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Nuclear Thermal Propulsion Transportation Systems for Lunar/Mars Exploration

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NUCLEAR THERMAL PROPULSION TRANSPORTATION SYSTEMS FOR LUNAR/MARS EXPLORATION

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ABSTRACT

Nuclear thermal propulsion technology development is underway at NASA and DoE for SEI missions to Mars, with initial near-earth flights to validate flight readiness. Several reactor concepts are being considered for these missions, and important selection criteria will be evaluated before final selection of a system. These criteria include: safety and reliability, technical risk, cost, and performance, in that order. Of the concepts evaluated to date, the NERVA derivative is the only concept that has demonstrated full power, life, and performance in actual reactor tests. Other concepts will require significant design work and must demonstrate proof-of-concept. Technical risk, and hence, development cost should therefore be lowest for the NDR concept, and the NDR concept is currently being considered for the initial SEI missions. As lighter weight, higher performance systems are developed and validated, including appropriate safety and astronaut-rating requirements, they will be considered to support future SEI applications. A space transportation system using a modular NTR system for lunar and Mars missions is expected to result in significant life cycle cost savings. Finally, several key issues remain for NTRs, including public acceptance and operational issues. Nonetheless, nuclear thermal rockets are believed to be the "next generation" of space propulsion systems - the key to space exploration.

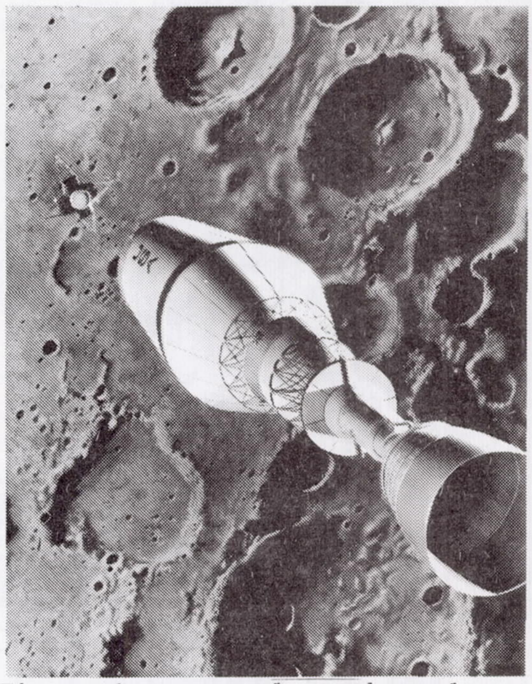

Figure 1 A Nuclear Thermal Rocket prepares to dock with a lunar landing vehicle returning from the moon. Artwork by Pat Rawlings.

INTRODUCTION

NASA and DOE are developing nuclear rocket technology for possible use on lunar outpost missions, and for Mars exploration missions. The Space Exploration Initiative outlined by President Bush on July 20, 1989, the 20th anniversary of Apollo 11, calls for a return to the Moon "to stay" early in the next century, followed by a journey to Mars using systems "space tested" in the lunar environment. Establishing and sustaining permanent outposts on the Moon will require the development of an efficient, reusable, space transportation system for moving humans and substantial quantities of cargo.

Earlier NASA studies[1,2] assumed the development and availability of a new, advanced liquid oxygen, liquid hydrogen fueled chemical space engine for lunar space transportation primary propulsion. Returning piloted and cargo lunar transfer vehicles would also carry an aerobrake through the entire lunar mission for use in returning to low earth orbit. Without aerodynamic braking at Earth return, "all propulsive" chemical systems would require initial masses in low Earth orbit (IMLEO) on the order of 275-300 metric tons. The higher IMLEO range corresponds to a more "Apollo-like" expendable mission mode with significant jettisoning of expended stages and/or propellant tanks.

The solid core nuclear thermal rocket (NTR) represents the next major evolution in propulsion technology[3,4] and is ideally suited to perform piloted, cargo, or combination lunar and Mars missions. With twice the specific impulse (I_{sp}) of a chemical propulsion system, a fully reusable, "all propulsive," single stage NTR-powered lunar transfer vehicle is possible (see Figure 1). Operating in the combined mode, a piloted NTR can deliver and return significant quantities of payload. In the cargo-only mode, a robotic NTR vehicle could deliver self-landing lunar habitation modules to equatorial or lunar polar orbit staging nodes from which deployment to locations over the entire lunar surface would be possible.

In addition to these performance benefits, the use of NTR for lunar missions would provide valuable operating experience and serve as a technology proving ground before undertaking the more demanding interplanetary missions to Mars.

A reusable NTR lunar mission profile is indicated in figure 2. The major system components would be launched to low earth orbit by a heavy lift launch vehicle. Mating of the engine, main propellant tank, and payload would be autonomous,

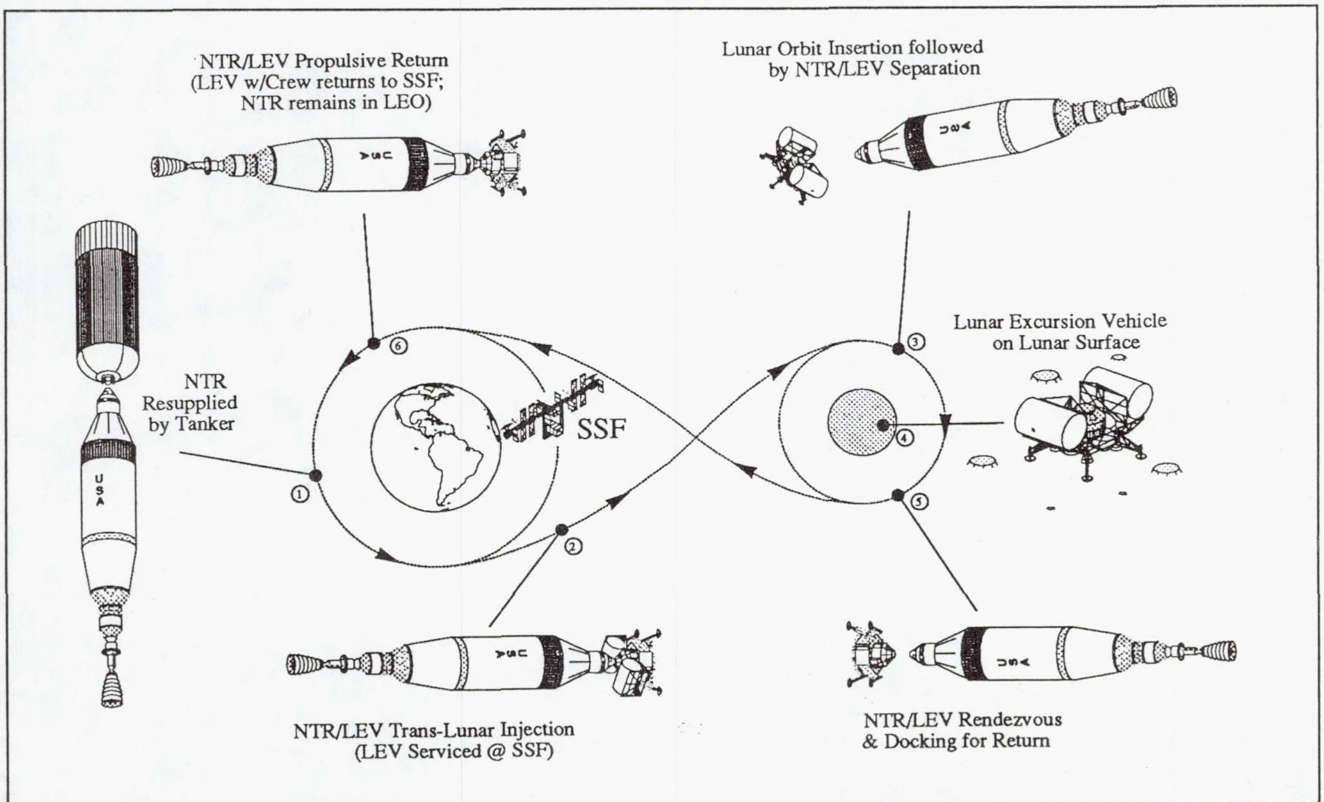

Figure 2 Fully Reusable Nuclear Thermal Rocket Scenario

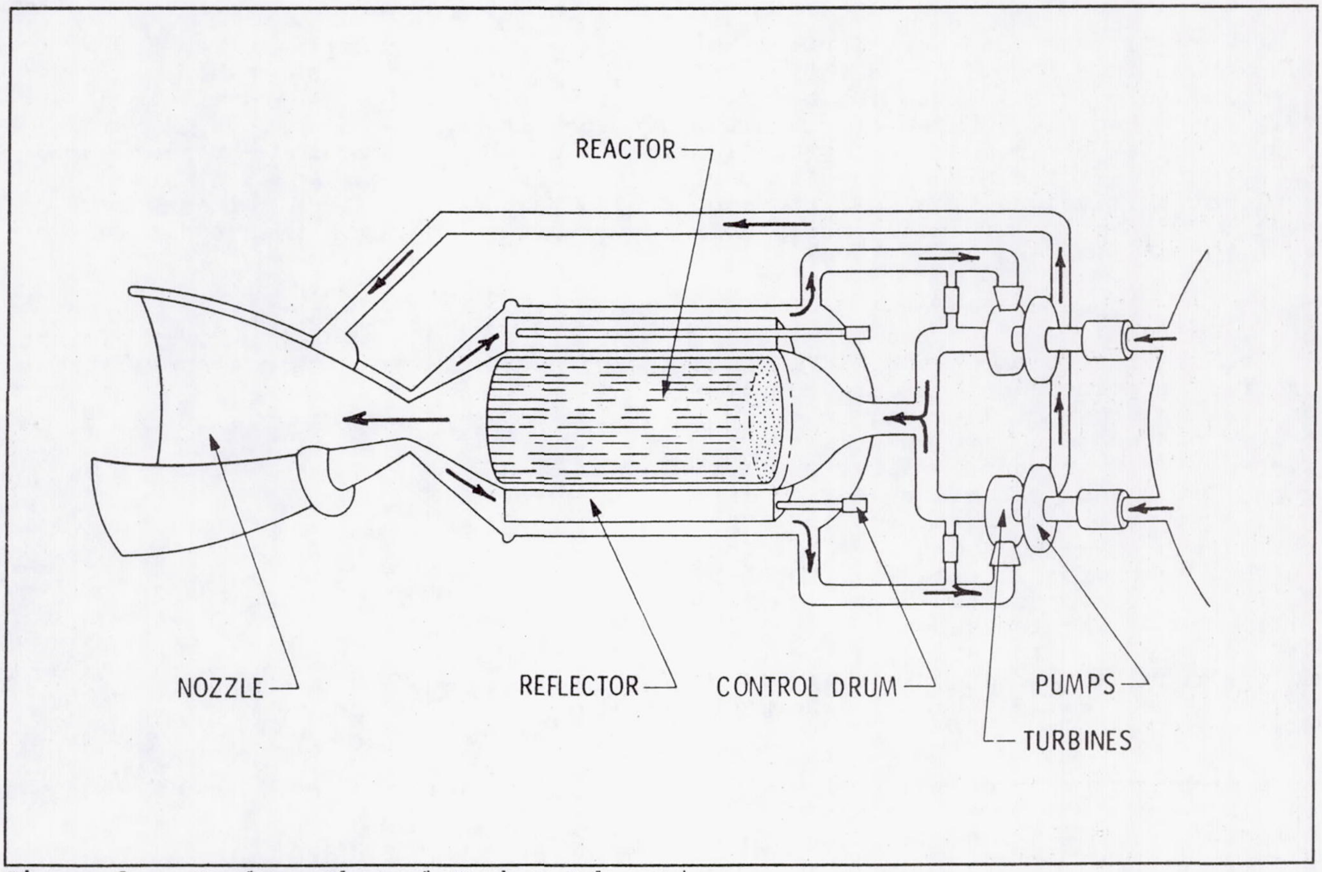

Figure 3 Nuclear Thermal Rocket Schematic

minimizing on-orbit assembly by astronauts. The nuclear engine would be radioactively "cold" during earth-to-orbit launch, and would not pose a radiation threat under even the worst launch accident scenario. After system checkout in low earth orbit, hydrogen propellant flow would start as the reactor is started (see Figure 3), and the heat from the reactor would heat the hydrogen; the hydrogen would then expand through the engine nozzle, producing thrust, and the rocket would quickly accelerate away from the earth. After just a few minutes, the reactor would be turned off and the rocket would then "coast" to the moon. The reactor would be turned on again for a few minutes, to propulsively brake into lunar orbit. The payload would then leave the NTR transit vehicle, descend to the lunar surface, perform the mission, and finally return to the NTR. After docking, the entire lunar excursion vehicle could be returned to earth orbit for subsequent refueling and reuse.

The benefits of nuclear thermal propulsion systems for the Mars exploration missions have been well documented. The National Space Council's Synthesis Group called the nuclear thermal rocket "the only prudent propulsion system for Mars transit."[5] Mars missions fall into two classes: (1) long on-surface stay times (conjunction-class) during which time the planets rotate about the sun and permit minimum transit times for both out-bound and in-bound transits, and (2) short surface stay times, on the order of 30 to 90 days, which require much longer transit times for travel between earth and Mars and return, thus exposing the astronauts to increased exposure to dangerous intergalactic cosmic radiation and possible solar flares, as well as the undesirable effects of weightlessness.[6] Similarly, the shorter transit times enabled by the NTR reduces the deleterious effects of weightlessness and other psychological effects on the astronauts.

Another important consideration in the selection of a propulsion system for a mission of this magnitude is the overall life cycle cost for the complete exploration program, including both the lunar missions and the Mars missions. The very high specific impulse of the NTR engine permits major reductions in initial launch costs, since much less propellant mass must be launched. Perhaps more importantly, if the NTR is used to perform the lunar missions and the Mars exploration missions, the cost of developing a new advanced chemical-aerobrake system (with only marginally acceptable performance), can be eliminated. This could save 10s of billions of dollars!

The U.S. has been interested in nuclear thermal rockets for many years. Very promising early work at the Los Alamos Scientific Laboratory on the ROVER project, led to the formation of the NERVA (Nuclear Engine for Rocket Vehicle Application) program, a joint NASA - Atomic Energy Commission program, (see Figure 4)[7]. A number of reactors were built and tested, verifying design life, restart capability, and performance. From 1955 until the program was stopped in 1973, the nation invested about $1.4 billion in this technology. Escalated to 1992 dollars this represents about $10 billion! During the same time period, the country also investigated the technology required for a nuclear airplane, and some interesting reactor concepts were explored.[8,9]

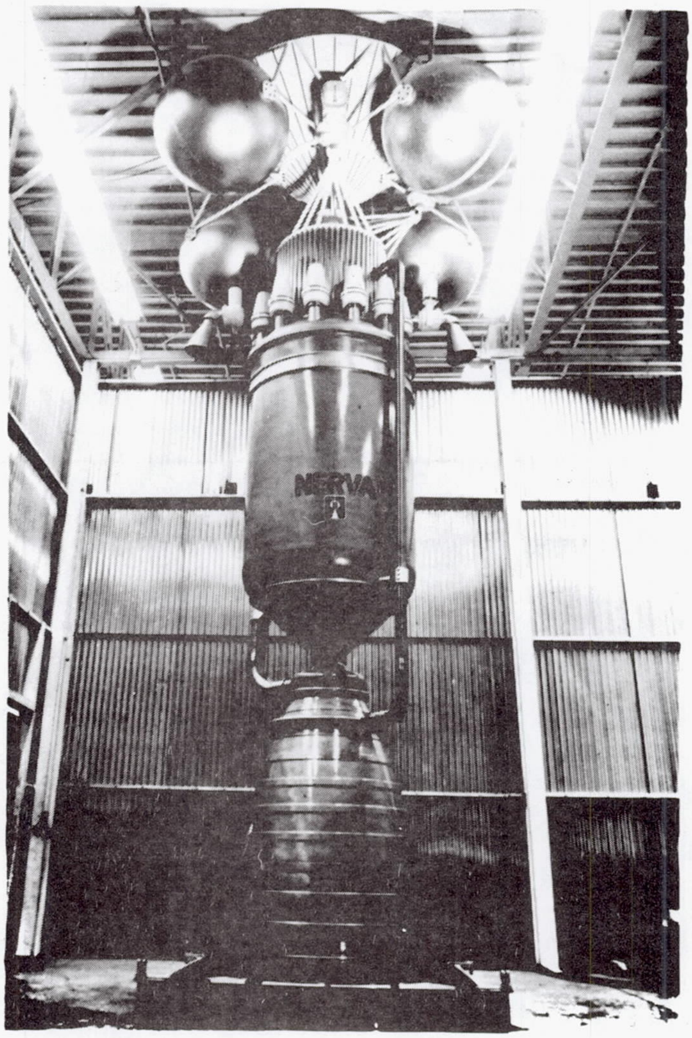

Figure 4 NERVA Flight Engine Configuration

At a press conference January 13, 1992 in Albuquerque, New Mexico, the U.S. Defense Department announced a nuclear rocket technology development program, using an advanced particle bed reactor concept. The main applications described would be for upper stages and orbital transfer vehicles. To date, $130 million have been spent on the program.

A similar program was initiated in the Commonwealth of Independent States, (the former Soviet Union), approximately four years after the start of the ROVER-NERVA program. The CIS conducted extensive nuclear and non-nuclear subsystem tests, including extensive reactor tests at Semipalatinsk. No engine system level tests have been conducted.

CONCEPT COMPARISONS

A workshop was conducted by NASA, DOD and DOE in July, 1990 to identify and evaluate potential NTR concepts.[10] Over seventeen concepts were identified, including solid core, liquid core and gaseous core concepts. The solid core concepts are considered to be lower technical risk, and are being considered by NASA for SEI missions.[11,12]

Of the solid core concepts, any of three reactor types; thermal (typical of the NERVA concept shown in figure 4); heterogeneous (such as the particle bed reactor -

PBR); or fast reactors, can probably be developed through full system ground test completion by the year 2006, provided adequate funding is provided.[8,9]

The CIS also has presented a heterogeneous solid core nuclear thermal reactor concept with two metric tons thrust (see Figure 5), with impressive performance characteristics, and this concept is also being evaluated.[13]

Safety, reliability and risk management were identified as critical attributes for all SEI missions. In addition, important figures-of-merit (FOM) were identified for consistent concept comparisons. Some of these include: specific impulse, initial mass in low earth orbit, engine thrust, engine weight, and propellant exit temperature.

For SEI missions, these figures-of-merit must be related to engine system technical objectives to perform a consistent comparison. The most important performance parameter, from an engine design standpoint, is the propellant exit temperature. A temperature of about 2700 K corresponds to a specific impulse of about 925 seconds, (with a nozzle chamber pressure of 1000 psia, and a nozzle expansion ratio of 500:1). Temperatures in this range were achieved with composite fuels in the NERVA program, so it is believed that this temperature can be achieved with relatively low technical risk. Appropriate safety, reliability and design margins will be required, of course, for astronaut-rated systems. Higher temperatures have been proposed for several of the concepts, and NTP systems should be designed to evolve to these temperatures as they become available. System reusability will ultimately become a goal to minimize operations cost when interplanetary travel becomes "routine."

Engine thrust level is also an important design parameter and strongly affects the ground test facility and exhaust cleanup system cost. Total mission thrust requirements may be met with a single engine, or clustered engines may be used to provide redundancy and important potential abort capabilities. Thrust levels from 25,000 pounds to 250,000 pounds force are being studied.

Engine lifetimes up to one hour for a single burn, or up to ten hours total may be required depending on the mission. Restartability will be necessary.

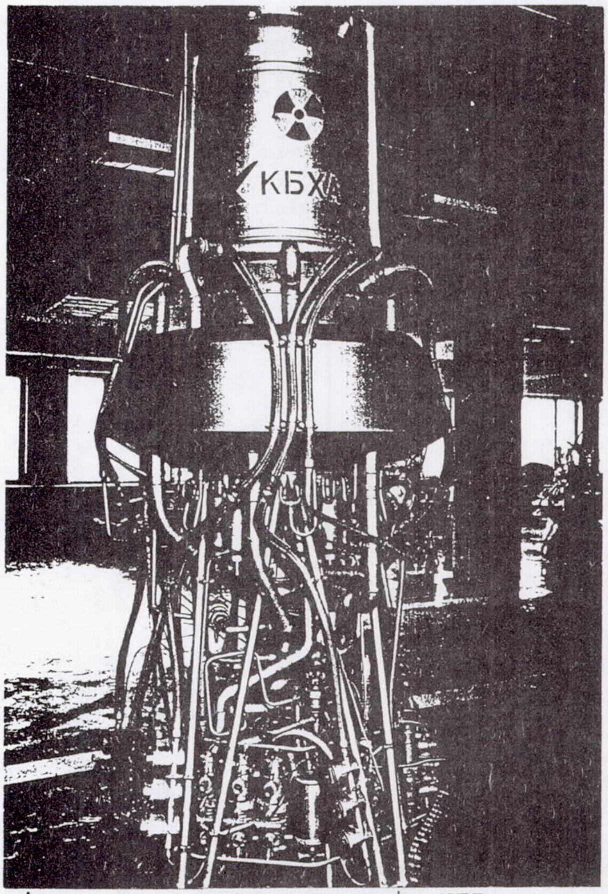

Figure 5 CIS Prototypic NTR

NERVA-Derived Reactor (NDR)

The NDR concept is the current "baseline" concept for the SEI missions; specific impulse is estimated to be about 925 seconds. In the original NERVA baseline, duplex fuel particles of coated uranium carbide were dispersed in hexagonally-shaped graphite matrix fuel elements each having 19 axial coolant channels and coated with zirconium or niobium carbide to reduce the hydrogen-to-graphite reaction. Interspersed among the fuel elements were cooled support elements, attached to an upstream core support plate, to restrain the core in the direction of flow. An assembly of fuel and support elements was used to form the NERVA core with each fuel element producing approximately 1 to 1.2 megawatts of thermal power.

Improved composite fuels and coatings may be required for prismatic fuel elements initially to obtain 2700 K, system design will accomadate evolution to binary carbide and/or ternary carbide fuels as they are developed (2900-3100 K). There is a substantial NERVA database; detailed system design and full system tests have been completed, and system improvements have been identified. NDR concept development is expected to be the lowest technical risk, lowest cost, and shortest development schedule to technology readiness. The concept may evolve to higher performance if binary or ternary carbide fuel development is successful.

Particle Bed Reactor (PBR) Concept

A distinguishing feature of the PBR is the direct hydrogen cooling of small (500-700 µm diameter) coated particle fuel spheres. The fuel is packed between two concentric porous cylinders, called "frits," which confine the fuel but allow coolant penetration. A number of these small annular fuel elements would be arrayed in a cylindrical moderator block to form the PBR core. Coolant flow is directed radially inward, through the packed bed and hot frit, and axially out through the inner annular channel. Because of the large heat transfer area envisioned in a PBR element, bed power densities 2 to 10 times larger than the peak power densities demonstrated in the NERVA program may be possible.

Some particle manufacturing capability exists, derived from the high temperature gas-cooled reactor programs. Very high fuel temperature capability has been claimed for this concept, but must be verified. Since there are relatively low structural loads on the fuel particles, the high strength outer coating on the particle may help to contain fission products. Very large surface area to volume ratio maximizes the heat transfer area for each particle, and the tiny particles have a very short heat transfer path, so the fuel kernel temperature and the sphere surface temperature can be maximized. Very high bed power density may provide somewhat higher system thrust/weight. A more detailed conceptual design is underway for an astronaut-rated SEI mission to verify this potential.

Proof-of-concept testing will be required to verify (1) mass loss (particle life-time) versus temperature at prototypic power generation rates and cooling flow rates, and (2) coolant flow distribution, control, and stability. Currently no experimental reactor exists that is capable of the very high power densities required to test these fuel elements. The high surface to volume ratio may also promote higher corrosion rates in the hydrogen flow field, and shorter reactor life at a given temperature. The DoD PBR technology program was initiated to address these critical proof-of-concept issues.

CIS Reactor Concept

The CIS reactor is a heterogeneous design that uses a hydrogen-cooled ZrH moderator and ternary carbide fuel material, (see Figure 6). Warm hydrogen from the moderator is used to power the turbine. The relatively cool operating temperature of the moderator and core support should enhance the overall robustness of the design. The fuel element is an axial flow design with a high surface-to-volume ratio. Power densities of up to 40 MW/liter with minimum core mass characteristics of about 0.3 MW/kg are claimed. Maximum fuel element operating temperature is expected to be about 3200 K. During reactor tests, gas exit temperatures of 3100 K for one hour and 2000 K for 4000 hours, was demonstrated. Life of the CIS element at ROVER-NERVA demonstrated temperatures is expected to exceed 25 hours. The design allows for optimization of the power density across the core by changing the spacing of the fuel elements in both the radial and circumferential directions. This provides a more uniform fuel and exit gas temperature at each element, thus reducing the required margins between the design point and the limiting fuel element temperature that must be maintained to provide life and reliability requirements. Thus, this concept offers the potential for improved performance and longer life than other concepts evaluated; a detailed study of the CIS concept must be conducted to verify this potential, and is currently underway with Aerojet and the CIS.

Fast Reactor (CERMET) Concepts

Ceramic-Metal (CERMET) concepts were studied, and some concept design work was done in the 1960s; fuel processing and fabrication techniques were studied extensively for the nuclear airplane program.[8,9] Refractory metal structural integrity may result in improved fission fragment retention by this fuel compared to other concepts; however, this must be verified in nuclear tests. The rugged construction may offer improved shock loading. Thus, the concept may provide additional safety margins. High temperature performance (to 3100 K) has been claimed for cermet fuels. System thrust/weight may be lower than other concepts because of higher mass required for fast reactors, thus, overall mission performance may be lower. However, if a requirement for very low release of fission fragments is imposed, this concept could be the only way of meeting the requirement. An important effort early in the project will be to evaluate fuel lifetime versus temperature versus fission fragment release for each fuel type in an actual nuclear, hot hydrogen environment, to provide the basis for this important decision.

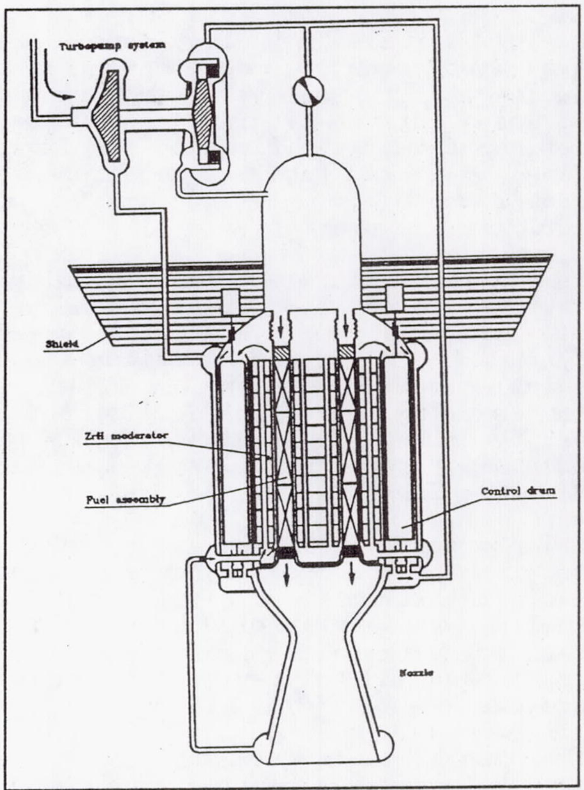

Figure 6 Schematic Cross-Section of CIS Prototypic NTR Concept

Thus, of the U.S. concepts compared above, only the NDR concept has a detailed design completed for a manned mission, and only the NDR has demonstrated proof-of-concept in an actual nuclear test. While the other concepts offer certain performance advantages, these advantages must be proven by testing, and a detailed design of an astronaut-rated system must be completed. These emerging concepts will then be considered for possible SEI applications.

CURRENT PROJECT PLANNING

NASA and DOE have initiated a technology development project for nuclear rocket propulsion systems for Space Exploration Initiative (SEI) missions to the Moon and to Mars.[12] The project includes both nuclear electric propulsion (NEP) and nuclear thermal propulsion (NTP) technology development. The Nuclear Propulsion Office at the NASA Lewis Research Center is leading the project team with participation by NASA-MSFC and JPL, and several Department of Energy Laboratories for reactor technology development.

Interagency (NASA/DoE/DOD) teams were formed in 1991 to evaluate technology development plans, and to identify and clarify open issues regarding:

- Mission Analysis
- Nuclear Safety Policy
- Fuels/Materials Technology
- NEP Technology
- NTP Technology
- Nuclear Facilities

The Mission Analysis Panel developed consistent nuclear propulsion reference mission scenarios to guide the development of facility requirements, assessed mission operations and abort scenarios, and quantified mission options that nuclear propulsion provides for various concepts and advanced technologies. The

Fuels/Materials Technology Panel, NEP Technology Panel and the NTP Technology Panel evaluated technology development plans and recommended facility requirements. The Nuclear Safety Policy Working Group defined appropriate safety and environmental policies for the program, recommended an independent safety review process, and defined safety verification testing policies and criteria. The Test Facilities Panel evaluated facility requirements and options and recommended new facility requirements and existing facility modifications required that should be initiated early in the project.

Presently, the project is being planned to respond to the SEI mission requirements, as they are developed by the agency mission planners. These mission requirements will probably remain a "moving target" for some time as SEI studies continue, the Synthesis Group recommendations are evaluated, and finally, the mission architecture is selected.[5] The project will include an iterative, parallel systems engineering and enabling technology development phase, followed by extensive system testing to verify technology readiness. This project is currently planned to develop the technology through full system ground testing by about 2000, followed by first cargo Mars mission in 2008, and first piloted-Mars mission in 2010.

Major ground facilities are recognized to be a long lead time (and high cost) requirement for the project and should be initiated as soon as possible. For nuclear thermal propulsion, a "nuclear furnace" will be required to test full size fuel elements in a relevant nuclear environment, and a full system ground test facility with full effluent cleanup will be required to completely verify technology readiness, and to provide the confidence to proceed with initial flights of NTR systems.

The possible use of existing experimental facilities in the CIS could possibly result in earlier testing than would be possible in the U.S., and this option is currently under investigation. Cost savings may be possible.

Both lunar and Mars NTR vehicle applications are being studied. Using NTR powered lunar vehicles can substantially reduce system life cycle cost as well as provide much needed operational experience before higher risk Mars missions are undertaken. Studies continue to evaluate the potential for a modular NTR vehicle/propulsion design approach.[14] The current lunar NTR vehicle design shown in figure 7 is similar in configuration to earlier NTR lunar shuttle designs for lunar and interplanetary applications. It contains two distinct modules which would be assembled in space. The main propellant tank has a diameter of 10 meters, a forward dome, and a 10 degree conical aft section with a 3.6 meter spherical end cap radius. The tank reduces forward radiation scattering to the crew and helps to reduce stage shielding requirements. A command and control, and reaction control system (RCS) module would be located in the stage forward section to control robotic cargo missions.

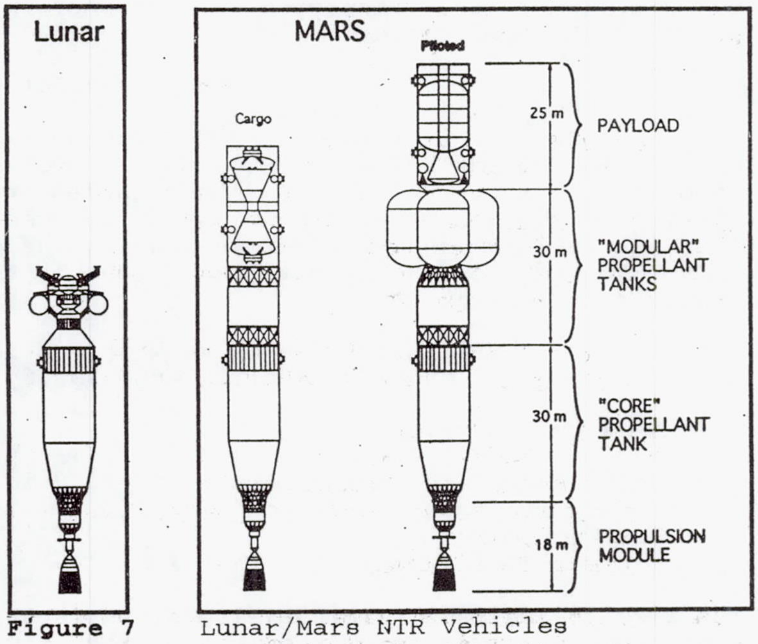

Figure 7 Lunar/Mars NTR Vehicles

The "propulsion module" contains the NTR engine and a small run tank. The run tank has hemispherical forward and aft domes and a cylindrical barrel section about 4 meters in diameter. The "wet" propulsion module has been sized both in dimensions and mass for deployment from the Space Shuttle cargo bay as a single autonomous unit. Using a 925 second (specific impulse), high expansion ratio nozzle at 500:1, and a composite fuel NDR as representative of the largest engine envelope envisioned (length 11.8 meters, nozzle diameter 4.2 meters), and allowing space allocation for a docking system and propellant transfer lines, the run tank length and LH_2 capacity are estimated to be 5.8 meters and 3.9 tons, respectively. The run tank can therefore be used for engine startup and cooldown, and for short duration burns.

Current Mars cargo and piloted NTR modular configurations are also shown in figure 7. The propulsion module and core propellant tank would be common with the Lunar vehicle, and would be completely demonstrated in the lunar missions before a mission to Mars is attempted. Common, modular propellant tanks would be added as needed for either the Mars cargo vehicle or the piloted Mars vehicle. Common interfaces would be included between structures to provide electrical and pneumatic continuity. The modular propellant tanks could be jettisoned after use, to reduce overall vehicle inert mass and total propellant requirements. The cargo vehicle shown carries two cargo landers, while the piloted vehicle contains the crew habitat and Earth return capsule.

Other options currently being studied include NTR engine clusters to provide possible redundancy benefits. Clusters of two and three 25,000 - 50,000 lb_f engines have been studied, with various pumping and run tank options. Figure 8 shows a cluster of three 50,000 pound force engines, close coupled to a core tank. More work is planned in this area. An artist's concept of an NTR for first lunar outpost mission, using a single launch approach is shown in Figure 9.

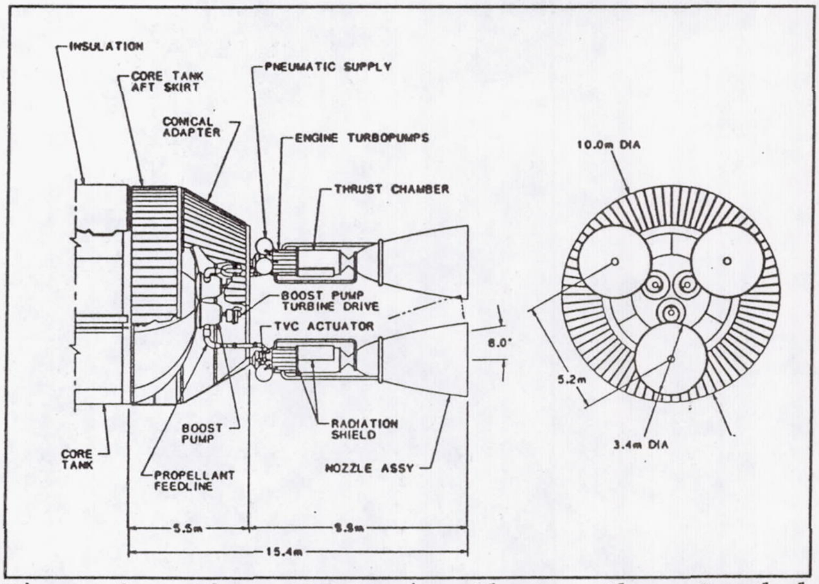

Figure 8 Three NTR Engine Cluster Close-Coupled to Core Tank

KEY ISSUES

One of the most important issues associated with the use of any nuclear system in space relates to the question of public acceptance of nuclear systems. NASA recognizes that strong public support (and congressional funding) for SEI missions and space nuclear propulsion systems will be required to overcome vocal opposition to nuclear systems in general. Public acceptance planning is underway and efforts will continue throughout the life of the program. Project planning emphasizes astronaut safety, system reliability and integrity, and protection of the environment, both on the ground at test facilities, and in outer space.

Another key issue relates to the location of the major ground test facilities. The "Not-in-my-Backyard" syndrome will undoubtedly limit the viable candidates for this important testing. While the CIS facilities are in place and will be studied, the environmental issues associated with any test site must not be minimized.

Safety review processes are in place in the U.S., that have been used successfully for launch approval of other nuclear systems (RTG's). This process will be used for the launching of NTR systems, and is expected to ensure mission safety and success.

There are operational issues with NTR systems that present significant technical challenges. For example, since the first flights of NTR systems will be unmanned, instrumentation, controls, and health management systems must be developed and verified to ensure mission safety and success, with on-board computer controllers. With a 45-minute communication lag-time between earth and Mars, it is unrealistic to think that earth controllers will be of use during critical startup and shutdown maneuvers in Mars orbit.

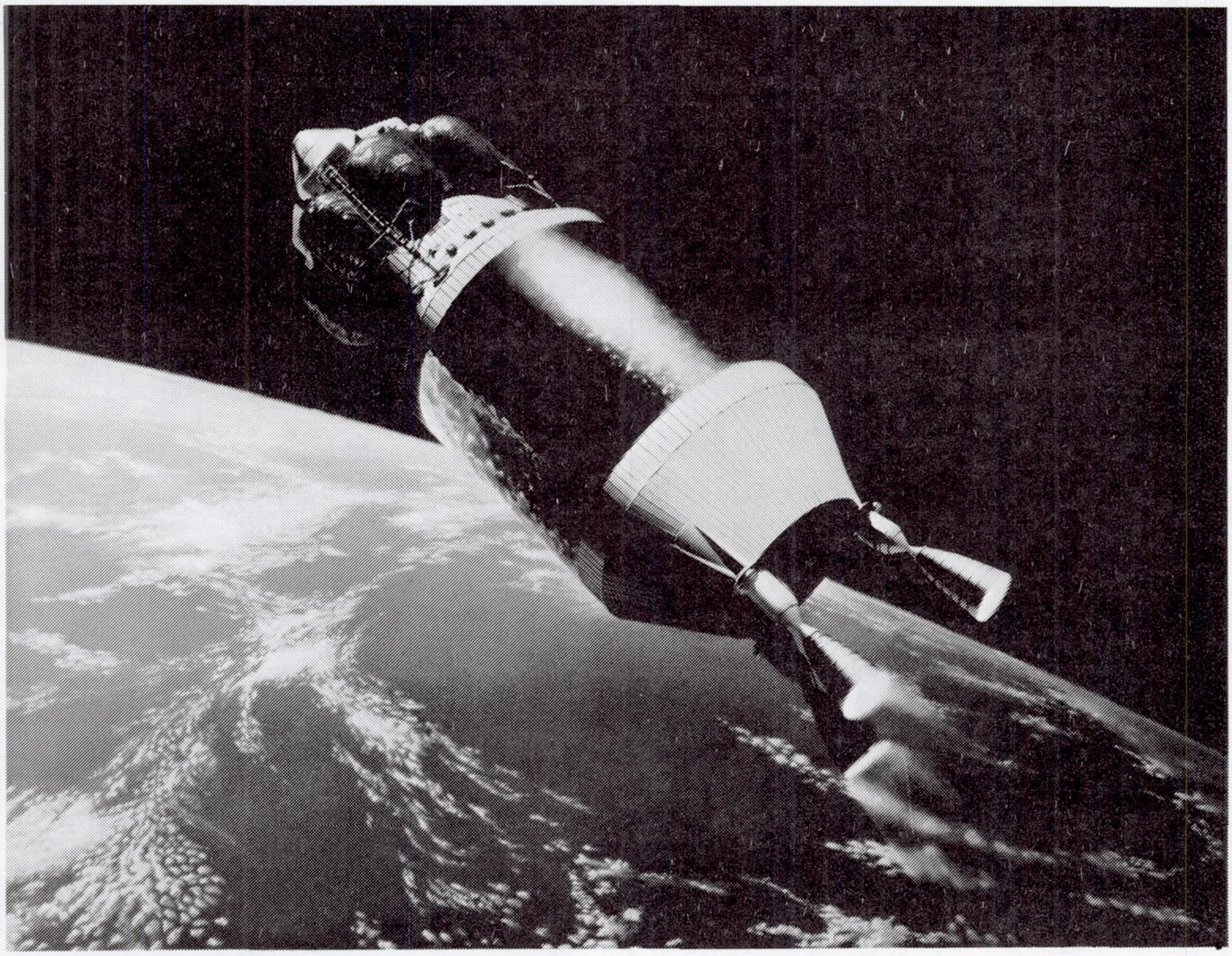

Figure 9 NTR Concept for First Lunar Outpost Mission Using Three 25K Engines in a Cluster

Finally, ultimate disposal of nuclear reactors at the end of their useful life must be carefully considered by mission planners to ensure that there is no possibility of re-encounter with the earth.

In summary, nuclear thermal propulsion technology development is underway at NASA and DoE for SEI missions to the moon and Mars. Several reactor concepts are being considered for these missions, and important selection criteria will be evaluated before final selection of a system. These criteria include: safety and reliability, technical risk, cost, and performance, in that order. Of the concepts evaluated to date, the NERVA derivative is the only concept that has demonstrated full power, life, and performance in actual reactor tests. Other concepts will require significant design work and must demonstrate proof-of-concept. Technical risk, and hence, development cost should therefore be lowest for the NDR concept, and the NDR concept is currently being considered for the initial SEI missions. As lighter weight, higher performance systems are developed and validated, including appropriate safety and astronaut-rating requirements, they will be considered to support future SEI applications. A space transportation system using a modular NTR system for lunar and Mars missions is expected to result in significant life cycle cost savings. Finally, several key issues remain for NTRs, including public acceptance and operational issues. Nonetheless, nuclear thermal rockets are believed to be the "next generation" of space propulsion systems - the key to space exploration.

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13. ABSTRACT ***(Maximum 200 words)***

Nuclear thermal propulsion technology development is underway at NASA and DoE for SEI missions to Mars, with initial near-earth flights to validate flight readiness. Several reactor concepts are being considered for these missions, and important selection criteria will be evaluated before final selection of a system. These criteria include: safety and reliability, technical risk, cost, and performance, in that order. Of the concepts evaluated to date, the NERVA derivative is the only concept that has demonstrated full power, life, and performance in actual reactor tests. Other concepts will require significant design work and must demonstrate proof-of-concept. Technical risk, and hence, development cost should therefore be lowest for the NDR concept, and the NDR concept is currently being considered for the initial SEI missions. As lighter weight, higher performance systems are developed and validated, including appropriate safety and astronaut-rating requirements, they will be considered to support future SEI application. A space transportation system using a modular NTR system for lunar and Mars missions is expected to result in significant life cycle cost savings. Finally, several key issues remain for NTRs, including public acceptance and operational issues. Nonetheless, nuclear thermal rockets are believed to be the "next generation" of space propulsion systems—the key to space exploration.

14. SUBJECT TERMS
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