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Paper Session III-B - Journey into Tomorrow: Developing Nuclear Propulsion for the Space Exploration Initiative

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JOURNEY INTO TOMORROW:
DEVELOPING NUCLEAR PROPULSION FOR THE SPACE EXPLORATION INITIATIVE

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ABSTRACT

The Space Exploration Initiatve (SEI) calls for a return to the Moon and carrying out human exploration of Mars. Trips to Mars involve considerably more time and more complex operations than trips to the Moon; hence, there is a keen interest in developing better space transportation systems. Nuclear propulsion, either nuclear thermal propulsion (NTP) or nuclear electric propulsion (NEP), offers the potential of reduced trip times and/or reduced mass into low Earth orbit, compared to chemical propulsion systems . In addition, the greater performance benefits of nuclear propulsion can provide the added margin for greater operational flexibility, including mission abort options and increased launch windows. During the 1950's and 1960's, experimental and analytical studies showed the feasibility of nuclear propulsion. NASA, in cooperation with other agencies and organizations, is currently planning a technology development program for nuclear propulsion. The overall objective is to develop at least one NTP concept and one NEP concept for piloted and robotic (e.g., cargo) missions to Mars.

BACKGROUND

On July 20, 1989, the 20th anniversary of the Apollo 11 lunar landing, President Bush committed the United States to a long-term vision of space exploration. He stated: "First for the coming decade--for the 1990's--Space Station Freedom--the critical next step in all our space endeavors. And next--for the new century--back to the Moon. Back to the future. And this time, back to stay. And then--a journey to another planet--a manned mission to Mars."

Later that year, the President approved a national space policy, reaffirming that a long-range goal of the civil space program is to "expand human presence and activity beyond Earth orbit into the solar system." As part of the Fiscal Year (FY) 1991 budget, the Bush Administration strongly endorsed the Space Exploration Initiative, a focused, multi-decade program of human exploration of the Moon and Mars. In a speech on May 11, 1990, President Bush expressed a desire to have astronauts on Mars by the time of the 50th anniversary of the Apollo 11 landing, in 2019. The Synthesis Group made the recommendation that the first Mars landing be even earlier than that.

A number of studies, such as those conducted by NASA, the National Research Council, and the Synthesis Group, have identified nuclear propulsion as greatly enhancing the manned mission to Mars. These studies confirmed earlier ones, some dating back to the 1950's, that showed nuclear propulsion to have a very high payoff for piloted exploration. The Nuclear Engine for Rocket Vehicle Applications (NERVA) technology was developed extensively between 1955 and 1972, when the program was halted. About $1.4 billion in then-year dollars was spent by NASA and the Atomic Energy Commission on this program. If escalated to 1991 dollars, this translates to about $9.6 billion. The program culminated with a full system test that demonstrated the required lifetimes, restartability and performance required for the system. Thus, the practicality of a nuclear rocket using a solid graphite reactor was established.

Based upon more current studies and assessments, NASA requested $11 million in its FY 1991 SEI budget to reinitiate work on nuclear propulsion, although budget constraints limited the final amount to $500,000. The Administration then requested $7 million for nuclear propulsion for FY 1992 for NASA, with a parallel Department of Energy (DOE) budget request of $14 million. The final amounts appropriated were $5 million each for both NASA and DOE.

NASA has also held discussions with both the Department of Energy and the Department of Defense (DoD) on establishing a broadly based program of technology development in nuclear propulsion. The involvement of DOE and DoD is in keeping with the guidance from the National Space Council that both agencies will be participants with NASA in SEI. However, what is more important is that this mutual cooperation will result in maximum use of available resources, with a minimum of duplication involved. Given today's economic environment, this is crucial.

NASA is also developing nuclear propulsion program and project plans. These plans call for assessment of options and key technologies to assure that the best nuclear propulsion system is developed for SEI purposes. Overall coordination of this work is through NASA's Lewis Research Center (LeRC) which has established a Nuclear Propulsion Office to be the project office for NASA's nuclear propulsion program.

This paper provides an overview of the NASA nuclear propulsion prgram and will cover the following topics: missions from Earth to Mars, the attributes and benefits of nuclear propulsion, and the NASA nuclear propulsion program.

MISSIONS TO MARS

Mars' orbital geometry in relation to Earth presents some interesting challenges. The orbit of Mars has a marked eccentricity of more than 9%, as compared to the eccentricity of Earth, which is less than 2%. Mars' distance from the sun ranges from 206 x 10^6 kilometers to as much as 249 x 10^6 kilometers. For comparison, the Earth-sun distance varies from 147 x 10^6 kilometers at perihelion to only 152 x 10^6 kilometers at aphelion. Mars has a revolution period of about 687 Earth days. Moreover, the orbit of Mars is inclined 1.85 degrees to the orbit of Earth. As can be seen, a mission to Mars is more complicated than a mission from Earth to the Moon. Both the departure point (Earth) and the destination (Mars) are constantly changing positions relative to one another.

In effect, a mission from Earth to Mars becomes a double rendezvous problem: a rendezvous with Mars that must take into account the return flight to rendezvous with Earth. As a result of the Earth-Mars geometry, the launch oportunities from Earth occur every 26 months, and the two planets have an orbital geometry that repeats at approximately 15-year cycles.

In designing a mission to Mars, consideration must be given to several variables. The first is trip time, which includes both outbound and inbound times. Next is surface stay time, which is influenced by the class of mission. The third variable is vehicle performance, as defined by specific impulse and thrust. Next, there are initial mass into low-Earth orbit, or IMLEO, constraints. This includes consideration of the capacity of the launch vehicles that will be available for SEI and the number of launches required for the mission. And, finally, there are abort and operational considerations.

Given the Earth-Mars orbital geometry and propulsive energy considerations, there are two basic classes of roundtrip missions with a stopover at Mars, as shown in Figures 1 and 2. The first is the long-stay, or conjunction-class, mission which allows a long stay-time at Mars on the order of 500 days. This class of mission has a number of advantages, including lower energy requirements and significantly less launch mass. In addition, a Venus flyby is not required, there are longer launch windows available, and elliptical parking orbits can be optimized.

The other type of mission is the short-stay, or opposition class, mission. This one involves a stay time at Mars of only 30 days, but it also involves longer transit times. Among the advantages of this class of mission are that there is a shorter overall trip time (by at least one year) and the transfer vehicle usually returns in time to be reused on the next launch opportunity.

To summarize, the long stay-time missions can be accomplished with short transit times while the short stay-time missions minimize the overall time the astronauts would be gone from Earth. With improved propulsion systems, some flexibility can be achieved between these two extremes. It has been suggested that the first mission to Mars should be a short stay-time mission because of the unknowns facing the first crew. Another option being considered is to design missions such that aborts can be successfully made at various times, such as 30, 60 or 90 days, into the stay on Mars.

There is a fundamental tradeoff involved between transit time and IMLEO. Figure 3 shows that transit time can be reduced by increasing IMLEO. However, there will probably be a practical constraint on IMLEO given the Earth-to-orbit vehicles available for the early Mars missions. For a given IMLEO, the more efficient nuclear propulsion systems offer the shorter transit times.

NUCLEAR PROPULSION CONCEPTS

Ideas on the use of nuclear power for space propulsion can be traced to the writings of Dr. Robert H. Goddard and others before World War II. From this early work, the two general types of nuclear propulsion were developed: nuclear electric propulsion (NEP), which involves using the reactor to provide the electrical power for some type of electromagnetic thruster system, and nuclear thermal propulsion (NTP), which involves the direct heating of the propellant.

The all-chemical propulsion system will theoretically permit manned flights to Mars. However, it is constrained by being on the order of twice as massive as a nuclear propulsion system because of the less efficient utilization of propellant. The mass penalty can be largely overcome through the use of an aerobrake at Mars to eliminate the need for a chemical propulsive braking maneuver. This would in turn reduce the overall propellant requirements and make chemical propulsion with aerobrake competitive to nuclear propulsion. However, as shown in Figure 4, the chemical propulsion plus aerobrake option would place the spacecraft in an elliptical orbit in which the periapsis should line up with the desired landing site on Mars. The nuclear propulsion system, through the use of propulsive braking, will place the spacecraft in a circular orbit. In this sense, the chemical propulsion with aerobrake system is less flexible than the nuclear option because it is not as easy to change landing sites should something, such as a Martian sandstorm, prevent landing at the planned primary landing site. Also, the aerobrake technology needs further development.

To meet the SEI requirements for safe, reliable, fast transport to Mars, significant advances in space nuclear propulsion technology must be achieved. SEI missions will have high performance requirements. Table 1 summarizes the nuclear propulsion requirements as developed for two joint NASA/DOE/DoD-sponsored workshops that were held in the summer of 1990. The two-fold purpose of the workshops was to develop a database of promising concepts and to identify high-impact technological issues common to many concepts. The results of the NEP and NTP workshops were assembled and assessed by five technology review panels that included representatives from NASA, DOE, and DoD and their contractors. The panel assessments were presented to a joint NASA/DOE/DoD steering committee which recommended a number of high priority tasks to be pursued in the nuclear propulsion program.

Nuclear Electric Propulsion The generic NEP system consists of electric thrusters powered by a nuclear reactor as shown in an engineering sketch of a concept (Figure 5), which was used at the NEP workshop sponsored by the Jet Propulsion Laboratory (JPL) in Pasadena, California in June 1990. Listed in Table 2 are the space nuclear power and electric propulsion concepts presented at the NEP workshop. The nuclear power source concepts presented span a range of fuel types, power conversion subsystems and reactor coolants. Reactors based on the SP-100 technology or the NERVA technology were judged to have the nearest term availability. Thermal-to-electric power conversion subsystems based on the Rankine cycle or the closed Brayton cycle were judged to have the nearest term availability.

The chief benefits of nuclear electric propulsion derive from the high specific impulse (2000 to 10,000 seconds) of electric engines. At electric power levels of hundreds of kilowatts to megawatts, electric engines can significantly reduce propellant mass and trip times for robotic interplanetary exploration and cargo missions. At higher power levels of 1 to 100 MWe and higher, electric propulsion can dramatically reduce IMLEO and trip time for piloted interplanetary missions.

A number of electric propulsion concepts were also reviewed during the workshop process. Of these, ion and magnetoplasmadynamic (MPD) thrusters were judged to have the nearest term technology availability. The chief benefits of using an ion engine are that it is highly efficient, converting greater than 70% of input electrical power to thrust power, it is well understood, and it has a substantial developmental history. Furthermore, ion engines have been tested in space several times.

The NEP workshop pointed out that much work remains to be done. The key issue is to increase the specific power (kWe/kg) of the NEP system.

Nuclear Thermal Propulsion The basic features of a nuclear thermal propulsion (NTP) system are shown in Figure 6, which is based on the solid-core reactor system. Basically, as shown in Figure 7 for a solid core reactor, the NTP uses a nuclear reactor to heat the working fluid (usually hydrogen) directly to very high temperatures of ~2300 to ~3100 degrees K for solid cores, and higher for liquid-core and gas-core reactors. The hot hydrogen expands through a nozzle, with a turbopump forcing the hydrogen through the system. The nonnuclear components are similar to the components on chemical propulsion systems except that they must be designed to operate in a high radiation environment

In parallel with the NEP workshop, an NTP workshop was hosted by NASA's LeRC in July 1990 to help identify the NTP technology development requirements. Seventeen NTP concepts (Table 3) were presented at the workshop and were compared against the set of baseline parameters previously noted in Table 1, to provide a starting point for comparisons and discussions.

NERVA-based concepts (either NERVA or the proposed "Enabler" concept) were judged to have the nearest term technology availability by the workshop. In terms of intermediate term technology availability, the concepts included the particle bed reactor, the pellet bed reactor, cermet reactor, wire core reactor, "Dumbo" (folded flow) reactor and the low-pressure concept. The more advanced (and potentially higher performing) concepts based on gas-core reactors, foil reactors, and liquid-core reactors were judged to have the farthest term technology availability. As with NEP, the NTP workshop participants recommended certain high-priority, near-term technologies should be addressed to make NTP operational. These fall into both the propulsion and the reactor technologies.

NASA NUCLEAR PROPULSION PROGRAM

As noted earlier, the Space Exploration Initiative has established a visionary yet focused and evolutionary approach to space exploration: completing Space Station Freedom, returning to the Moon and then human exploration of Mars. Within the framework of SEI, it is recognized that mission studies and technology development must precede the actual missions. Accordingly, NASA has established a Civil Space Technology Initiative to develop the needed technologies, including nuclear propulsion. The technology initiative is aimed at reducing mission risk, lowering life cycle costs, and achieving the performance goals. The planning for exploration technology development has four themes:

- Capitalizing on the existing national space research and technology foundation

- Beginning now to make the necessary investments to meet the long-range technology needs and establish a commitment to long-term exploration technology development

- Seeking out innovative technological solutions to exploration technology challenges, and

- Performing technology development in parallel with exploration mission design studies.

Nuclear propulsion is one of the key technologies that needs to be pursued aggressively in the near term for Mars exploration objectives, because innovative solutions in these areas will have a major impact in developing and enabling exploration mission architectures and schedules. With this in mind, NASA has established a nuclear propulsion program as part of the Civil Space Technology Initiative to develop the nuclear propulsion technologies that will satisfy the mission requirements coming out of the SEI studies. The nuclear propulsion program is aimed at reaching Technology Readiness Level 6 by the year 2006. This means a system validation model demonstrated in a relevant/simulated environment. This would allow nuclear propulsion to support subsequent flight tests that will enable a manned Mars mission by 2016 or sooner.

The nuclear propulsion program recognizes that there are several competing concepts in both NTP and NEP. In order to expedite the technology development, the nuclear propulsion program is being organized into a parallel, iterative, dual-path approach of concept development and technology development. The goals of the nuclear propulsion program are to develop the technologies required to safely apply space nuclear propulsion systems to improve the mission performance for human missions to Mars; and to identify and develop at least one space nuclear thermal propulsion system and one nuclear electric propulsion system that, alone or in combination with other propulsion systems, meets the propulsion requirements for piloted and cargo missions to Mars and for which technical feasibility issues have been resolved.

Overall, the plan is to develop nuclear propulsion in a logical, step-wise evolutionary path following a strategy of developing a safe, reliable, high-performance nuclear propulsion technology for exploration of the solar system. Of critical importance is developing a consensus on the safe use of nuclear propulsion in order to achieve public acceptance. It is also important that we use all of the resources available to achieve our goals. This means having a broad outreach as part of the nuclear propulsion program.

CONCLUSION

As part of the Space Exploration Initiative, NASA has begun a new study of nuclear propulsion in cooperation with the Department of Energy and the Department of Defense. Two workshops were held to develop a database of promising concepts and to identify high-impact technological issues. Ongoing technical panel activities are providing the necessary input for the nuclear propulsion program and project plans. And the Synthesis Group has provided its guidance for the future of SEI, which recommends use of nuclear thermal propulsion for the initial lunar/Mars missions.

The plans NASA is preparing will provide a roadmap for the development of the technology for advanced space nuclear propulsion. The completion of this program will greatly enhance the space transportation capabilities of the United States in proceeding with the Space Exploration Initiative and future outer planet missions.

Mission characteristics

	Minimum Energy (Hohmann)	Fast Transfer
• Short trip times outbound and return (days each way)	≈195-275	≈120-160
• Long stay time (days)	≈560-370	≈625-550
• Total mission duration	≈950-920	≈865-870

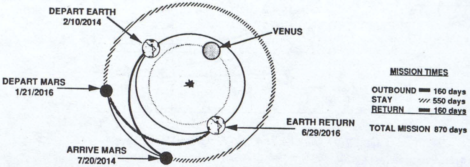


Figure 1. Example of a Long Stay-Time Mission to Mars.

Characteristics

- Short outbound/long return trip time or reverse
- Short stay time (≈30 days)
- Requires energetic transfer inside Venus orbit subjecting spacecraft to greater thermal and radiational loading
- 95% of total mission time is spent in transit
- Total mission duration is on the order of 500 days

	Minimum Energy	Fast Transfer
Outbound	≈165-285	≈117-189
Surface Stay	≈30	≈30
Inbound	≈245-320	≈213-221
TOTAL	≈440-685	≈360-440

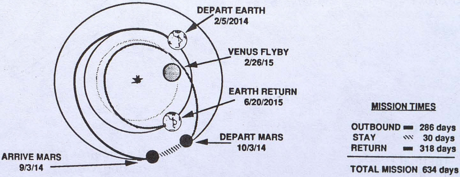
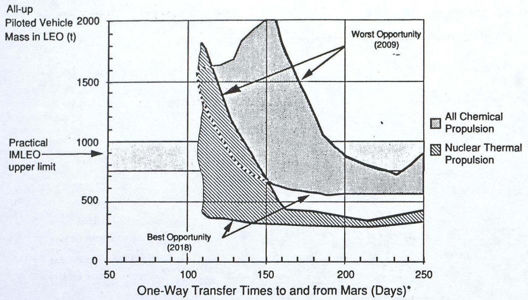
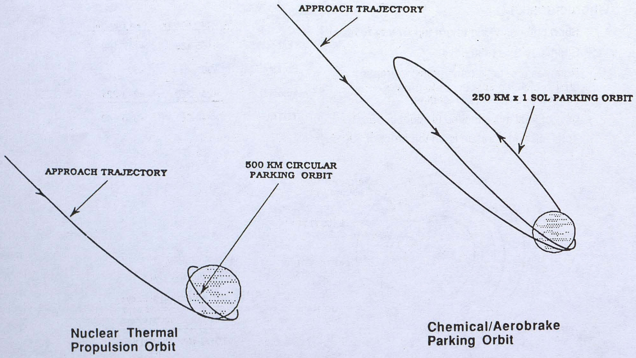


Figure 2. Example of a Short Stay-Time Mission to Mars.



* Total mission durations range from 820-960 days

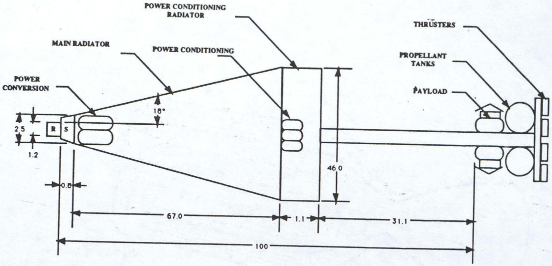
Figure 3. Comparison of All Chemical Propulsion with Nuclear Thermal Propulsion for a Range of Long Stay-Time Missions to Mars.



Nuclear Thermal Propulsion Orbit

Chemical/Aerobrake Parking Orbit

Figure 4. Comparison of Mars Capture Orbits for Nuclear Thermal Propulsion and Chemical/Aerobrake Systems.



DMENSIONS IN METERS
NOT DRAWN TO SCALE

Figure 5 **Schematic of a Nuclear Electric Propulsion (NEP) Vehicle/System as Used in the 1990 NEP Workshop.**

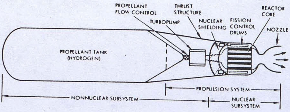


Figure 6 **Basic Features of a Nuclear Thermal Propulsion System (Solid-Core Reactor)**

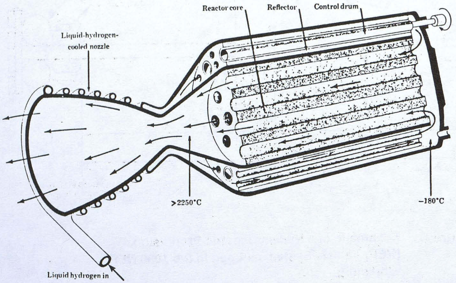


Figure 7 Cutaway of a Solid-Core Rocket.

TABLE 1 NUCLEAR PROPULSION BASELINE PARAMETERS

	Nuclear Thermal Propulsion		Nuclear Electric Propulsion		
Parameter	Baseline	Variation from Baseline	Baseline	Variation from Baseline	Comments/ Rationale
Engine Availability (y)	2015	2004 - 2017	2015	2004 - 2017	One year before scheduled launch in 2016
Thrust/engine (kN)	334	110 - 1 110	N. S.	N. S.	Baseline NTP: 3 perigee burns
Specific impulse (m/s)	9 065	9 065 - 11 760	58 800	39 200 - 98 000	NTP: 8 330 m/s is approximately the prior Rover technology and will do the mission
Engine thrust/ weight	6	6 - 10	N. S.	N. S.	NTP w/o shielding. Shielding is to be considered.
Nr of engines	1	Multiple	N. S.	N. S.	
Reactor power (MWt)	1 500	500 - 5 000	N. S.	N. S.	
Low electric power (kWe)	0	25 - 50 (dual mode)	N. S.	N. S.	NTP baseline is not dual mode
High electric power (MWe)	0	1 - 5 (dual mode)	10	5 - 70	NTP baseline is not dual mode
Propulsion operating time	250 min/ mission	250 - 1 000 min/mission	5 y	3 - 10 y	
Number of missions	1	1 - 5	3	1 - 5	
Number of cycles per mission	6	1 - 30	15	2 -25	1 cycle is an expendable engine

TABLE 2 LIST OF SPACE NUCLEAR POWER AND ELECTRIC PROPULSION CONCEPTS PRESENTED TO THE 1990 NUCLEAR ELECTRIC PROPULSION WORKSHOP

THRUSTERS

- Pulsed Electro Thermal Thruster
- Pulsed Plasmoid Thruster
- Ion Thruster
- Deflagration Thruster
- Steady-State MPD Thruster
- Burst Mode MPD Thruster
- Pulsed Inductive Thruster
- Ion Cyclotron Resonance Thruster
- Electron Cyclotron Resonance Thruster

POWER SYSTEMS

- Gas Core Reactor
- Pellet Bed Reactor
- 10-MWe Nuclear Rankine System
- Thermionic System (in-core)
- Rankine Cycle NEP
- Thermionic Concept (TORCHLITE)
- MMW Continuous Power Option
- Enabler (NERVA-based) System
- SP-100 Growth Power System

TABLE 3 LIST OF NUCLEAR THERMAL PROPULSION CONCEPTS PRESENTED TO THE 1990 NUCLEAR THERMAL PROPULSION WORKSHOP

- Dual Mode
- Gas Core - Open Cycle A
- Gas Core - Open Cycle B
- Gas Core - Light Bulb
- Enabler (NERVA-based)
- Low-Pressure Core
- Particle Bed Reactor
- Nuclear rocket using Indigenous Martion Fuel (NIMF)
- Wire Core Reactor
- Advanced DUMBO
- Pellet Bed Reactor
- Foil Reactor
- Liquid Annulus Reactor
- Droplet Core Reactor
- Boiling Metal Reactor
- Tungsten Reactor
- Cermet Reactor