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# ADVANCED HYBRID NUCLEAR PROPULSION MARS MISSION PERFORMANCE ENHANCEMENT

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## Abstract

Nuclear electric propulsion (NEP), compared with chemical and nuclear thermal propulsion (NTP), can effectively deliver the same mass to Mars using much less propellant, consequently requiring less mass delivered to Earth orbit. The lower thrust of NEP requires a spiral trajectory near planetary bodies, which significantly increases the travel time. Although the total travel time is long, the portion of the flight time spent during interplanetary transfer is shorter, because the vehicle is thrusting for much longer periods of time. This has led to the supposition that NEP, although very attractive for cargo missions, is not suitable for piloted missions to Mars. However, with the application of a hybrid approach to propulsion, the benefits of NEP can be utilized while drastically reducing the overall travel time required. Development of a dual-mode system, which utilizes high-thrust NTP to propel the spacecraft from the planetary gravitational influence and low-thrust NEP to accelerate in interplanetary space, eliminates the spiral trajectory and results in a much faster transit time than could be obtained by either NEP or NTP alone. This results in a mission profile with a lower initial mass in low Earth orbit. In addition, the propulsion system would have the capability to provide electrical power for mission applications.

## INTRODUCTION

For a piloted Mars vehicle, NEP can reduce both the propellant mass and the interplanetary trip time. With the much higher specific impulse, less propellant is consumed as compared to NTP. In interplanetary heliocentric space, the high-efficiency propulsion system allows continuous acceleration over much of the trip, allowing the vehicle to attain much higher speeds, thus reducing the travel time. However, low-thrust propulsion requires spiral trajectory escape and capture at Earth and Mars, which causes the overall trip time to become longer than that of an NTP vehicle.

Additional benefits of electric propulsion for use with Mars piloted missions include decreased variation with opportunity, lengthened Earth launch windows, longer Mars stay windows, and more flexible mission abort strategies (Doherty 1991). Because of decreased variation in propellant consumption, the vehicle can be designed for multiple mission opportunities without major changes in vehicle design. Impulsive thrust propulsion methods, which include chemical and NTP systems, have very wide variations in total propellant requirements for different mission opportunities. The Mars stay time can be reduced without changing the propellant requirements, thereby providing continuous ability to leave Mars up to the planned departure date. Electric propulsion also provides mission abort options and flexibility. Hack et al. (1991) have shown that a 10-MWe vehicle downgraded to 5 MWe has a continuous abort capability to return to Earth with minimal time and propellant penalty.

## Hybrid Mission

The hybrid Mars mission described in this paper is both hybrid propulsion and a combination of mission profiles and techniques that appear to offer benefit. Hybrid propulsion--the use of both low-thrust electric propulsion and high-thrust rockets--can be used to eliminate the trip time associated with near-planetary body spiral trajectories while employing the benefit of high-efficiency electric propulsion for the interplanetary portion of the mission. The system proposed for this application is nuclear electric, consisting of a boiling potassium fast reactor with a direct rankine conversion system coupled with a solid core nuclear thermal rocket. Although it is possible to couple these systems by utilizing the same nuclear heat source for both systems, separate reactors are preferred if tens of thermal megawatts are required for electrical generation (Kirk et al. 1991). Integration issues, which drive the cost, mass, and complexity of a hybrid system, tend to add mass over that saved by a common nuclear reactor and common shield. Although an integrated system could be developed and used, this analysis assumes separate systems with consequent mass and performance numbers.

## Power and Propulsion System

The advanced power system is a derivative of the Rotating Multimegawatt Boiling Liquid-Metal Reactor (RMBLR) design developed as part of the U.S. Department of Energy multimegawatt program (Coomes et al. 1991). The 10-MWe power source uses a boiling liquid-metal reactor with a direct rankine cycle. The five major components are a cermet-fueled, boiling metal fast reactor; a shadow shield; two radial flow turbines with two superconductive alternators; power-conditioning equipment; and a heat rejection thermal control system.

The fast flux reactor uses boiling alkali metal coolant and cermet fuel. The cermet fuel is composed of a refractory-metal matrix, such as tungsten, with 93% enriched uranium nitride (UN) as the fuel material. A cermet fuel was selected because of its superior thermal characteristics and capability to withstand the high stresses imposed by enhanced fission gas release and fuel swelling. Also, the enclosed coolant channel configuration eliminates crossflow instabilities that occur during boiling in open lattice cores.

The Ljungström turbine provides high power density, will not destabilize the vehicle during load changes, has good thermal dynamic characteristics, and is compatible with a low exit quality working fluid. The Ljungström turbine has no stators, but instead uses two sets of counterrotating blades for each stage. Staging occurs in the radial direction, resulting in a series of concentric blade rings attached to each disk. The disks, connected to a counterrotating alternator, rotate in opposing direction. Using this design, a very compact machine with balanced rotational inertia results. This is important for space applications, because excessive vehicle torque cannot be tolerated. In a radial flow turbine, the working fluid velocity is perpendicular to the axis of rotation and parallel to the acceleration, with uniform blade speed along the entire length of the blade. This allows better optimization of the flow and work coefficients, resulting in fewer stages required than for a comparable axial flow machine. Through careful thermal expansion design, the Ljungström turbine has superior ability to handle rapid thermal transients and load ramping compared to equivalent axial flow machines. The exit quality of the turbine can be as low as 70%, exhibiting the same erosion resistance of an axial flow machine having an exit quality of 88%. In addition, less insulation is required because the higher temperatures are in the center of the machine, with the outer stages at the condenser temperature. Overall Ljungström turbine machine efficiency is 1% to 2% higher than the axial design.

The electric propulsion system consists of magnetoplasmadynamic (MPD) thrusters, as well as power conditioning and thermal control systems. Three-phase alternating current is fed through transformers and rectifiers to the thruster. The MPD thruster system has a specific impulse of 5000 s, a power input-to-thrust generated efficiency of 50%, and a mass of 8460 kg for a 10-MWe system (Coomes et al. 1991).

The nuclear thermal propulsion system, used for high-thrust maneuvers near planetary bodies, uses a nuclear engine for rocket vehicle applications (NERVA) derivative technology, solid-core, hydrogen rocket. The specific impulse is 925 s, with a 334,000-N (75,000-lbf) thrust and a mass of 4500 kg (Clark et al. 1991). This specific impulse corresponds to a chamber pressure of 2700 K achieved using composite fuels developed in the NERVA program. The mass includes a man-rated shield for the rocket, which, if shared with the nuclear electric reactor shielding, would represent the increased shielding requirements due to the reactors in close proximity, which would include scattering effects and neutron flux linkages between the reactors.

## CONCLUSIONS

The nuclear hybrid propulsion scheme is a viable alternative for short-duration Mars missions. By utilizing the high specific impulse and small propellant masses of electric propulsion to achieve rapid heliocentric transit, and nuclear thermal propulsion for impulsive maneuvers near planetary bodies to eliminate the very long spiral time associated with electric propulsion alone, a mission that is both mass effective and of short duration is possible. Using the same reactor to provide both electrical power production and thermal heating of gaseous propellant for high thrust, does not appear to offer the significant mass savings needed to warrant development of the technology. However, reducing the thrust for the thermal propulsion would not seriously impact the propulsion mass required for Mars capture and escape, implying that an electric power reactor could be used for both functions, provided that high-temperature operation could be tolerated for the short durations necessary to produce the specific impulse needed for a viable thermal propulsion system.

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