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# A LOW-ALPHA NUCLEAR ELECTRIC PROPULSION SYSTEM FOR LUNAR AND MARS MISSIONS

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Abstract

The advantages of using electric propulsion are well-known in the aerospace community. The high specific impulse and, therefore, lower propellant requirements make it a very attractive propulsion option for the Space Exploration Initiative (SEI). Recent studies have shown that nuclear electric propulsion (NEP) is not only attractive for the transport of cargo but that fast piloted missions to Mars are possible as well, with alphas on the order of 7.5 kg/kW. An advanced NEP system with a specific power (alpha) of 2.5 kg/kW or less would significantly enhance the manned mission option of NEP by reducing the trip time even further. This paper describes an advanced system that combines the PEGASUS Drive with systems of the Rotating Multimegawatt Boiling Liquid Metal (RMBLR) power system that was developed as part of the DOE multimegawatt program and just recently declassified. In its original configuration, the PEGASUS Drive was a 10-MWe propulsion system. The RMBLR was a 20-MW electric power system. By combining the two, a second-generation PEGASUS Drive can be developed with an alpha less than 2.5 kg/kW. This paper will address the technology advancements incorporated into the PEGASUS Drive, the analysis of a fast piloted mission and an unmanned cargo transport Mars mission, and the integration of laser power beaming to provide surface power.

## INTRODUCTION

The current goal of the American space program is the expansion of human presence into the solar system. The development of a permanent presence in space will require a continuous movement outward from Earth. The desire is to establish a permanent base on the moon and to land an American on Mars by the 50th Anniversary of the Apollo 11 lunar landing. The Space Synthesis Group, under Retired General Thomas Stafford, examined various architectures and technologies necessary to accomplish these goals, and a major concern was the logistic support required for both personnel and supplies. A global support infrastructure for power and propulsion must be developed to sustain this outward movement. An infrastructure based on an integrated energy approach is needed. Two areas that easily lend themselves to this are electric propulsion and planetary surface power. Incorporating the space transportation requirements into integrated planning and taking advantage of hardware commonality, a multimegawatt nuclear electric propulsion can meet the needs for both fast piloted missions and much slower cargo transport missions. In addition, if the NEP system included a long-life (7 to 10 years) power source, it looks very attractive as a dual function system that would double as the surface energy source when coupled with a beam-power transmission system (Bamberger 1990). This integrated energy approach to space power and space propulsion would reduce the number of new systems and technologies that need to be developed, provide a commonality of system hardware, and reduce the economic impact of SEI.

The high specific impulse and, therefore, lower propellant requirements make it a very attractive propulsion option for the Space Exploration Initiative (SEI). Recent studies (George, Hack and Dudzinski 1991) have shown that not only is electric propulsion attractive for the transport of cargo, but fast piloted missions to Mars, on the order of 400 days, are possible using near-term low power nuclear electric propulsion (NEP) with an alpha on the order of 7.5 kg/kW. An advanced NEP system with an alpha of 2.5 kg/kW or less would significantly enhance the manned mission option of NEP by reducing the trip time even further.

The Rotating Multimegawatt Boiling Liquid Metal (RMBLR) power system (Johnson et al. 1987) was developed as part of the DOE multimegawatt program and just recently declassified. The RMBLR was a family of reactor concepts ranging in power output from 10 MWe to 500 MWe. All of these were direct Rankine cycle systems. The PEGASUS Drive (Coomes et al. 1987), in its original configuration, was a 10-MW nuclear electric propulsion system. By incorporating the technology advances of the RMBLR concept in reactor design, power conversion, and ultra-light fabric heat rejection systems, a second-generation PEGASUS Drive can be developed with an alpha less than 2.5 kg/kW. This propulsion system would allow a 400-MT Mars cargo vehicle, assembled and loaded in low Earth orbit (LEO), to deliver 193 MT of supplies and hardware to low Mars orbit 282 days after escaping Earth orbit.

Incorporating a laser power transmitter into the PEGASUS Drive and adding a laser power receiver to the Mars surface cargo manifest would make available 2 MW of electric power on the Mars surface. Upon arrival at Mars, the cargo transport vehicle would place its cargo into the desired parking orbit around Mars. The unloaded spacecraft would then proceed to Mars synchronous orbit above the desired landing sight. The laser transmitter would be activated and PEGASUS would be ready to beam energy to the surface to operate automated systems deployed from the cargo load. When the crew arrives later, this same system would provide the surface power needed to maintain the crew and support exploration activities. The availability of megawatt levels of electric power on the Mars surface would greatly enhance and even expand the mission options possible for Mars exploration.

## MISSION ANALYSIS

Any number of mission profiles may be devised for a manned Mars expedition, depending on the assumptions made concerning desired objectives and available technology. The split-sprint Mars mission scenario allows optimum transport of personnel and materials, making this the mission of choice. An unmanned nuclear electric cargo vehicle, staged in LEO, is sent to Mars carrying all the necessary supplies and equipment needed to establish the Mars outpost. The manned mission, also staged in LEO, would follow later. Using a nuclear electric propulsion system with an alpha of 7.3 kg/kWe, a 303-MT spacecraft in LEO could transport astronauts to Mars, allow them to stay 30 days and then return all in 412 days (George, Hack and Dudzinski 1991), an outbound leg of 165 days, a stay in Mars orbit of 30 days, and a return leg of 217 days. The mass breakdown for a typical fast piloted Mars mission is presented in Table 1.

The transport time for the cargo spacecraft is not a critical issue but efficient mass transport is. The outbound leg for the cargo vehicle is 282 days to deliver 193 MT to Mars orbit. If the cargo vehicle is not returned to earth, several unique mission options (Coomes and Bamberger 1990) available for the system left in Mars orbit. Coupling the nuclear electric power system to a beam-power transmission system, electric power can be supplied from geosynchronous Mars orbit (GMO) to the surface to support a broad range of activities. Automated systems deployed from the cargo vehicle or left operating when the crew returns to Earth could convert raw materials on the Mars surface into usable form, which would then be available to the manned flights that follow. Finally, a backup return vehicle would be available, should the primary manned spacecraft become disabled. The crew could reconfigure the two spacecraft (already in orbit around Mars) and use the propulsion system of the cargo vehicle to propel them home. The mass breakdown for a Mars NEP cargo vehicle is presented in Table 2. The trip time includes 282 days for the outbound leg. With a 30-day stay time at Mars and reconfiguring the cargo vehicle as a piloted emergency return vehicle, the return trip would take 345 days. This is an abort or backup option offered by the split mission approach.

TABLE 1. Mars Piloted Vehicle Mass Summary

| SPACECRAFT COMPONENTS | MASS (kg) |
|---|---|
| Transit Habitat and ECCV | 53,300 |
| Power System | 62,400 |
| Propulsion System | 5,800 |
| Propellant | 169,900 |
| Propellant Tankage | 16,100 |
| Structure & Miscellaneous | 4,500 |
| Total Spacecraft Mass | 303,000 |

TABLE 2. Mars Cargo Vehicle Mass Summary

| PROPULSION SYSTEM | MASS(kg) | POWER SYSTEM | | MASS(kg) |
|---|---|---|---|---|
| MPD Thruster Assembly | 1,160 | Reactor System | | 3,620 |
| Engine Control Assembly | 80 | UN Fuel | 860 | |
| High-Current Buss | 1,360 | Molybdenum | 1,520 | |
| Rectifier Assembly | 330 | Vessel & Reflector | 1,240 | |
| Transformer Assembly | 3,190 | Support Structure | | 350 |
| AC Buss Components | 110 | Potassium Inventory | | 200 |
| Thermal Control Systems | 280 | Shadow Shield | | 5,100 |
| Subsystem Total | 6,510 | Turbines & Alternators | | 3,120 |
| Contingency Mass (10%) | 650 | Fabric Heat Pipe Radiator | | 1,700 |
| Structural Mass (20%) | 1,300 | Auxiliary Cooling | | 500 |
| Propulsion System Total | 8,460 | Power System Total | | 14,590 |

| SPACECRAFT COMPONENTS | MASS (kg) |
|---|---|
| Supplies, Lander, Rover, etc. | 168,750 |
| Power & Propulsion | 23,050 |
| Power Transmitter | 25,000 |
| Propellant (Outbound) | 55,000 |
| Propellant (Crew return) | 66,000 |
| Propellant Tankage | 18,000 |
| Navigation, Command, & Control | 13,200 |
| Structure & Miscellaneous | 30,000 |
| Total Spacecraft Mass | 400,000 |

## PROPULSION SYSTEM

Electric propulsion systems have not been seriously considered for use with large spacecraft because of the lack of a suitable electric power source to drive them. However, recent efforts to develop megawatt-class space power sources show such systems to be technologically feasible, and a multimegawatt lightweight nuclear electric propulsion system would enable missions of almost any conceivable duration and scope. A 10-MWe Mars cargo transport vehicle is a very viable system. A magnitoplasmadynamic (MPD) thruster coupled with a nuclear electric power plant provides the most attractive electric propulsion system. The propulsion system itself is simple, compact, and extremely rugged. Such a propulsion system is described in the following sections.

MPD Thruster System

The MPD thruster system is composed of thrusters, propellant tanks, power conditioning, and thermal control subsystems. The thruster assembly consists of seven MPD engines that are used one at a time. All seven engines are connected in parallel to a high-current buss, but each has a separate propellant valve and contactor for the cathode current feed. Performance development may change the electrode shape somewhat, but the overall dimensions of a multimegawatt thruster will remain about the same (King and Vondra 1984). Each engine is assumed to have a center-body cathode 3 cm in diameter and 10 cm long, with an anode about 12 cm inside diameter and of a comparable length. With the present understanding of cathode physics, thruster lifetime (which is limited by the cathode) is about 2,000 hours. The most massive part of the MPD engine is the anode heat removal system.

Electric Power Source

PEGASUS, the proposed power source for the MPD thruster system, is a 10-MWe boiling liquid-metal reactor power system. The system employs a direct rankine power cycle and is designed to meet the power requirements for a 10-MWe electric propulsion system and the operational needs of the power system and spacecraft itself. The power system is composed of five major subsystems or components: a cermet-fueled, boiling liquid-metal fast reactor; a shadow shield; three radial flow Ljungström derivative turbines each, driving a counterrotating superconducting alternator; a power conditioning subsystem; and a heat rejection/thermal control subsystem.

Reactor The reactor selected for the PEGASUS system is a fast reactor using a boiling alkali metal coolant and cermet fuel. A reactor system designed to operate in space (Coomes 1988) should take maximum advantage of the space environment rather than be a simple extrapolation of terrestrial reactor systems. The RMBLR (Johnson et al. 1987) does just that. The cermet fuel is composed of a refractory-metal alloy (Mo-7Re-3Hf) matrix with highly enriched uranium nitride (UN) as the fuel material. The UN/moly alloy cermet fuel was selected because of the high fissile density of UN (30% greater than $UO_2$), the high-temperature strength of the molybdenum alloy, and the ruggedness of cermet. The use of cermet fuel blocks with internal coolant flow channels, the use of UN in a matrix of refractory metal alloy of molybdenum, hafnium, and rhenium, and the arrangement of these fuel blocks provides unique characteristics (Barner et al. 1986) that are in direct contrast to typical clad fuel-pin core designs, even those using UN as the fuel. Also, the enclosed coolant channel and radial-inflow configuration eliminates crossflow instabilities that occur during boiling in open lattice cores.

Power Conversion Although the energy conversion system is the heart of any power system, it has received relatively little or no development attention. The belief is that sufficient experience and technology exist to design, build, test and produce turbomachinery for space-power systems. The only major issues needing resolution are the development of the high temperature materials and the development of bearings and seals to provide the desired system lifetimes. For terrestrial systems, this belief may be true. However, for space and even extraterrestrial applications, this is not the case. The absence of gravity, the lack of a stable mounting platform, and the hard vacuum that exists in space place special requirements on rotating machinery not normally considered on earth. The most important is the need for a system that will not destabilize the platform to which it is attached during startup/shutdown or load changes. Of secondary importance is the need for a high-power density; its importance depends on launch costs. These issues lead to a very different power conversion approach in the development of the RMBLR and in the power conversion system studies conducted by the Air Force Wright Research and Development Center (Giellis et al. 1990).

Because the largest alkali metal turbines ever developed were systems of less than 50 kWe output, the decision was made to review various turbine configurations to determine whether any one of the available basic designs had any intrinsic qualities that would make it more suitable for space applications. This effort led to the choice of the Ljungström turbine (Ljungström 1949) as the ideal turbine design for space applications. This design is unique in several respects. It has no stators; all blade rows rotate. Each set of blades in a stage is attached to blade rings which are attached by expansion rings to the two rotating disks. Staging occurs in the radial direction and results in a series of concentric blade rings attached to each disk. These disks rotate in opposite directions, providing the machine with two counterrotating shafts, each driving an alternator. This provides a natural means of balancing rotational torques that result during startup, shutdown, and load variations. By taking advantage of this counter rotation and modifying the standard, a single, very compact machine can be built. The flow through the machine is perpendicular to the axis of rotation and parallel to the acceleration forces acting on the blades. The blade speed is uniform along the entire length of each blade, resulting in maximum and average blade efficiency being the same. Because the flow vector and the acceleration vectors are parallel, this design is very tolerant of moist vapor. Typical exit qualities of axial flow machines are on the order of 88% or greater, while the Ljungström turbine should have the same erosion resistance with exit qualities as low as 70%. Through careful design to accommodate thermal expansion, it also has the capability of rapid startup.

The modified Ljungström turbine is coupled to a counterrotating superconducting alternator to provide the electrical output. Superconducting alternators are chosen to develop the electrical power because of their high power-to-weight ratio. Each superconducting alternator is expected to operate at 1500 Hz and 10 to 20 kVA with a continuous output power capability of 5 MWe (Dodge et al. 1987). The overall power conversion subsystem is expected to have a specific weight on the order of 0.5 kg/kW and an efficiency of 98%.

Heat Rejection and Thermal Control Heat rejection for the PEGASUS is accomplished by means of high- and low-temperature heat rejection subsystems. The high temperature subsystem handles waste heat rejection from the turbines. The low temperature subsystem takes care of waste heat from the alternator and other components requiring cooling. The high-temperature heat rejection system consists of three ceramic fabric heat-pipe radiators, associated pumps, piping, and structure. The radiator is sized to reject 21.5 MW of waste heat from the system during full-power operation.

The low-temperature heat rejection system consists of an auxiliary cooling system designed to reject waste heat produced within the alternator and other equipment operating at much lower temperatures. The auxiliary cooling system has its own working fluid, pumps, and radiator. This system utilizes helium as its working fluid and is composed of a Sterling cycle cryogenic cooler, an auxiliary chiller, a low-temperature radiator, and associated pumps and piping. The cryogenic cooler removes heat from the liquid helium and transfers this heat to the auxiliary coolant in the chiller. A closed loop system is used to pump this coolant through the auxiliary cooling radiator located around the perimeter of the main radiator. Before returning to the chiller, this coolant is used to cool pumps and other components.

## CONCLUSIONS

Cargo transport has never been a time-critical activity. This makes a nuclear electric cargo vehicle the ideal spacecraft to carry the equipment and supplies necessary to sustain human expansion into the solar system. However, nuclear electric propulsion also has the ability to preform fast piloted missions with trip times on the order of 400 days with only a moderate alpha. Utilizing the advanced technologies developed under the Department of Energy's Multi-Megawatt Program, an upgraded PEGASUS Drive propulsion system, with an alpha less than 2.5, would significantly enhance the mission performance of NEP used for the Mars cargo transport and fast piloted missions. In addition, nuclear electric propulsion, when coupled with a beam-power transmission system, provides significant Mars surface mission enhancement, opening many new mission options not previously possible with chemical or nuclear thermal propulsion systems.

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