NASA/TM—2006-214106

Use of High-Power Brayton Nuclear Electric Propulsion (NEP) for a 2033 Mars Round-Trip Mission

Melissa L. McGuire
Glenn Research Center, Cleveland, Ohio

Michael C. Martini and Thomas W. Packard
Analex Corporation, Brook Park, Ohio

John E. Weglian and James H. Gilland
Ohio Aerospace Institute, Brook Park, Ohio

March 2006

The NASA STI Program Office . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program Office plays a key part in helping NASA maintain this important role.

The NASA STI Program Office is operated by Langley Research Center, the Lead Center for NASA's scientific and technical information. The NASA STI Program Office provides access to the NASA STI Database, the largest collection of aeronautical and space science STI in the world. The Program Office is also NASA's institutional mechanism for disseminating the results of its research and development activities. These results are published by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA's counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services that complement the STI Program Office's diverse offerings include creating custom thesauri, building customized databases, organizing and publishing research results . . . even providing videos.

For more information about the NASA STI Program Office, see the following:

- Access the NASA STI Program Home Page at ***http://www.sti.nasa.gov***

- E-mail your question via the Internet to help@sti.nasa.gov

- Fax your question to the NASA Access Help Desk at 301–621–0134

- Telephone the NASA Access Help Desk at 301–621–0390

- Write to:
  NASA Access Help Desk
  NASA Center for AeroSpace Information
  7121 Standard Drive
  Hanover, MD 21076

NASA/TM—2006-214106

Use of High-Power Brayton Nuclear Electric Propulsion (NEP) for a 2033 Mars Round-Trip Mission

Melissa L. McGuire
Glenn Research Center, Cleveland, Ohio

Michael C. Martini and Thomas W. Packard
Analex Corporation, Brook Park, Ohio

John E. Weglian and James H. Gilland
Ohio Aerospace Institute, Brook Park, Ohio

Prepared for the
Space Technology and Applications International Forum (STAIF–2006)
sponsored by the University of New Mexico's Institute for Space
and Nuclear Power Studies (UNM-ISNPS)
Albuquerque, New Mexico, February 12–16, 2006

National Aeronautics and
Space Administration

Glenn Research Center

March 2006

Acknowledgments

The reactor, shield, power conversion, power management and distribution, and heat rejection systems were sized using SRPS_Opt, created by Lee Mason, NASA Glenn Research Center. Robert Adams, NASA Marshall Space Flight Center, led the overall 2004–2005 RASC Mars Orbiter study and is the point of contact for the NEP-Rankline and the chemical studies. The Space Propulsion and Mission Analysis Office, led by Glen Horvat, was instrumental in supporting this study.

Available from

NASA Center for Aerospace Information
7121 Standard Drive
Hanover, MD 21076

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov

Use of High-Power Brayton Nuclear Electric Propulsion (NEP) for a 2033 Mars Round-Trip Mission

Melissa L. McGuire
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Michael C. Martini and Thomas W. Packard
Analex Corporation
Brook Park, Ohio 44142

John E. Weglian and James H. Gilland
Ohio Aerospace Institute
Brook Park, Ohio 44142

Abstract

The Revolutionary Aerospace Systems Concepts (RASC) team, led by the NASA Langley Research Center, is tasked with exploring revolutionary new approaches to enabling NASA to achieve its strategic goals and objectives in future missions. This paper provides the details from the 2004-2005 RASC study of a point-design that uses a high-power nuclear electric propulsion (NEP) based space transportation architecture to support a manned mission to Mars. The study assumes a high-temperature liquid-metal cooled fission reactor with a Brayton power conversion system to generate the electrical power required by magnetoplasmadynamic (MPD) thrusters. The architecture includes a cargo vehicle with an NEP system providing 5 MW of electrical power and a crewed vehicle with an NEP system with two reactors providing a combined total of 10 MW of electrical power. Both vehicles use a low-thrust, high-efficiency (5000 sec specific impulse) MPD system to conduct a spiral-out of the Earth gravity well, a low-thrust heliocentric trajectory, and a spiral-in at Mars with arrival late in 2033. The cargo vehicle carries two moon landers to Mars and arrives shortly before the crewed vehicle. The crewed vehicle and cargo vehicle rendezvous in Mars orbit and, over the course of the 60-day stay, the crew conducts nine-day excursions to Phobos and Deimos with the landers. The crewed vehicle then spirals out of Martian orbit and returns via a low-thrust trajectory to conduct an Earth flyby. The crew separates from the vehicle prior to Earth flyby and aerobrakes for a direct-entry landing.

Introduction

This paper details a Revolutionary Aerospace Systems Concepts (RASC) study investigating a high-power nuclear electric propulsion (NEP) space transportation architecture to support a manned mission to Mars. The RASC project, led by the NASA Langley Research Center, is tasked with exploring revolutionary new approaches to enabling NASA to achieve its strategic goals and objectives in future missions. For this study, two vehicle concepts were designed, both using a high-power NEP system with Brayton power conversion and magnetoplasmadynamic (MPD) thrusters. The first vehicle is the Mars Transfer Vehicle (MTV) which carries the crew from the Earth to Mars and back again. The second vehicle, the Cargo Transfer Vehicle (CTV), delivers additional cargo necessary for the mission from the Earth to Mars.

This paper details one of the four space transportation architectures selected by the 2004-2005 RASC Mars Obiter Study for analysis. The other three investigated were nuclear thermal propulsion (Borowski, Packard, and McCurdy, 2006), NEP with Rankine power conversion, and chemical propulsion. In order for the architectures to be compared across an even playing field, all four started with the same mission

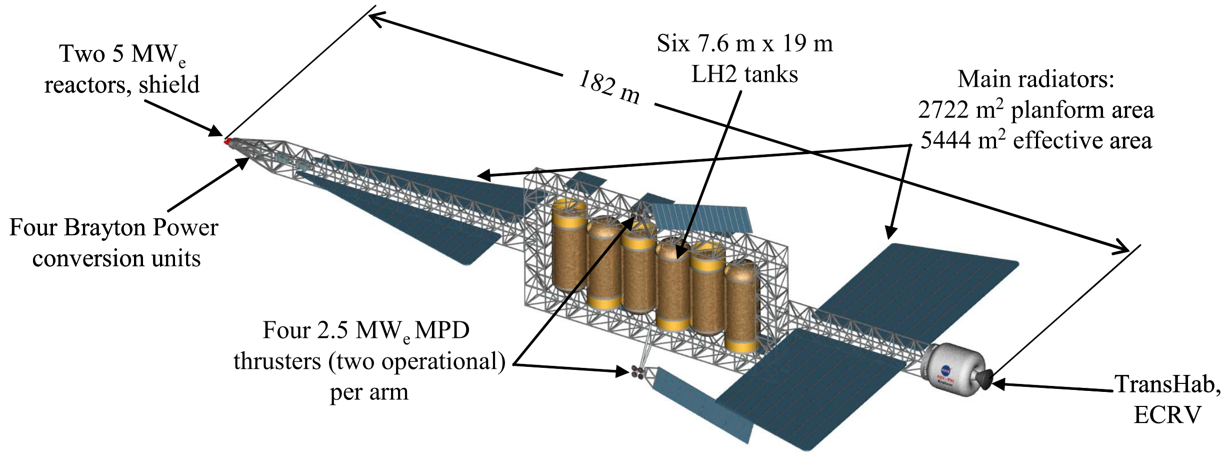


Figure 1.—Mars Transfer Vehicle.

and payload assumptions. The mission consisted of a split profile with the cargo elements sent out on one vehicle and the crew sent out on a second vehicle. Each transportation architecture in the RASC study assumed the same cargo and crew payloads. These study requirements led to a mission that was not optimized specifically for an NEP system.

Vehicle Configurations

Mars Transfer Vehicle (MTV)

In order to provide the required artificial gravity for the crew during the Trans-Mars Injection (TMI) outbound and Trans-Earth Injection (TEI) inbound trajectory legs, the Mars Transfer Vehicle was configured to allow a rotation about the center of gravity. The crew is located in an inflated Transportation Habitat (TransHab) at one end of the NEP vehicle while the Brayton power conversion system and the nuclear reactors are located at the other end. To minimize the translation of the center of gravity over the mission, the LH2 tanks are located at the center of the vehicle configuration. The MTV uses two reactors, each providing 5 MW_e, and a total of four Brayton power conversion units. There are two thruster arms with four 2.5 MW_e MPD thrusters (two operational, two spare) on each arm. Each thruster arm has a radiator to reject heat from the power processing units (PPU). The total planform area of the PPU radiators is 136.7 m^2 (273.4 m^2 effective radiating area). Six LH2 tanks that are 7.6 m in diameter and 19 m long occupy the middle truss section of the vehicle and store the 279.4 MT of propellant. The main radiator is comprised of two sections of double-sided flat panels attached to the center truss structure on either side of the propellant tanks due to center of gravity requirements. The total planform area of the main radiator is 2722 m^2 (5444 m^2 effective radiating area). The MTV is 182 m long and must be assembled in orbit. The configuration of the MTV is shown in figure 1.

Cargo Transfer Vehicle (CTV)

The Cargo Transfer Vehicle is modeled after the NEP configuration used in the 2002 RASC Callisto mission entitled HOPE (McGuire, et al., 2003, and Borowski et al., 2003). Since the cargo vehicle does not require the artificial gravity spin, the propellant tanks are located at the far end from the reactor to prevent splitting up the radiator into two sections. This avoids having the hot heat-rejection fluid routed around the cryogenic tanks, as is required in the MTV configuration. Like the MTV, the CTV has double-sided radiator panels attached to the central truss structure of the vehicle. The total planform area of the main radiator is 1361 m^2, which provides 2722 m^2 effective radiating area. The CTV uses one reactor and

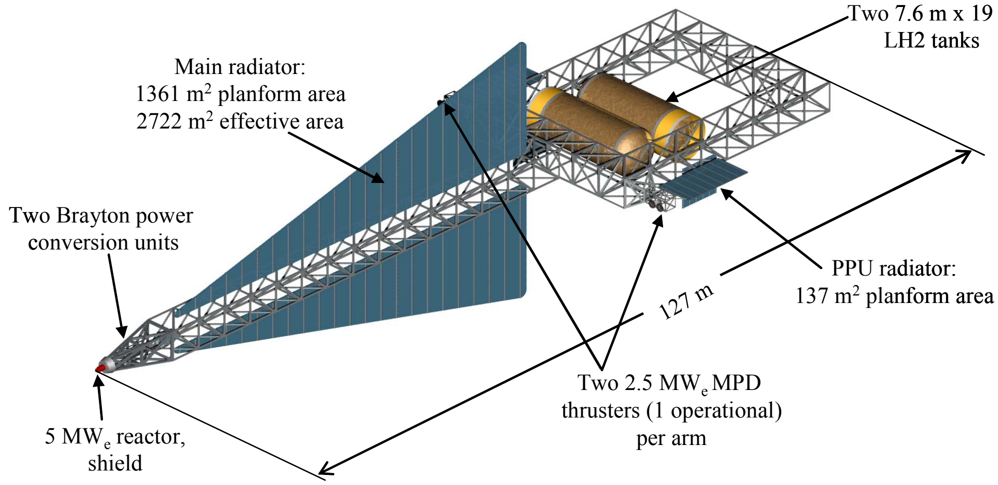


Figure 2.—Cargo Transfer Vehicle.

two Brayton power conversion units to provide 5 MW$_e$ power. The four 2.5 MW$_e$ MPD thrusters are mounted on the outside of the truss section that contains the propellant tanks with two thrusters, one of which is a spare, on each side. The total planform area of the PPU radiators is 273.4 m^2 (546.8 m^2 effective radiating area). The CTV only has two of the 7.6 m diameter, 19 m long LH2 tanks, storing the 63.9 MT of propellant. The CTV is 127 m long and, like the MTV, must be assembled in orbit. The configuration of the CTV is shown in figure 2.

Assumptions

Mission Assumptions and Outline

The RASC Mars Orbiter mission was configured as an opposition class (short stay) Earth-to-Mars round-trip mission. A crew of six is deployed to Mars, but does not perform any Mars surface operations. Rather, they perform two nine-day excursions to Phobos and Demos before returning home to Earth. The total stay-time in Mars orbit is 60 days. The components of the NEP stages of both vehicles are launched on heavy-lift Magnum expendable launch vehicles (ELVs) and assembled in a circular Low Earth Orbit (LEO) at 1000 km altitude and 28.5° inclination. The Magnum is assumed to be capable of delivering 80 MT into LEO in a payload shroud 7.5 m wide by 30 m long.

The CTV conducts a spiral escape from Earth and follows a low-thrust trajectory to Mars to pre-deploy two moon landers (for landing on Phobos and Deimos) in Mars orbit prior to the crew's arrival. After assembly and checkout, a second NEP stage with the TransHab begins the spiral escape from LEO. After the NEP stage has cleared the Van Allen belts and is ready to escape Earth, the crew is launched on a smaller ELV (Delta IV Heavy class) in an Earth crew return vehicle (ECRV) and docks with the NEP stage in a high orbit. At this point, the mated NEP stage with the inflated TransHab and ECRV is referred to as the MTV. The MTV uses the reaction control system (RCS) thrusters to spin the MTV end-over-end upon Earth escape to provide artificial gravity (38 percent of Earth gravity, equal to Mars gravity) to the crew in the TransHab module. The MPD thrusters provide for "side thrusting" by thrusting along the axis of rotation. Once the MTV has reached Mars space, the vehicle performs a spin down maneuver, and the MTV spiral captures into the same Mars orbit as the CTV.

After 60 days of Mars orbit operations, the MTV spiral escapes from Mars orbit and follows a low-thrust trajectory back to Earth. During the heliocentric portion of the flight, the RCS thrusters induce another end-over-end spin for artificial gravity (38 percent of Earth gravity) for the crew in the TransHab. At Earth arrival, the ECRV separates from the MTV with the crew onboard to perform a direct-entry aerobrake and parachute landing on Earth.

Payload Assumptions

With this mission architecture, the cargo (moon landers) is sent out on a separate vehicle than the crew. The crew only carries enough supplies and cargo to last them through the TMI leg, the 60-day stay, and the TEI leg of the trip. All cargo necessary to carry out moon-landing operations at the destination is sent out on the CTV. The CTV payload consists of two moon landers designed by a team led by the NASA Langley Research Center as part of this RASC study. These landers are designed to take three crew on nine-day excursions to the surfaces of Deimos and Phobos, and then return to Mars orbit to rendezvous with the MTV.

The MTV payload consists of an inflatable TransHab and an ECRV. The TransHab is similar to the TransHab design from the Human Exploration and Development of Space (HEDS) design reference mission 4.0 study (Joosten, 2002). The TransHab mass includes enough consumables for a 545-day round-trip mission. Any missions with total trip times longer than 545 days must add an additional 2.45 kg/person/day to the dry-mass allocation. The crew are onboard the MTV for a total of 612 days, so this adds 984.9 kg of consumables to the TransHab for this study. The mass of the TransHab also includes approximately 1900 kg of water for radiation protection and 400 kg for the environmental control and life-support system. The ECRV carries the crew during the final aerobrake for an Earth landing at the end of the mission. Table 1 shows the masses for each of the piloted and cargo payload elements as set by the RASC study. These masses already contain the appropriate contingency for each item, so no additional contingency was added to the payloads in this study.

TABLE 1.—RASC 2004 PAYLOADS

Element	Mass (MT)	Vehicle
TransHab: includes food for 545 days, 6 crew	35.0	MTV
Earth crew return vehicle (ECRV)	7.0	MTV
ECRV docking structure	8.0	MTV
Two moon landers for 9-day missions	42.5	CTV

Power System

This study assumes a high-temperature, liquid-metal, fission reactor with a Brayton power conversion system to generate the electrical power required to supply the MPD thrusters. The reactor was based on an advanced version of the early reactor concept for the Jupiter Icy Moons Orbiter study. The fission reactors use liquid-metal coolant loops, which operate at a temperature of about 1600 K, in order to represent "mid-term" technology (Mason, 2001), consistent with the 2033 mission timeframe. Each reactor coolant loop transfers heat to the Brayton system's working fluid via a heat source heat exchanger (HSHX), producing a Brayton turbine inlet temperature of 1500 K. The Brayton unit includes a recuperator to improve system efficiency by pre-heating the working fluid from the compressor outlet with the turbine exhaust before it reaches the gas cooler. The recuperator reduces the heat load of both the gas cooler and the HSHX, which in turn reduces the size of the radiators and the reactor. The heat rejection system uses a pumped NaK working fluid to remove heat from the Brayton working fluid via the gas cooler and transfers that heat to the radiator panels via water heat pipes. A turbine inlet temperature of 1500 K requires a very high-temperature turbine blade material (possibly ceramic) or active cooling of the blades, and a reactor temperature of 1600 K necessitates the use of refractory metals or other high temperature material for the reactor. A schematic of the Brayton power conversion system is shown in figure 3.

The MTV uses two reactors sized to provide 5 MW_e net electrical power, each. Neutron interactions between the two reactors were not considered. The cargo vehicle only requires one reactor sized to provide 5 MW_e net electrical power. The component masses and radiator areas for both vehicles are presented in table 2. The reactor system includes the radiation shield, which is composed of layers of tungsten (gamma shield) and lithium hydride (neutron shield). The MTV's shields are much heavier than the CTV's due to the crew's more stringent radiation limits. The radiator is double-sided, so heat is rejected from both sides of the radiator panels. Because of this, the effective area for rejecting heat is double the physical area of the radiator panels. The radiator design is described by Siamidis and Mason (2006).

TABLE 2.—POWER SYSTEM PARAMETERS.

	MTV		CTV	
Reactor system mass	18088	kg	4973	kg
Brayton power conversion system mass	8748	kg	4374	kg
Heat rejection system mass	33456	kg	16728	kg
PMAD system mass	20484	kg	9648	kg
Radiator area (effective)	5444	m^2	2722	m^2
Radiator area (physical)	2722	m^2	1361	m^2

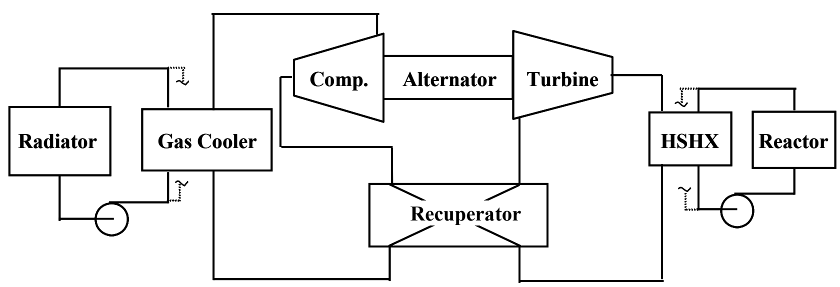
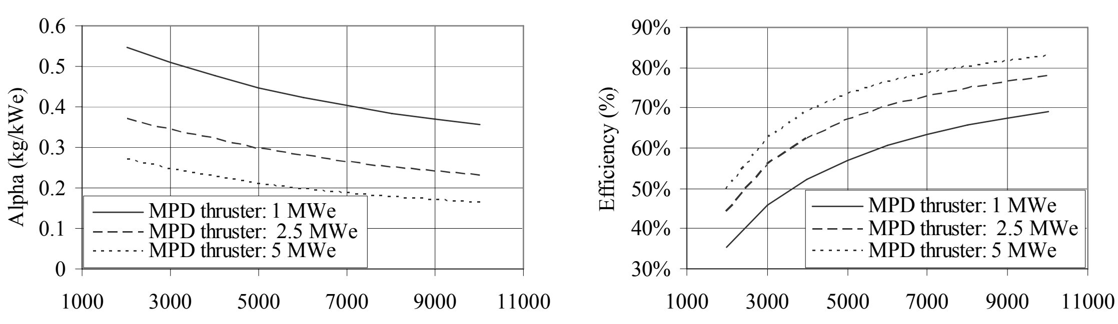


Figure 3.—Schematic of the power conversion system.



(a) Near term MPD thruster alpha (b) Near term MPD thruster system efficiency

Figure 4.—MPD system alpha and efficiency versus I_{SP}.

Propulsion System

This study used magnetoplasmadynamic (MPD) thrusters using hydrogen propellant. Besides operating at a high specific impulse (I_{SP}), the MPD thrusters also have the added advantages of a high-power capability and a compact size. This analysis used high power MPD thrusters operating at 2.5 MW_e per thruster at a constant I_{SP} of 5,000 sec with a thruster lifetime of 7500 hr.

The MPD thrusters use cryogenically-stored liquid Hydrogen (LH2) propellant. This mission utilized the 2.5 MW_e thrusters assumed in the 2002 HOPE study (McGuire et al., 2003). The MTV vehicle used four operating thrusters for a total power level of 10 MW_e and had 4 non-operating spares for redundancy. Likewise, the CTV used two operating thrusters at a total power level of 5 MW_e and had two non-operating spares for redundancy. The mass of the thrusters is I_{SP} dependant. Since a constant I_{SP} was used in this analysis, the mass of the thrusters was calculated using the system alpha (mass/kW_e) for an I_{SP} of 5000 sec. The thrusters were run at an I_{SP} of 5000 sec due to higher efficiencies at this specific impulse. See figure 4 for the dependency of system alpha and MPD thruster efficiency versus operating I_{SP}.

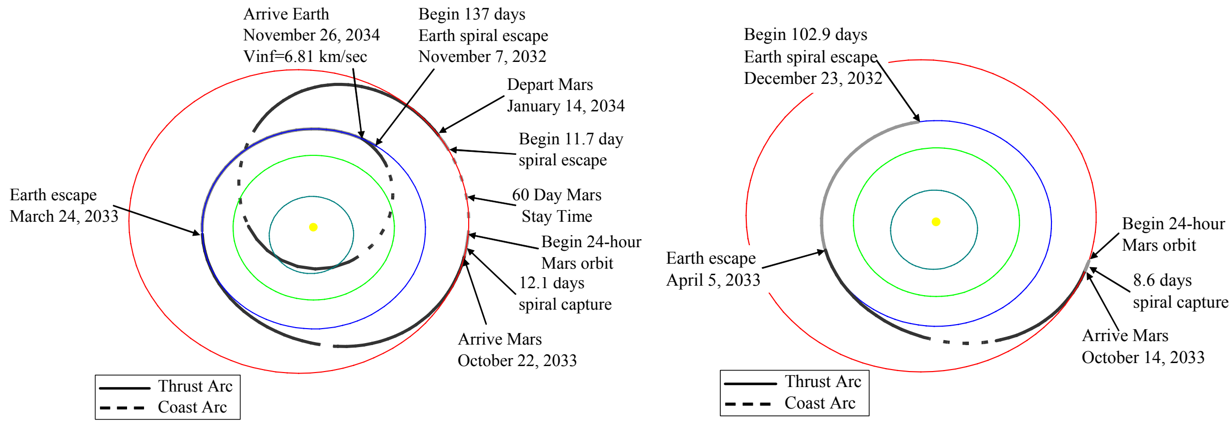
One power processing unit (PPU) and one radiator are assumed per thruster. The system alpha of the PPU and radiator is assumed to be 2.5 kg/kW_e. This included the mass for the power conditioning at the turbine (transformer to increase the voltage to 1 kV), the 1 kV transmission line, the PPU to convert power at the other end, and the Parasitic Load radiator (PLR) to reject waste heat. The sink temperature is assumed to be 250 K at Earth orbit for a worst-case sizing. The effective radiator areas for the two vehicles were: CTV = 273.4 m^2 for a rejection of 5 MW_e, and MTV = 546.8 m^2 for a rejection of 10 MW_e.

Trajectory

Both the MTV and the CTV begin in LEO at 1000 km altitude, spiral out from the Earth, and follow a low-thrust trajectory to Mars. The CTV captures into a 24.65-hr period Mars orbit (radius of periapse = 3643 km, radius of apoapse = 37,186 km, orbital period = one Martian day). The MTV spiral-captures into the same Mars orbit 12 days later. After a 60-day stay at Mars, the MTV returns the crew to Earth on a flyby trajectory. The crew aerobrakes at Earth in the ECRV for a direct-entry that is constrained to 13 km/sec at 125 km altitude. The trajectories for the vehicles were optimized using the VARITOP trajectory optimization program (Williams, 1994). The trajectory for the MTV and CTV are shown in figure 5. The dates and times of each mission phase as well as the total mission time and total crew time (for the MTV) are shown in table 3.

TABLE 3.—MISSION EVENT LIST

Mission event	MTV				CTV		
	Date	Time of segment (days)	Mission time (days)	Crew time (days)	Date	Time of segment (days)	Mission time (days)
Begin Earth escape spiral	11/7/2032	-	-	0	12/23/2032	-	0
Escape Earth	3/24/2033	137	137	0	4/5/2033	103	103
Mars capture	10/22/2033	212	349	212	10/14/2033	192	295
Complete Mars capture spiral	11/3/2033	12	361	224	10/22/2033	9	304
Begin Mars escape spiral	1/2/2034	60	421	284			
Escape Mars	1/14/2034	12	433	296			
Arrive Earth	11/26/2034	316	749	612			



(a) MTV trajectory (b) CTV trajectory

Figure 5.—CTV and MTV trajectories.

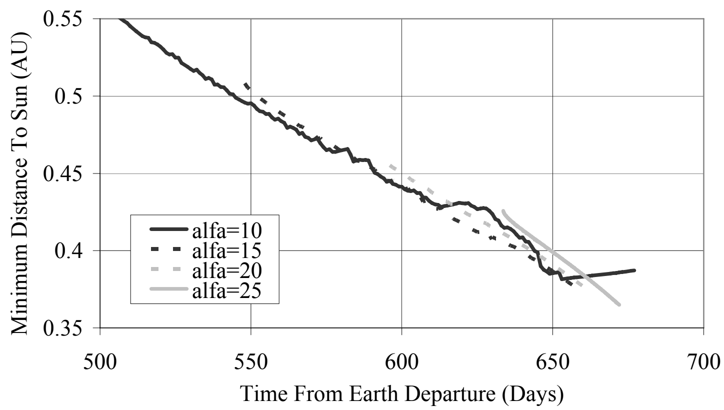


Figure 6.—Effect of trip time on the minimum distance to the Sun.

The study requirements on the total round-trip time and stay time at Mars were not optimal for an NEP mission and led to a close approach to the sun (0.41 AU) in the return trajectory. Such a close approach to the sun could require additional shielding to protect the crew, the power system, and the electronics; however, these effects were not included in this study. VARITOP was used to determine how the trip time affected the closest approach to the Sun for varying propulsion specific masses. While the propulsion specific mass does not have much of an effect, figure 6 shows that increasing the trip time actually decreases the closest distance to the Sun. Reducing the trip time could be accomplished by increasing power and/or reducing I_{SP}, however, this would raise the power or propulsion system masses. These trade-offs were not performed as part of this study. Since the MTV passes within the orbit of Venus (0.7233 AU), a Venus flyby may be able to improve the trip time and/or the closest approach to the Sun. A preliminary investigation using a Venus flyby, subject to the RASC mission constraints, did not show any improvement to the trip time. Similarly, another mission profile using a stay time at Mars longer than 60 days might allow for a more favorable return trajectory, but this was beyond the scope of this study, since the RASC mission requirements did not allow for changing the Mars stay-time.

Mission Mass Summary

The mass breakdown for the MTV and CTV is shown in table 4. A common contingency factor of 25 percent was applied to all dry masses other than the RASC payloads in this analysis in order to get a final mass with contingency. A 1 percent contingency was applied to the LH2 propellant masses.

TABLE 4.—MASS AND POWER SUMMARY FOR THE MTV

Subsystem	MTV Mass (MT)			CTV Mass (MT)		
	Baseline	Contingency	Total	Baseline	Contingency	Total
Power system						
Reactor (liquid metal)—2 x 5 MW_e	18.1	4.5	22.6	5.0	1.2	6.2
Brayton conversion system	8.7	2.2	10.9	4.4	1.1	5.5
Radiator	33.5	8.4	41.8	16.7	4.2	20.9
Power management and distribution	20.5	5.1	25.6	9.7	2.4	12.1
Propulsion system						
MPD thrusters—4 active, 4 spares	2.4	0.6	3.0	0.9	0.2	1.1
PPU, radiators, electrical lines, etc.	23.3	5.8	29.1	11.7	2.9	14.6
Tank details						
LH2 tanks—six 7.6 m x 19 m	41.5	10.4	51.9	15.6	3.9	19.5
LH2 feed lines	3.7	0.9	4.6	2.4	0.6	3.0
Tank attachments	1.2	0.3	1.5	1.2	0.3	1.5
Refrigeration System	6.0	1.5	7.5	6.0	1.5	7.5
LH2 propellant	276.6	2.8	279.4	63.3	0.6	63.9
Structure						
5 m square box truss (total of 52)	13.9	3.5	17.4	11.2	2.8	14.0
Radiator connection to the truss	0.8	0.2	0.9	0.7	0.2	0.9
Artificial gravity balance	2.0	0.5	2.5	N/A	N/A	N/A
ECRV docking structure	8.0	2.0	10.0	N/A	N/A	N/A
Vehicle communications/avionics	0.2	0.1	0.3	0.2	0.1	0.3
RCS system, tanks, thrusters, prop.	7.0	1.8	8.8	N/A	N/A	N/A
RASC payload						
Trans habitat	-	-	34.96	N/A	N/A	N/A
ECRV	-	-	7.0	N/A	N/A	N/A
Additional Consumables for 67 days	-	-	1.0	N/A	N/A	N/A
Phobos/Deimos landers	N/A	N/A	N/A	-	-	42.5
Total NEP stage mass	190.7	47.7	238.4	85.62	21.4	107.0
Total NEP stage mass with payload	233.7	47.7	281.4	127.12	21.4	149.5
Total NEP wet mass with payload	-	-	560.7	-	-	213.5

Conclusion

This study has developed a space transportation architecture based on high-power nuclear electric propulsion using Brayton power conversion and magnetoplasmadynamic propulsion to support a manned Mars mission. The architecture consists of a cargo transfer vehicle with one 5 MW_e fission reactor and a Mars transfer vehicle with two 5 MW_e fission reactors. The RASC study fixed the mission parameters to investigate the performance of 4 different technological approaches to accomplishing the mission. Unfortunately, these mission parameters were not optimal for this architecture and led to several difficulties. The Mars Transfer Vehicle makes a very close approach to the sun (0.41 AU) during the return trajectory in order to rendezvous with Earth. Adjusting the stay-time at Mars and/or utilizing a Venus flyby could be used to increase this distance. The trajectory sequence requires the MTV to begin thrusting before the CTV; however, this occurs before the crew is on board. The MTV similarly departs Earth and begins the heliocentric portion of the flight before the CTV, even though the CTV arrives at Mars, first. A better approach would be to launch the CTV on an earlier opportunity than the MTV to pre-deploy the cargo in the proper orbit before any resources associated with the MTV are launched.

References

Borowski, S. K., McGuire, M. L., Mason, L. S., Gilland, J. H. and Packard, T. W., "Bimodal NTR Propulsion for an Artificial Gravity HOPE Mission to Callisto," in proceedings of *Space Technology and Applications International Forum (STAIF-2003)*, edited by M. El-Genk, AIP, New York, 2003.

Borowski, S. K., Packard, T. W., McCurdy, D. R., "Crewed Orbiter/Moon Survey Mission to Mars using 'Bimodal' NTR Propulsion," in these proceedings of *Space Technology and Applications International Forum (STAIF-2006)*, AIP, New York, 2006.

Joosten, B. K., "Preliminary Assessment of Artificial Gravity Impacts to Deep-Space Vehicle Design", JSC Document no. EX-02-50, NASA Johnson Space Center, Houston, CA, 2002.

Mason, L. S., "A Comparison of Brayton and Stirling Space Nuclear Power Systems for Power Levels from 1 Kilowatt to 10 Megawatts," NASA/TM 2001-210593, NASA Glenn Research Center, Cleveland, Ohio, 2001.

McGuire, M. L., Borowski, S. K., Mason, L. S., and Gilland, J. H., "High Power MPD Nuclear Electric Propulsion (NEP) for Artificial Gravity HOPE Missions to Callisto," in proceedings of *Space Technology and Applications International Forum (STAIF-2003)*, AIP, New York, 2003.

Siamidis, J., Mason, L., "A Comparison of Coolant Options for Brayton Power Conversion Heat Rejection Systems," in these proceedings of *Space Technology and Applications International Forum (STAIF-2006)*, AIP, New York, 2006.

Williams, S. N., "An Introduction to the Use of VARITOP, A General Purpose Low-Thrust Trajectory Optimization Program," Jet Propulsion Laboratory, JPL D-11475, 24 January 1994.

Appendix—Nomenclature

CTV	Cargo transfer vehicle
ECRV	Earth crew return vehicle
ELV	Expendable launch vehicle
HSHX	Heat source heat exchanger
I_{SP}	Specific impulse
LEO	Low Earth orbit
LH2	Liquid hydrogen
MPD	Magnetoplasmadynamic
MT	Metric ton (1000 kg)
MTV	Mars transfer vehicle
NEP	Nuclear electric propulsion
PLR	Parasitic load radiator
PPU	Power processing unit
RASC	Revolutionary aerospace systems concepts
RCS	Reaction control system
TEI	Trans-Earth injection
TMI	Trans-Mars injection
TransHab	Transportation habitat

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
March 2006

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Use of High-Power Brayton Nuclear Electric Propulsion (NEP) for a 2033 Mars Round-Trip Mission

5. FUNDING NUMBERS
WBS 463169.03.03

6. AUTHOR(S)
Melissa L. McGuire, Michael C. Martini, Thomas W. Packard, John E. Weglian, and James H. Gilland

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135−3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E−15441

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546−0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM—2006-214106

11. SUPPLEMENTARY NOTES
Prepared for the Space Technology and Applications International Forum (STAIF–2006) sponsored by the University of New Mexico's Institute for Space and Nuclear Power Studies (UNM-ISNPS), Albuquerque, New Mexico, February 12–16, 2006. Melissa L. McGuire, NASA Glenn Research Center; Michael C. Martini and Thomas W. Packard, Analex Corporation, 1100 Apollo Drive, Brook Park, Ohio 44142; and John E. Weglian and James H. Gilland, Ohio Aerospace Institute, 22800 Cedar Point Road, Brook Park, Ohio 44142. Responsible person, Melissa L. McGuire, organization code PBM, 216–977–7128.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category: 13

Available electronically at http://gltrs.grc.nasa.gov

This publication is available from the NASA Center for AeroSpace Information, 301–621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***
The Revolutionary Aerospace Systems Concepts (RASC) team, led by the NASA Langley Research Center, is tasked with exploring revolutionary new approaches to enabling NASA to achieve its strategic goals and objectives in future missions. This paper provides the details from the 2004-2005 RASC study of a point-design that uses a high-power nuclear electric propulsion (NEP) based space transportation architecture to support a manned mission to Mars. The study assumes a high-temperature liquid-metal cooled fission reactor with a Brayton power conversion system to generate the electrical power required by magnetoplasmadynamic (MPD) thrusters. The architecture includes a cargo vehicle with an NEP system providing 5 MW of electrical power and a crewed vehicle with an NEP system with two reactors providing a combined total of 10 MW of electrical power. Both vehicles use a low-thrust, high-efficiency (5000 sec specific impulse) MPD system to conduct a spiral-out of the Earth gravity well, a low-thrust heliocentric trajectory, and a spiral-in at Mars with arrival late in 2033. The cargo vehicle carries two moon landers to Mars and arrives shortly before the crewed vehicle. The crewed vehicle and cargo vehicle rendezvous in Mars orbit and, over the course of the 60-day stay, the crew conducts nine-day excursions to Phobos and Deimos with the landers. The crewed vehicle then spirals out of Martian orbit and returns via a low-thrust trajectory to conduct an Earth flyby. The crew separates from the vehicle prior to Earth flyby and aerobrakes for a direct-entry landing.

14. SUBJECT TERMS
Cargo; Trajectories; Flyby missions; Aerospace systems; Nuclear electric propulsion; Space transportation; Manned Mars missions; Mars missions; High temperature; Brayton cycle

15. NUMBER OF PAGES
17

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	