OPERATIONAL SAFETY ASSURANCE

Although operational safety assurance is outside the main theme of this paper, it is important to emphasize that safety is an intrinsic and critical component of the technology development program now under way. Any launch and space operation of a nuclear power source will have to be fully compliant with all relevant US safety recommendations, criteria, guidelines, and standards to ensure mission operations safety.

This is wholly consistent with past and present practices regarding nuclear system developments and operations. The current SP-100 space reactor technology development program considers safety as a high priority, integral part of the development program. For example, the operational safety considerations for a generic SP-100 system design are currently being assessed for all mission phases from prelaunch to final disposition. These are shown in table 7, and best illustrate the level of safety awareness in this reactor technology development program.

SUMMARY

For human exploration of the moon and Mars, nuclear reactor power systems are essential for outposts or bases requiring hundreds of kilowatts to multi-megawatt power levels. Likewise, nuclear reactor power systems in the 2–10-megawatt power range will be required for the high-performance electric-propulsion cargo vehicles that will be needed to transport the vast amount of material necessary to assemble and sustain planetary manned outposts and bases. The use of nuclear reactor systems with 30–120-kilowatt-electric power outputs, when combined with an electric propulsion system, can significantly reduce the flight times for unmanned scientific probes to the far reaches of our solar system.

Space-based nuclear reactor power systems may also one day be use-

Table 7: SP-100 Operational Safety Considerations

Prelaunch ground handling considerations

- Non-operating and free of radioactive fission products
- Unirradiated fuel presents no radiation hazard
- Fuel primarily uranium-235 with traces of uranium-234
- Uranium-235 and -234 are alpha emitters—readily blocked
- Multiple radiation barriers
- Negligible radiation levels escape reactors

Launch and ascent considerations

- Designed to prevent accidental startup during:
  nominal launch ascent, or
  accidental re-entry resulting in water immersion, soil burial or impact on granite
- Insufficient energy exists during credible accidents to expose fuel
- Total radioactivity in the core is small and represents a negligible biological hazard even if exposed

Space operations considerations

- Started after reaching operational orbit or planetary surface destination
- No reactor core disruption due to power system component failure
- Rapid shutdown if core endangered
- Reactor design provides a final shutdown at end of mission

ful for earth-oriented applications, such as GEO communications platforms, and LEO microgravity materials processing facilities.

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