NASA/TM—2003-212349

High Power MPD Nuclear Electric Propulsion (NEP) for Artificial Gravity HOPE Missions to Callisto

Melissa L. McGuire, Stanley K. Borowski, and Lee M. Mason
Glenn Research Center, Cleveland, Ohio

James Gilland
Ohio Aerospace Institute, Brook Park, Ohio

December 2003

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—2003-212349

High Power MPD Nuclear Electric Propulsion (NEP) for Artificial Gravity HOPE Missions to Callisto

Melissa L. McGuire, Stanley K. Borowski, and Lee M. Mason
Glenn Research Center, Cleveland, Ohio

James Gilland
Ohio Aerospace Institute, Brook Park, Ohio

Prepared for the
Space Technology and Applications International Forum (STAIF–2003)
cosponsored by the American Institute of Aeronautics and Astronautics
and the University of New Mexico
Albuquerque, New Mexico, February 2–6, 2003

National Aeronautics and
Space Administration

Glenn Research Center

December 2003

Acknowledgments

The authors wish to thank Kurt J. Hack, Leon P. Gefert, and Robert D. Falck of the Systems Analysis Branch of NASA Glenn Research Center (GRC) for their assistance and guidance throughout this study. In addition, we wish to thank Shawn Krizan of Analytical Mechanics Associates at NASA Langley Research Center (LaRC) for his CAD design of the 1/8th g_E PCTV developed jointly by LaRC and GRC. We also thank Thomas Packard of Analex Corporation at GRC, for his CAD designs of the Callisto cargo and tanker vehicles also shown in this paper.

This report contains preliminary findings, subject to revision as analysis proceeds.

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

High Power MPD Nuclear Electric Propulsion (NEP) for Artificial Gravity HOPE Missions to Callisto

Melissa L. McGuire, Stanley K. Borowski, and Lee M. Mason
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135
Melissa.L.McGuire@grc.nasa.gov

James Gilland
Ohio Aerospace Institute
Brook Park, Ohio 44142

Abstract: The following paper documents the results of a one-year multi-center NASA study on the prospect of sending humans to Jupiter's moon, Callisto, using an all Nuclear Electric Propulsion (NEP) space transportation system architecture with magnetoplasmadynamic (MPD) thrusters. The fission reactor system utilizes high temperature uranium dioxide (UO_2) in tungsten (W) metal matrix "cermet" fuel and electricity is generated using advanced dynamic Brayton power conversion technology. The mission timeframe assumes on-going human Moon and Mars missions and existing space infrastructure to support launch of cargo and crewed spacecraft to Jupiter in 2041 and 2045, respectively.

REVOLUTIONARY AEROSPACE SYSTEMS CONCEPTS (RASC) STUDY GOALS

The RASC 2002 multi-center study focused on a Human Outer Planet Exploration (HOPE) mission to Callisto, a moon of Jupiter (Troutman, 2003). The main objectives of the HOPE study were (1) to develop revolutionary aerospace systems concepts allowing human exploration missions into the outer solar system and (2) to identify critical technology requirements for realizing of these systems. The results of the HOPE analysis will help guide NASA technology investments in the future that could enable human space missions beyond the Moon and Mars.

Why Callisto?

The key requirements considered in selecting a worthy exploration destination beyond Mars were (1) the opportunities for conducting interesting science and (2) the availability of in-situ resources to support a human mission. The body chosen for the HOPE study was Callisto, the third largest satellite in the Solar System, and the outermost Galilean moon of Jupiter. Orbiting at a distance of ~1.9 million kilometers, Callisto is located beyond Jupiter's main radiation belts making its local environment more conducive to human exploration. Callisto is an icy, rocky world with a surface gravity of ~0.127 g_E and a composition consisting of water-ice and rock in a mixture ratio of 55:45. Besides having significant quantities of water-ice for propellant production, Callisto's heavily cratered and ancient landscape (~4 billion years old) has a relatively low albedo indicating that significant quantities of non-ice materials and asteroid dust may reside on its surface.

MISSION DESCRIPTION

The HOPE mission consists of sending a crew of six on an expedition to Callisto to establish an outpost and propellant production facility near the Asgard asteroid impact site, a region where the surface crust is potentially rich in water ice. An "all NEP" space transportation system architecture is examined in this paper. It uses a split mission approach involving separate multi-megawatt electric (MW_e)-class cargo, tanker and piloted vehicles each propelled by hydrogen MPD thrusters. Fully automated cargo and tanker vehicles depart first to pre-deploy both orbital and surface assets at Callisto prior to the arrival of the crew onboard the artificial gravity Piloted Callisto Transfer Vehicle (PCTV). The NEP cargo vehicle delivers three different landers for crew ascent / descent, surface habitation and propellant production. The later carries an In-Situ Resource Utilization (ISRU) processing plant and several combination "bulldozer / rover" surface vehicles used to produce liquid oxygen (LOX) and hydrogen (LH_2) propellant from the Callisto surface ice. This propellant is supplied to the reusable crew ascent / descent vehicle allowing crew rotation / re-supply sortie missions between the orbiting PCTV and the surface habitat every 30 days. A small, mobile nuclear surface Brayton power system, also carried on the ISRU lander, provides ~250 kW_e to power the ISRU plant and surface habitat, and to recharge the fuel cell power systems of the surface vehicles. The NEP tanker delivers LH_2 "return" propellant to Callisto orbit that is subsequently transferred to the PCTV for its trip back to Earth. The tanker remains in orbit where it will function as an orbital propellant depot and refinery once larger scale water extraction and propellant manufacturing operations begin on Callisto. The low thrust trajectory profiles of the cargo and tanker vehicles involve a slow spiral away from the Earth-Moon L1 Lagrange point, a direct heliocentric transfer to Jupiter and then a gradual spiral into Callisto orbit (Melbourne, 1965). Once these vehicles are on station and operating properly, the PCTV departs from L1 using a similar, though higher energy, trajectory to Callisto. After a surface exploration period lasting ~120 days, the "refueled" PCTV begins its spiral escape from Callisto on a direct return to Earth and an eventual capture back at L1.

Baseline Mission Ground Rules and Technology Assumptions

The HOPE study established a set of mission and transportation system requirements which included the following: (1) all Callisto-bound spacecraft must depart from the Earth-Moon L1 staging node; (2) the PCTV must transport a crew of six to and from the Jovian moon in less than five years; and (3) it must provide the crew with an artificial gravity (g_a) environment of ~1/8th g_E or higher if the in-space transit time exceeds one year; (4) half of the six person crew will explore the surface for a period of 30 days with longer stays requiring crew rotation and re-supply; and (5) the crew ascent / descent, surface habitat and ISRU landers are limited in mass to 40 metric tons (t; 1 t = 1000 kg).

Also assumed in this study is the availability of highly reliable, autonomous systems, "zero boil-off" (ZBO) cryofluid management, routine propellant transfer both in space and on the surface of Callisto, and last but not least, long-life, reusable LOX/LH_2 chemical rocket engines. Maximum hardware commonality among the different vehicles is also utilized wherever possible. Specifically, the cargo and tanker vehicles use a common nuclear power system to provide the electricity for their sustained, low thrust (~24 lb_f at 6.4 MW_e), long duration operation. The low thrust trajectory / mission analysis code, VARITOP (Williams, 1994) was used in analyzing this all NEP architecture. Lastly, all the vehicles evaluated utilized advanced "far-term" technology projections (Mason, 2001) for the reactor, power conversion, heat rejection, and power management and distribution (PMAD) systems.

Nuclear Power System Technology Assumptions

High temperature (> 2000 K), gas-cooled fission reactors provide a continuous and abundant source of thermal energy for the NEP vehicles considered in this study. The reactors are fueled with enriched uranium-235 in the form of uranium dioxide (UO_2) contained within a tungsten (W) metal matrix "cermet" fuel element with W-alloy cladding. Electrical power is generated using modular, high power, closed cycle, Brayton thermodynamic heat engines. A helium-xenon gas mixture, circulating within a hermetically sealed gas loop in each Brayton engine, picks up thermal energy from the reactor and is then expanded through a single shaft turbine-alternator-compressor unit to generate electricity. Waste heat is rejected to space via radiators. The Brayton engines operate at about 50,000 rpm and the alternator can provide multi-phase, high voltage AC power for the various loads onboard the individual spacecraft. "Far-term" technology performance levels (Mason, 2001) consistent with the 2040 timeframe are featured in the NEP vehicle designs presented here. Examples of these advanced technologies include high temperature material Brayton units with turbine inlet temperatures of ~2000 K, lightweight (~1.5 kg/m^2), "large-scale" (~1500 to 3250 m^2) deployable radiators, and high voltage PMAD (~5000 volts).

Thruster System Technology Assumptions

Magnetoplasmadynamic (MPD) thrusters using hydrogen propellant are featured in this “all NEP” space transportation system architecture. Besides operating at a high specific impulse (Isp) value, the MPD also has the added advantages of a high power handling capability and a compact size. In the basic concept of MPD thruster operation, current flows from an outer annular anode to a central cylindrical cathode and through the hydrogen plasma. The radial current (J) and its self-induced azimuthal magnetic field (B) generate an axial (JxB) Lorentz force on the plasma that accelerates it to high exhaust speeds. For this analysis, high power MPD thrusters operating at 2.5 MW_e per thruster and a constant Isp of 8,000 seconds are baselined. The thruster lifetime and efficiency are assumed to be 7500 hours and 64.5%, respectively. The individual thruster mass is estimated at 263 kg per thruster. The specific mass of the Power Processing Unit (PPU) for each 2.5 MW_e thruster is estimated to be ~1.25 kg/kW_e with one PPU assumed for each operating thruster.

Tanker Vehicle Characteristics and Mission Specifics

The NEP tanker vehicle is sized to hold both the “return” propellant requirements of the PCTV, as well as, the propellant needs of the tanker vehicle itself used in transporting its LH_2 cargo out to Callisto. Parametric analysis was conducted where the total electrical power level was varied with the outbound “L1-to-Callisto” trip time for a specified payload value. A reactor electrical power level of ~6.4 MW_e was determined to be optimal for the tanker mission placing it and its payload into orbit around Callisto several months before the departure date for the PCTV. As mentioned previously, far-term technology projections were assumed for the various power subsystems. A 15% contingency multiplier was also included on all masses. The tanker payload consists of four 19 m long by 7.6 m diameter tanks each holding ~48.6 t of LH_2 propellant. Each tank also has its own active refrigeration system for ZBO propellant storage during the ~3 year outbound journey to Callisto. The maximum LH_2 capacity of the tanker is ~195 t which covers the PCTV return propellant requirements for a variety of propulsion technologies such as the “bimodal” nuclear thermal rocket PCTV option discussed elsewhere (Borowski, 2003). Either a single, high power, highly reliable reactor system or smaller twin reactor systems can be used to supply the 6.4 MW_e of power necessary to maintain the ~24 lb_f of constant thrust supplied by the MPD thrusters. Two right triangle shaped, double-sided radiators provide the ~1500 m^2 of necessary heat rejection area. The overall length of the NEP tanker is ~135 m and its initial mass at L1 is approximately ~244 t (~81 t for the “dry” tanker vehicle structure, ~60 t of LH_2 propellant for the MPD thrusters, and ~103 t for the PCTV return propellant and additional propellant processing equipment mass). Figure 1 depicts an isometric view of the tanker vehicle along with its key features and dimensions. Table 1 provides trajectory information and mission mass details.

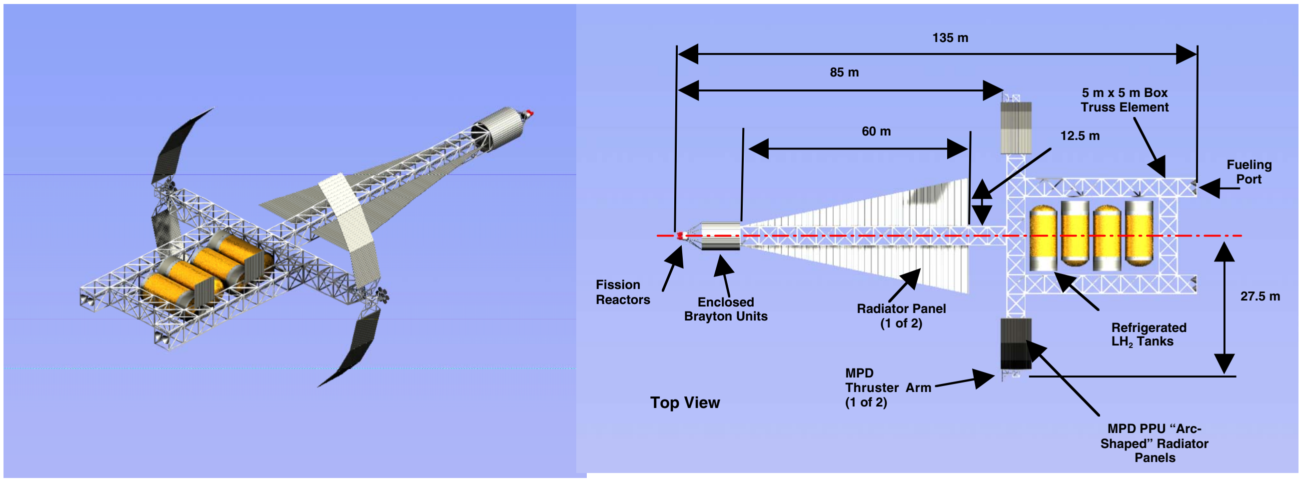

Figure 1. Far-Term NEP Tanker Vehicle Isometric and Representative Features

TABLE 1. Tanker Vehicle Trajectory and Mission Mass Details

Mission Leg	Date	Trip Time (days)	Propellant Mass (t)	Vehicle Mass (t)
Spiral Earth Departure from L1	September 16, 2041	21.2	2.5	244 – 241
Heliocentric Trip to Callisto	October 7, 2041	1012.8	46.9	241 – 194
Spiral Callisto Capture	July 16, 2044	90.3	10.5	194 – 183
Arrival at Callisto	October 14, 2044	(total ~ 3.07 yrs)	Total ~ 60	183

Cargo Vehicle Characteristics and Mission Specifics

The NEP cargo vehicle's function is to deliver 120 t of spacecraft hardware to Callisto orbit consisting of a reusable crew lander, a surface habitat, and a ISRU propellant processing plant -- each having a mass of ~40 t. The cargo vehicle uses the same far-term technology assumptions, 15% contingency factor and 6.4 MW_e nuclear power system as that used on the tanker vehicle. Besides the ~1500 m^2 of primary heat rejection area provided by the two double-sided, triangular-shaped radiators, the cargo and tanker vehicles also have four one-sided, arc-shaped radiator panels (two on each MPD thruster arm) used to dump waste heat from the four MPD thruster power processing units. The curved shape of the PPU radiators helps position them within the reduced radiation conical volume produced by the reactor radiation shields, thereby reducing radiation scatter forward to the payload elements. The LH_2 propellant for the cargo vehicle's MPD thrusters is stored in two 19 m long by 7.6 m diameter advanced composite material tanks each carrying its own active refrigeration system. The cargo vehicle has an overall length of ~130 m and its initial mass at L1 is ~242 t (~62 t for the "dry" cargo vehicle, ~60 t of LH_2 for the MPD thrusters and ~120 t for the crew, habitat and ISRU lander payload elements). An isometric view of the cargo vehicle including its key features and dimensions is shown in Figure 2 while trajectory information and mission mass details are provided in Table 2.

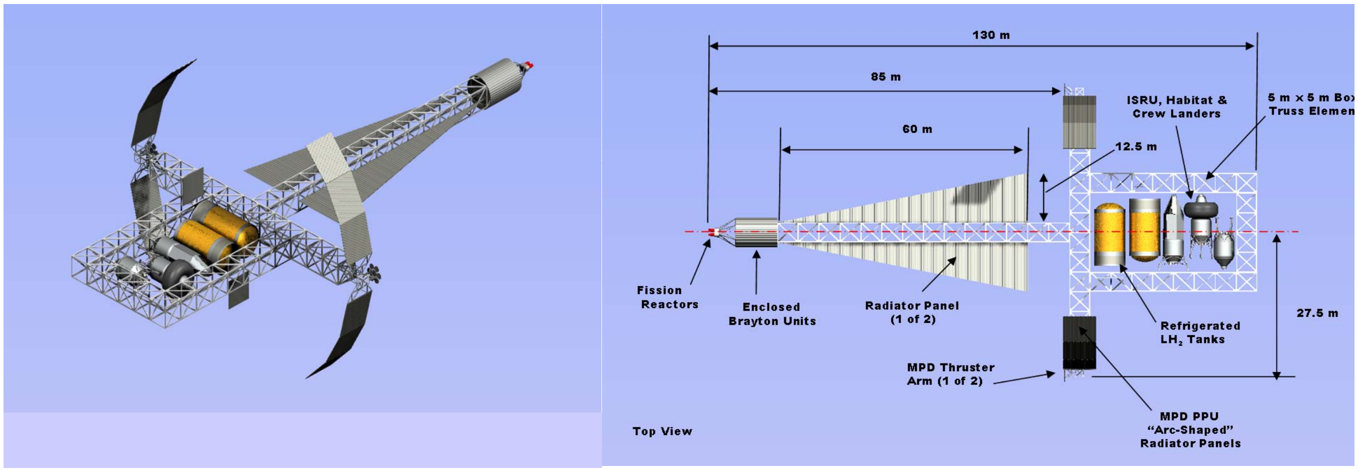

Figure 2. Far-Term NEP Cargo Vehicle Isometric and Representative Features

TABLE 2. Cargo Vehicle Trajectory and Mission Mass Details

Mission Leg	Date	Trip Time (days)	Propellant Mass (t)	Vehicle Mass (t)
Spiral Earth Departure from L1	September 17, 2041	21.03	2.4	242 – 239
Heliocentric Trip to Callisto	October 8, 2041	1003	46.9	239 – 192
Spiral Callisto Capture	July 7, 2044	89.28	10.4	192 – 182
Arrival at Callisto	October 4, 2044	(total ~ 3.04 yrs)	Total ~ 60	182

PCTV Characteristics and Mission Specifics

Unlike the "1-way" tanker and cargo vehicles, the PCTV is designed for round trip crew transport. It must therefore carry adequate life support and consumables, and provide an adequate artificial gravity environment to help ensure crew health during the ~4.5 year long mission to Callisto and back. While in transit, the crew resides inside the inflatable TransHab module, which is located at one end of a dumb-bell shaped structure attached to the front end of the PCTV (see Figure 3). A number of small LH_2 propellant tanks are positioned around the TransHab to reduce crew exposure to the deep space radiation environment. Four larger LH_2 tanks at the other end of the dumb-bell supply the MPD thrusters with the remaining propellant needed for the mission. These tanks also provide a counterbalance to the shielded TransHab module. As the vehicle rotates about its longitudinal spin axis at ~4 rpm, it produces an artificial gravity environment of ~1/8th g_E comparable to that on Callisto. Unfortunately, about halfway back to Earth, there is not enough propellant in the tanks to properly balance the vehicle so the crew is exposed to nearly a year in 0-g_E before arriving back at Earth. Although designed for round trip operations, the PCTV carries only the propellant it needs for the ~2.1 year outbound trip to Callisto which is ~74 t. Prior to initiating its spiral capture maneuvers, the PCTV jettisons its "spent" consumables and non-recyclable biowaste to reduce the outbound

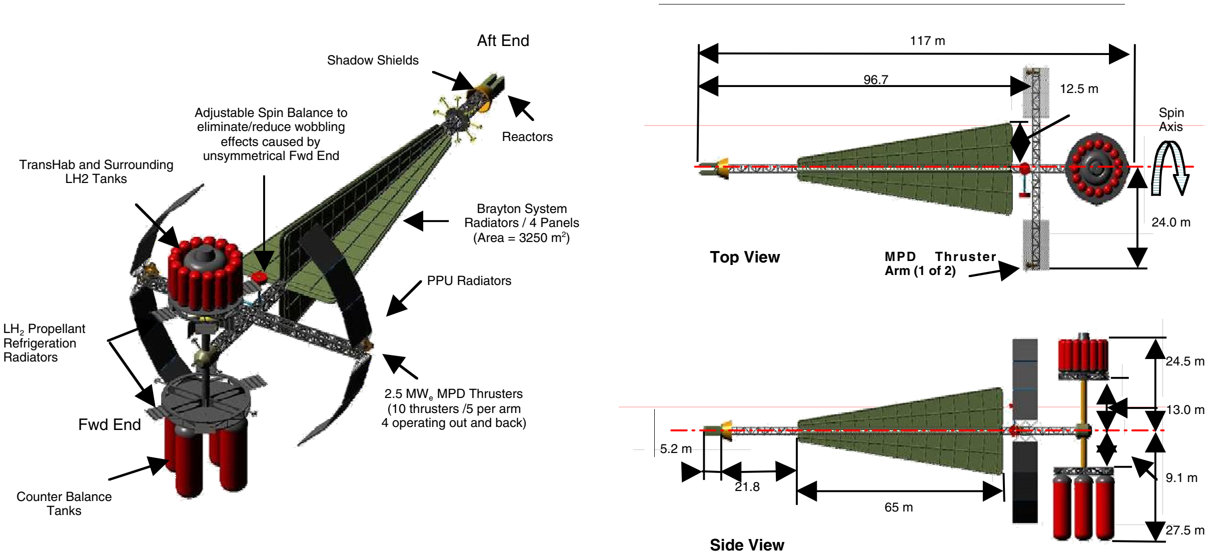

Figure 3. Far-Term NEP / MPD PCTV Isometric and Representative Features

propellant requirements and the vehicle's total reactor power level. To reduce crew trip time, the PCTV requires a higher electrical power level of ~8.2 MW_e . The reactor power system specific mass at this level is ~3.2 kg/kW_e. Four right triangle-shaped, double-sided radiator panels (~12.5 m in height by ~65 m in length) provide ~3250 m^2 of primary heat rejection area which includes a 25% increase in size due to view factor effects (see Figure 3).

During its 120 day stay at Callisto, the PCTV is re-supplied with ~53 t of propellant from the NEP tanker for the ~2.1 year trip back to Earth. The total mission trip time is approximately 4.5 years. The overall length of the PCTV is ~117 m and its initial mass at L1 is ~262 t (~109 t for the "dry" PCTV, ~74 t of LH_2 for the MPD thrusters and ~79 t for the TransHab, crew and consumables). Figure 3 depicts an isometric view of the PCTV along with its key features and dimensions. Table 3 provides trajectory information and mission mass details.

TABLE 3. Piloted Vehicle Trajectory and Mission Mass Details

Piloted Mission Leg	Date	Trip Time (days)	Propellant Mass (t)	Vehicle Mass (t)
Spiral Earth Departure from L1	December 11, 2044	13.6	~ 2	262 – 260
Heliocentric Trip to Callisto	December 25, 2044	703	64.5	260 – 196
Spiral Callisto Capture	November 27, 2046	50.2	7.5	196 – 188
Stay time at Callisto	January 17, 2047	120	N/A	175 – 228
Spiral Callisto Departure	May 17, 2047	61.1	9.1	228 – 219
Heliocentric Trip to Earth	July 17, 2047	689	43.2	219 – 176
Spiral Earth Capture at L1	June 5, 2049	6.5	~1	176 – 175
Arrival at Earth (L1 Staging Node)	June 12, 2049	Total ~ 4.5 yrs	Total ~ 127 (74 OB, 53 IB)	Final Mass ~175

CONCLUSIONS

A round trip HOPE mission to Callisto in under 5 years appears feasible in the 2045 timeframe using an advanced technology "all NEP" space transportation architecture employing multi-MW_e–class MPD thrusters. Examples of these advanced technologies include high temperature material Brayton rotating units with turbine inlet temperatures of ~2000 K, lightweight (~1.5 kg/m^2), "large-scale" (~1500 to 3250 m^2) deployable radiators, and high voltage PMAD (~5000 volts). Gas-cooled fission reactors using high temperature (> 2000 K) UO_2 in tungsten "cermet" fuel, tested during the 1960's, also need to be developed in order to achieve the high performance levels of the Brayton units assumed in this study. Because of Callisto's great distance from Earth (~8 times farther away than Mars), a split mission / vehicle approach is recommended for transporting crew and supplies. By using separate cargo, tanker and piloted vehicles, the size and mass of the individual vehicles can be reduced and hardware/system commonality can be maximized. The smaller, multi-vehicle mission approach also eliminates the need for large, complex "Battlestar Galactica"-size spacecraft and exotic propulsion technologies many of which still have major physics feasibility issues that need to be addressed. For the "all NEP" architecture examined here, the masses for the cargo, tanker and piloted vehicles are 242 t, 244 t, and 262 t, respectively, for a three vehicle total at L1 of ~748 t.

REFERENCES

Borowski, S.K., McGuire, M.L., Mason, L.M., Gilland, J.H., and Packard, T.J., "Bimodal NTR Propulsion for Artificial Gravity HOPE Missions to Callisto", presented at 20th Symposium on Space Nuclear Power and Propulsion, *Space Technology and Applications International Forum (STAIF-2003)*, February 2–6 2003, Albuquerque, New Mexico.

Mason, L.M., "A Comparison of Brayton and Stirling Space Nuclear Power Systems for Power Levels from 1 Kilowatt to 10 Megawatts", NASA/TM—2001-210593.

Melbourne, W.G., and Sauer, C.G., "Performance Comparisons with Pieced Solutions of Planetocentric and Heliocentric Trajectories for Low-Thrust Missions," Supporting Research and Advanced Development, Space Programs Summary 37–36, Vol. IV, pp. 14–19, Jet Propulsion Laboratory, Pasadena, California 1965.

Troutman, P.A., Bethke, K.A., Stillwagen, F.H., Caldwell, D.L., Manvi, R., Strickland, C.V., and Krizan, S.A., "Revolutionary Concepts for Human Outer Planet Exploration (HOPE)," presented at 20th Symposium on Space Nuclear Power and Propulsion, *Space Technology and Applications International Forum (STAIF-2003)*, February 2–6 2003, Albuquerque, New Mexico.

Williams, Steven 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.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
December 2003

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
High Power MPD Nuclear Electric Propulsion (NEP) for Artificial Gravity HOPE Missions to Callisto

5. FUNDING NUMBERS
WBS–22–706–87–02

6. AUTHOR(S)
Melissa L. McGuire, Stanley K. Borowski, Lee M. Mason, and James 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 – 13937

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—2003-212349

11. SUPPLEMENTARY NOTES
Prepared for the Space Technology and Applications International Forum (STAIF–2003) cosponsored by the American Institute of Aeronautics and Astronautics and the University of New Mexico, Albuquerque, New Mexico, February 2–6, 2003. Melissa L. McGuire, Stanley K. Borowski, and Lee M. Mason, NASA Glenn Research Center; James Gilland, Ohio Aerospace Institute, Brook Park, Ohio 44142. Responsible person, Melissa L. McGuire, organization code 7820, 216–977–7128.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Categories: 16 and 20 Distribution: Nonstandard
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)***

This documents the results of a one-year multi-center NASA study on the prospect of sending humans to Jupiter's moon, Callisto, using an all Nuclear Electric Propulsion (NEP) space transportation system architecture with magnetoplasmadynamic (MPD) thrusters. The fission reactor system utilizes high temperature uranium dioxide (UO_2) in tungsten (W) metal matrix "cermet" fuel and electricity is generated using advanced dynamic Brayton power conversion technology. The mission timeframe assumes on-going human Moon and Mars missions and existing space infrastructure to support launch of cargo and crewed spacecraft to Jupiter in 2041 and 2045, respectively.

14. SUBJECT TERMS
Nuclear electric propulsion; Jupiter; Space transportation system; Callisto; Fission; Magnetoplasmadynamics

15. NUMBER OF PAGES
13

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	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102