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Abstract

The advantages of using electric propulsion for propulsion are well-known in the aerospace community. The high specific impulse, lower propellant requirements, and lower system mass make it a very attractive propulsion option for the Space Exploration Initiative (SEI), especially for the transport of cargo. One such propulsion system is the PEGASUS Drive (Coomes et al. 1987). In its original configuration, the PEGASUS Drive consisted of a 10-MWe power source coupled to a 6-MW magnetoplasmadynamic (MPD) thruster system. The PEGASUS Drive propelled a manned vehicle to Mars and back in 601 days. By removing the crew and their associated support systems from the spacecraft and by incorporating technology advances in reactor design and heat rejection systems, a second generation PEGASUS Drive can be developed with an alpha less than two. Utilizing this propulsion system, a 400-MT cargo vehicle, assembled and loaded in low Earth orbit (LEO), could deliver 262 MT of supplies and hardware to Mars 282 days after escaping Earth orbit. Upon arrival at Mars the transport vehicle would place its cargo in the desired parking orbit around Mars and then proceed to synchronous orbit above the desired landing sight. Using a laser transmitter, PEGASUS could provide 2-MWe on the surface to operate automated systems deployed earlier and then provide surface power to support crew activities after their arrival. The additional supplies and hardware, coupled with the availability of megawatt levels of electric power on the Mars surface, would greatly enhance and even expand the mission options being considered under SEI.

INTRODUCTION

President Bush has chosen the expansion of human presence into the solar system as the focus of the American space program with the goal of landing of an American on Mars by the 50th Anniversary of the Apollo 11 lunar landing. Developing a permanent presence in space requires a continual stepping outward from Earth in a logical progressive manner. If we seriously plan to go and to stay, then we must not only plan what we are to do and how we are to do it, we must address the logistic support infrastructure that will allow us to stay once we arrive. In this way, a permanent human presence in space can be sustained.

The Space Synthesis Group, under Retired General Thomas Stafford, is examining various architectures and technologies necessary to establish permanently manned bases on the moon and on Mars. A major concern is the logistic support these bases will require. To provide this support, highly efficient cargo transport vehicles must be developed. Incorporating this need into integrated planning and taking advantage of hardware commonality, a multimegawatt nuclear electric cargo transport with a long-life power source coupled with a beam-power transmission system, looks very attractive as a dual function system by doubling as the surface energy source after its cargo transport function has been discharged (Bamberger 1990).

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, follows later using a chemical or nuclear-thermal propulsion system to transport Mars

astronauts. Transport time is not a critical issue for the cargo transport craft; efficient mass transport is, whereas transport time is the critical issue for piloted spacecraft. The mass breakdown of a typical cargo mission is presented in Table 1.

The use of a separate nuclear electric-propelled cargo vehicle offers several unique mission options (Coomes and Bamberger 1990) not possible with a chemically-powered cargo vehicle. Taking advantage of the fuel savings offered by electric propulsion and with no need for the life support, habitat, or additional shielding systems required on a manned vehicle, the cargo transport vehicle could carry enough supplies in a single flight to support several manned flights to Mars. Being sent in advance, it could carry return or reserve fuel for the manned return flight. 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 broader 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 space craft 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. Figure 1 shows the 282 day mission trajectory for the outbound cargo vehicle and the 345 day return leg for the reconfigured backup piloted vehicle after a 30 day stay at Mars.

TABLE 1. Mars Cargo Vehicle Mass Summary

PROPULSION COMPONENTS	MASS (kg)	POWER SYSTEM		MASS (kg)
MPD Thruster Assembly	700	Reactor		5,340
Engine Control Assembly	50	UN Fuel	1,024	
High Current Buss	817	Molybdenum	2,668	
Rectifier Assembly	200	Vessel & Reflector	1,648	
Transformer Assembly	1,911	Support Structure		1,359
AC Buss Components	69	Potassium Inventory		907
Thermal Control Systems	156	Shadow Shield		5,105
Subsystem Total	3,897	Turbines & Alternators		4,334
Contingency Mass (10%)	390	Fabric Heat Pipe Radiator		1,698
Structural Mass (20%)	857	Auxiliary Cooling		907
Propulsion System Total	5,150	Power System Total	19,650	

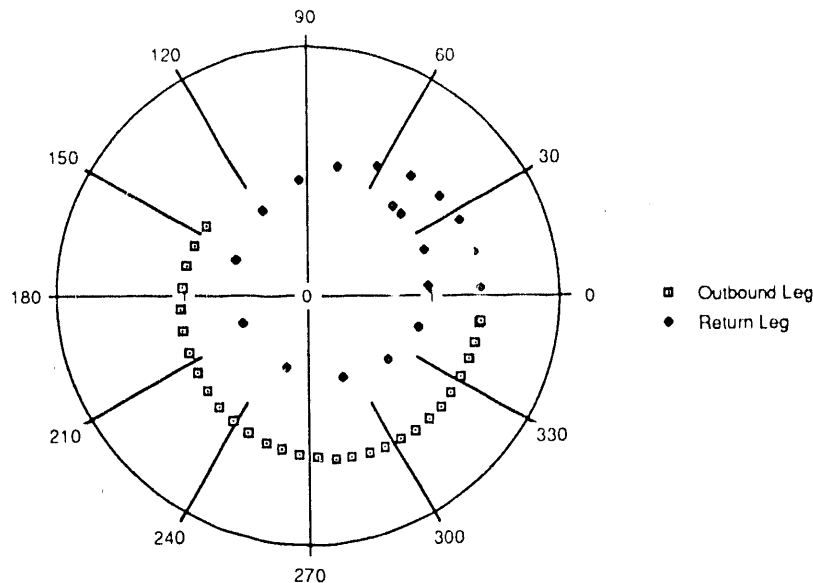| SPACECRAFT COMPONENTS	MASS (kg)
Supplies, Lander, Rover, etc.	168,000
Power & Propulsion	24,800
Power Transmitter	25,000
Propellant (Outbound)	55,000
Propellant (Crew return)	66,000
Propellant Tankage	18,000
Navigation, Command, & Control	13,200
Structure & Miscellaneous	30,000
Total Spacecraft Mass	400,000

FIGURE 1. Typical PEGASUS Drive Cargo and Emergency Return Vehicle Trajectories

Propulsion System

Electric propulsion systems have not been seriously considered for use with large spacecraft due to 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. The 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, which must remove approximately 300 kW. An allowance of 700 kg is made for the assembly of seven engines, contactors, and thermal control.

Three phase AC is fed through transformers and rectifiers to the thruster. Power control and regulation is confined to adjustments of the AC output from the alternator. A high voltage buss runs from near the turboalternator past the reactor shield to the transformer. To enhance reliability, the rectifier is designed to use 3,000 amperes radiation hardened diodes derated to 1,500 amperes. Eight diodes are connected in parallel in each of the units for full wave rectification of three phase AC. A contingency of 10% of the system mass is included, and 20% on top of that added for structure. The electrical system is 87% efficient while the MPD thruster is assumed to have a 50% conversion efficiency. A summary of the mass breakdown of the thruster system is provided in Table 1.

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 comprised of five major subsystems or components: a cermet fueled, boiling liquid metal fast reactor; a shadow shield; two radial flow Ljungstrom turbines with four superconducting alternators for power conversion; a power conditioning subsystem; and a heat rejection/thermal control subsystem. Table 1 includes a mass breakdown of the power subsystem.

Reactor Subsystem

The reactor selected for the PEGASUS system is a fast reactor using a 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 as the fuel material. A cermet fuel was selected because of its superior thermal characteristics and its capability to withstand the high stresses imposed by enhanced fission gas release and fuel swelling. A strong, relatively ductile metal matrix with a high thermal conductivity is well suited to the needs of a reactor where rapid power swings are necessary to meet varying power demands. Also the enclosed coolant channel configuration eliminates cross flow instabilities that occur during boiling in open lattice cores.

Reactor Design

A reactor system designed to operate in space should take maximum advantage of the space environment rather than be a simple extrapolation of terrestrial reactor systems. The split core radial-in-flow reactor core (Coomes 1988) does just that. Coolant flows radially inward through the core where it is boiled, exiting the fueled region as a vapor, and entering a central outlet plenum. The outlet plenum along the core central axis feeds two outlet manifolds located at either end of the reactor. The core is composed of monolithic fuel blocks with internal coolant channels and are held in concentric rings around a center plenum. These rings are stacked axially to produce a cylindrical core. Each axial level of the fuel is retained in its proper location in the core by grooved spacer discs that sandwich the rings of fuel blocks. These spacer discs accommodate thermal expansion and possible fuel swelling. The radial inward flow and the corresponding increase of specific volume of the potassium as boiling occurs, results in high vapor velocities, 25 to 40% of sonic, through the final fuel rings. This makes it possible to maintain adequate heat transfer under all operating conditions even as severe as a sudden order of magnitude increase in power. Since this is a boiling system, the core operates with a uniform core temperature throughout most of its volume. In addition, by removing the inner most ring of UN/Moly alloy cermet fuel and replacing it with a UN/Tungsten cermet, it is possible to operate this core design with 25 to 50°K of super-heat, eliminating the need for a moisture separation system at the core outlet.

Un-Cermet Fuel

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 in a radial-in-flow geometry 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.

A cermet fuel has a much greater resistance to thermal shock and stress (imposed by fission gas release) caused by sudden transients or cyclic operation over the life of the core and an ability for extended burnup providing long mission life. The strong, relatively ductile, high-thermally-conductive metal matrix and rugged configuration of the fuel block provides greater reliability than any other fuel material or fuel form. The absence of interconnecting porosity between the individual particles of UN and using 80% dense UN particles, increase the ability to retain fission products, thus minimizing fuel swelling over the life of the core. The combination of high thermal conductivity and thin fuel webs

between coolant channels allows high surface temperatures (1500°K) while maintaining relatively moderate peak fuel temperatures (1650°K). The fuel composition of approximately 25% average UN loading in a Mo-Re-Hf alloy matrix results in a configuration that has a negative reactivity worth for any water entering the core and central cavity. This eliminates the concern over water immersion that could result from a hypothetical launch abort accident. This negative worth of water is due to the poisoning effect the Re and Hf would have because of the softer spectrum that results from the addition of water to the core.

Reactor Control

Reactor control for this core configuration is accomplished by two independent control systems. One system is for coarse reactivity control to accommodate burnup and the second system provides operational control for load following. Burnup control is accomplished by adjusting the separation distance of the two core halves with the four rod drives connected to the movable core half. Split core control uses the change in core geometry to produce a sub-critical core configuration and thus controls reactor criticality directly. This provides a very rapid shutdown that is independent of delayed neutron effects and provides a much greater prompt drop effect. The operational control is accomplished by movable reflector segments located outside the pressure vessel and employs neutron leakage from the periphery of the core as the primary mechanism for operational control. Operational control system consists of 16 movable beryllium oxide reflector segments that are connected to individual control drive mechanisms located outside of the reactor containment can. This makes it possible for reflector segments to be withdrawn up to 25 cm from the reactor vessel.

Reactor Shielding Subsystem

The PEGASUS system incorporates a shadow shield to reduce radiation from the reactor to safe levels for equipment and cargo during full-power operation. The shield is a composite material of depleted LiH, W, and LiH (Barattino 1985). To maintain the physical integrity of the shield, it is cooled by the reactor inlet coolant.

Power Conversion Subsystem

Power conversion is accomplished by three turboalternators. The turbine designs incorporate a multi-stage radial out-flow design developed by Berger Ljungstrom (Ljungstrom 1949) in 1910. This turbine design is a very compact high power density turbine. The turbines are radial out-flow configurations designed to operate with an inlet pressure of 1.5 MPa and an exit quality of 70%. 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, and be capable of providing a continuous electric power output of 5 megawatts. (Doage 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 Subsystem

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 space craft to carry the equipment and supplies necessary to sustain human expansion into the solar system. Utilizing new and improved technologies developed under the Department of Energy's Multi Megawatt Program, an upgraded PEGASUS Drive propulsion system has the ability to meet the needs of a Mars cargo transport vehicle. Nuclear electric propulsion, when coupled with a beam-power transmission, provides significant mission enhancement opening new mission options not possible with other propulsion systems.

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