Space System Engineering

Project Prometheus - Electric Propulsion System

Group Project

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Abstract

This report summarizes the Prometheus project, which is currently being developed by the National Aeronautics and Space Agency (NASA), and focuses in detail on the Nuclear Electric Propulsion (NEP) system.. The Jupiter Icy Moon Orbiter (JIMO), the first spacecraft designed in the Prometheus project, is a robotic spacecraft with the mission to explore the three Jovian moons Europa, Ganymede, and Callisto. It will be the first spacecraft since Deep Space 1 to use an electric propulsion system, though, unlike Deep Space 1, it will be powered by a nuclear fission reactor. It will require a spacecraft bus power in the order of 100 kW, have a launch mass of 18 metric tons, a length of 76.2 m, and a lifetime of approximately 7 to 10 years. In order to radiate off the heat created by the nuclear reactor, the spacecraft will have radiator panels covering a total area of 120 m^2. JIMO is planned to have a specific impulse between 2000 and 9000 seconds, producing a theoretical top speed of 200,000 $\frac{m}{s}$. The project receives its funding under the umbrella operation "Vision for Space Exploration", as announced by George W. Bush in 2004, which is designed to extend the presence of humans across the solar system [6]. It was cut from 430 million to 100 million dollars in 2006, due to a reallocation of NASA's resources in an attempt to free up funds for the acceleration of the Crew Exploration Vehicle (CEV) development. This budget cut has temporarily stalled the advance of the project's development.

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1 Preface

This project is part of MAE 481 course at the California State University Long Beach (CSULB). Both Kai and Moritz researched relevant articles at the beginning of the project and plenty information was reviewed from Kai's Homework No.1.Many subsystem specific AIAA articles were used for this report. The workload has been divided up but reviewed and edited by each member, so the final decision was unanimous. Kai performed the layout and format of this report, using MiKTeX 2.7 and WinEdt 5.3. He wrote sections 3.2, 3.3 and 4, while Moritz wrote the abstract, sections 1,2,3.1 as well as the conclusion. Both team members worked equally on section 5; one team member prepared a subsection and gave it to the other for review and final editing.

2 Introduction

2.1 Scope

In this report, the Prometheus mission objectives, elements, and architecture, as well as payload, bus requirements, and general spacecraft characteristics are being addressed. A brief insight in the projects history is given, along with the current development status and the numerous challenges that still need to be addressed. Payload and general characteristics are pointed out. Furthermore, the Nuclear Electrical Propulsion (NEP) system is analyzed in greater detail.

2.2 Document Overview

This report focuses on the Prometheus project and the associated mission requirements. Section 3, mission overview and requirements, is divided into three subsections addressing the history, the mission objectives, and the mission elements and architecture of the Prometheus project. Section 4, analyzes the JIMO spacecraft, and is also divided into three subsections: the payload description, the derived bus requirements, and general characteristics. Section 5 describes the nuclear electric propulsion system and its performance characteristics. It is split up into three subsections: the overview and top level requirements, the subsystems and functional block diagrams, and the NEP justification. Section 6, the conclusion, summarizes the Prometheus project. The last section is the bibliography. All references used for the accumulation of the information for this report are listed there.

3 Mission Overview and Requirements

3.1 Background

The Prometheus project, originally named Nuclear Systems Initiative, was founded in 2003 by NASA in order to revive the option of using nuclear power in space. It is the first project to tackle this option since the Nuclear Engine for Rocket Vehicle Application (NERVA) project was cancelled in 1972.

NASA choose the name Prometheus, a god who, following the Greek mythology, gave the gift of fire to mankind, to indicates its hopes of establishing a new tool for understanding nature and expanding capabilities for the exploration of the Solar System.

The motivation came from the difficulties in using solar arrays to power the electric subsystems and payloads in long duration and deep space missions. The larger the distance of a spacecraft using solar arrays is to the sun, the less power will the solar panels be able to produce. Also, due to the fast decay of the quality of the solar cells, the time span of a mission becomes a critical factor, as the solar panels will not be able to obtain enough power in long-duration missions.

An additional benefit coming along with the usage of nuclear power is the possibility of using electric propulsion systems, such as Ion-thrusters, as primary propulsion systems. Electric propulsion systems have the benefit of using very little propellant at high exhaust velocities to produce thrust. Ion thrusters were successfully used onboard the Deep Space 1 as primary propulsion system.

In 2005, NASA cut the Prometheus budget in an attempt to free up funds for the acceleration of the Crew Exploration Vehicle (CEV) development. Due to this dramatic budget cut from 430 million to 100 million dollars, of which approximately 90 million dollars were used to compensate closeout costs on cancelled contracts [6], the Prometheus project has not seen significant progress ever since, and is still in an early development stage.

3.2 Mission objectives

The objective of this mission is to build and operate a spacecraft with a nuclear-reactor-powered electric propulsion system in order to conduct far-reaching and long-lasting exploration missions. In particular, the Prometheus JIMO mission was designed to explore three planet-sized moons: Europa, Ganymede, and Callisto. The goals are to find hints for life and water and to demonstrate the possibilities of a nuclear electric propulsion flight system to enable a range of new planetary and solar system missions.

Other aims include the investigation of the origins and evolutions of the moons, as well as the determination of the makeup of their interior structures, surface features and chemical composition. The project is also supposed to study the interactions between the entire Jupiter system and the atmospheres and interiors of its moons, as well as to determine the radiation environments around these moons and the rates at which the moons are weathered by materials hitting their surfaces [4].

This Vision for Space Exploration requires NASA to use nuclear power to satisfy propulsion power demands. A successful mission will verify new spacecraft hardware capabilities and open the door to larger missions in the future. In particular, these hardware components and characteristics include: high powered telecom, advanced temperature materials, high rate data transmission systems, radiation hardened electronics, heat rejection, a fission reactor, and the key technology, a suitable electric-ion propulsion system. These technologies have key value for NASA's future exploration needs.

3.3 Mission elements and architecture

JIMO is managed by the Jet Propulsion Laboratory (JPL). It will be responsible for delivering the mission module, which would include instruments procured competitively via a NASA announcement of opportunity. Northrop Grumman Space Technology (NGST) is the contractor for co-designing the spacecraft. The launch vehicle will be supplied by NASA. The reactor is being developed by the U.S. Department of Energy's Office of Naval Reactors, in Washington, D.C.[4].

Since funding for this project is unknown and JIMO is officially cancelled [5], timeline and architecture of the Prometheus mission are not clear. However, previous proposed schedules might be reconsidered and deserve mentioning. After development of the Deep Space Vehicle for outer solar system robotic exploration missions, its payload and space nuclear reactor technologies are extensible to other missions. Therefore, mission similar to JIMO (see Figure 1) might have following key features.

Use the TBD heavy lift expendable launch vehicle as specified by NASA to launch JIMO into high Earth orbit. The ion propulsion thrusters will spiral the spacecraft away from Earth and then on its journey to Jupiter. The nuclear reactor will be powered up once the probe is well out of Earth orbit and achieve orbit insertion at Jupiter within 8 to 5 years after launch. Archive all science data within 6 months and calibrate within 12 months. As for telecommunications, JIMO will have a 10 Mbit/s link and four 250 watt travelling wave tube amplifiers (TWTA), using antennas of 10 to 20 meters in length. Furthermore, downlink at least 500 gb per day to earth and be capable of doing science during all mission phase events.

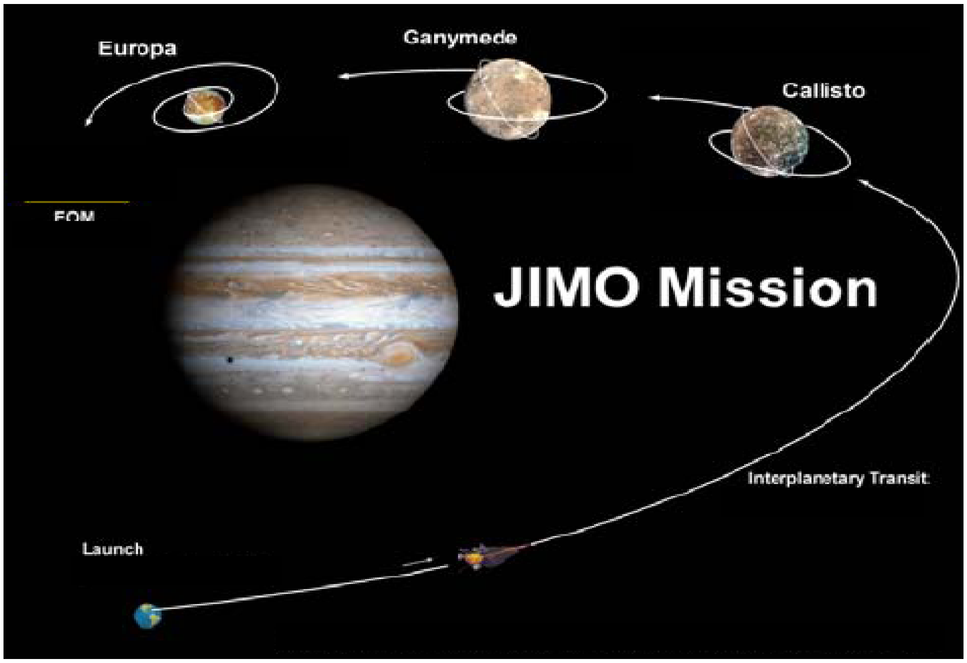


Figure 1: Prometheus JIMO Mission

4 Spacecraft

4.1 Payload description

Nuclear electric propulsion allows a spacecraft to carry heavier and higher power equipment than previously possible (1500 kg vs 50 kg - 150 kg) [3]. The missions and scientific payloads for Prometheus-class spacecrafts have yet to be determined. The first Prometheus-class spacecraft will likely be a relatively short duration (3-5 years) and scaled-down robotic trip as part of NASA's Return to the Moon, and Mars vision. Eventually, the technology could be expanded for use on outer-planetary missions, for example, JIMO. Therefore, the payload might be subject to change. But 10s of kWs of payload power enables high capacity science investigations, such as surface mineralogy studies from orbit with powerful active instruments (lasers) or global subsurface mapping through thick crusts with surface-penetrating radar. JIMO will have a kilowatt of power available for each individual instrument, whereas the Cassini space probe has a small plutonium unit, with a total power output of 900 watts for the spacecraft's entire suite of instruments.

4.2 Derived bus requirements

Prometheus-class spacecraft buses will likely be on the order of 100 kilowatt. By converting the reactor's heat to electricity, JIMO could operate with more than 100 times as much power as a non-fission system of comparable weight [2]. As previously mentioned, much of the payloads have yet to be determined, therefore the bus requirements are still very broad.

4.3 General characteristics

Figure 2 displays a rendering of the spacecraft and Table 1 its main characteristics. The radiator panels cover a total area of approximately 120 m^2, making the spacecraft look like a flying radiator.

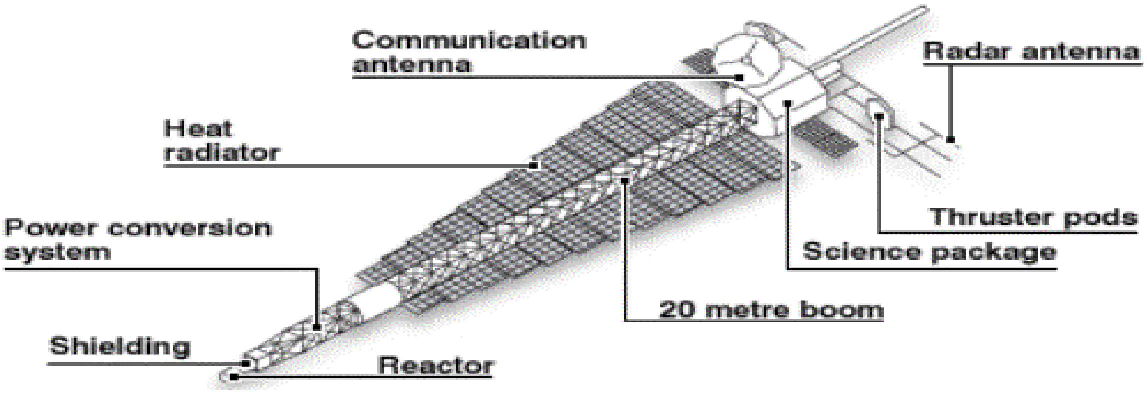


Figure 2: General Spacecraft Layout, JIMO

Table 1: Main Characteristics

Power required	100 kW
Launch Mass	18000 Kg
Length	76.2 m
Lifetime	7-10 years
Specific Impulse	2000-9000 sec
Radiation Tolerance	> 5 MRad
Exact Payload	TBD
Theoretical Top Speed	$200,000$ mph

5 Nuclear Electric Propulsion System

5.1 Overview and Top Level Requirements

To meet the needs of the next generation of solar system explorers, NASA needs to develop a new, safe and reliable propulsion systems based on nuclear technologies to conduct a long lasting and far reaching exploration mission. These driving requirements influence the mission itself on a top level, e.g. assembly in space due to the large required heat sink.
Nuclear Electric Propulsion (NEP) Space Science Mission Studies were performed to explore what characteristics were needed for an NEP system to provide optimal performance for the JIMO mission. Study outcomes are displayed in Table 2.

Table 2: Top Level Subsystem Requirements

Power required per thruster	10 to 50 kW
Lifetine	up to 10 years
Specific Impulse	5000-9000 sec
Efficiencies (Thruster and PPU)	$> 65\%$
Radiation Tolerance	> 5 MRad
Technology Maturity	Adequate TRL

Counting towards the Technology Maturity, following items of the project should be finished at the Preliminary Design Review (PDR):

- All major risks for the technology development must be resolved.
- All major manufacturing issues must be resolved.
- Plans to accumulate life data that provides confidence that hardware will last for the life of the project must be written and approved.

- Development models must be completed (e.g. high-fidelity computer models).

Figure 3 displays the findings of one of the studies performed. Payload mass and trip time are compared to several I_{sp}‘s. The specific system mass of the NEP vehicle has a clear impact on the flight duration: 50 kg/kW systems can prolong the flight as much as 50% compared to more technologically advanced 30 kg/kW system.

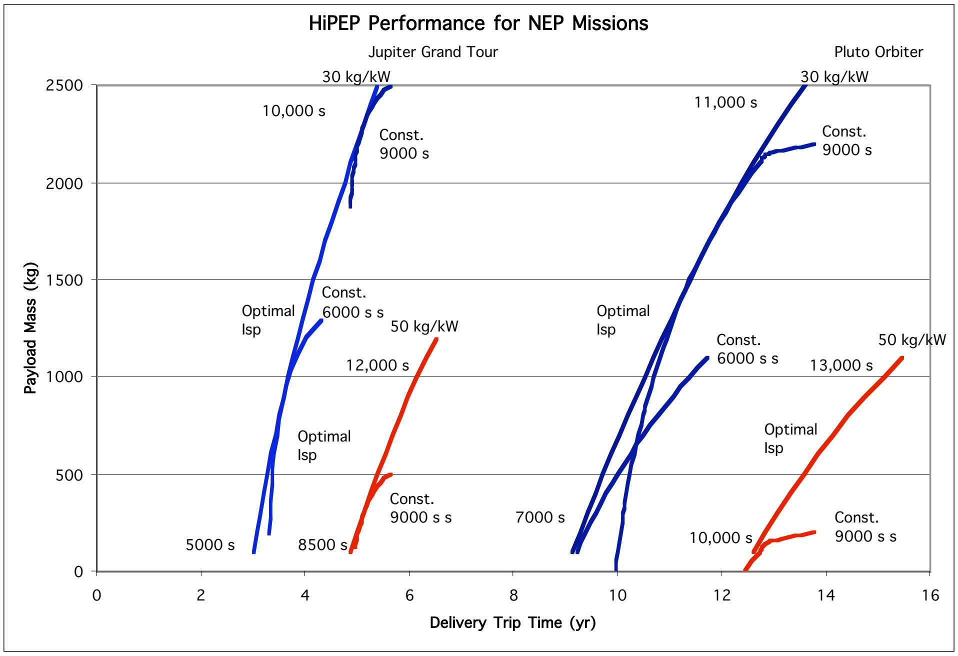


Figure 3: Payload Performance for Sample NEP Missions [7]

5.2 Subsystems and Functional Block Diagram

The JIMO electric propulsion system is broken up into three subsystems: Xenon Feed System, Power Processing Unit (PPU), and Gridded Ion Thruster. Ion propulsion systems provide thrust by expelling a stream of high velocity ions. Thrust equals mass flow rate times exhaust velocity. As the mass flow rate for ion thrusters is very low, they must provide very high velocity exhausts to achieve adequate thrust levels. Exhaust velocities for ion thrusters are between 20,000 to 100,000 m/s, as compared to a maximum of 4,500 m/s for chemical propulsion systems, while mass flow rates are between 5 to 10 mg/s, as compared to over 100 mg/s for chemical engines with equivalent thrusts. This saves fuel, and enables high-energy space missions that would not be possible using chemical propulsion due to their high fuel requirements. Despite the mass of the nuclear power reactor in the JIMO mission, the high exhaust velocities of the ion thrusters enable deep space missions with Δ V requirements on the order of 10 to 60 km/s. To propel the spacecraft to its destination, the ion thrusters must be operated for long durations to provide the required impulse. As a logical consequence,

the ion thruster subsystem must provide very long operating lifetimes on the order of years, as compared to chemical propulsion systems, which only require operating lifetimes on the order of hours.
Figure 4 shows the system and Figure 5 shows the functional block diagram.

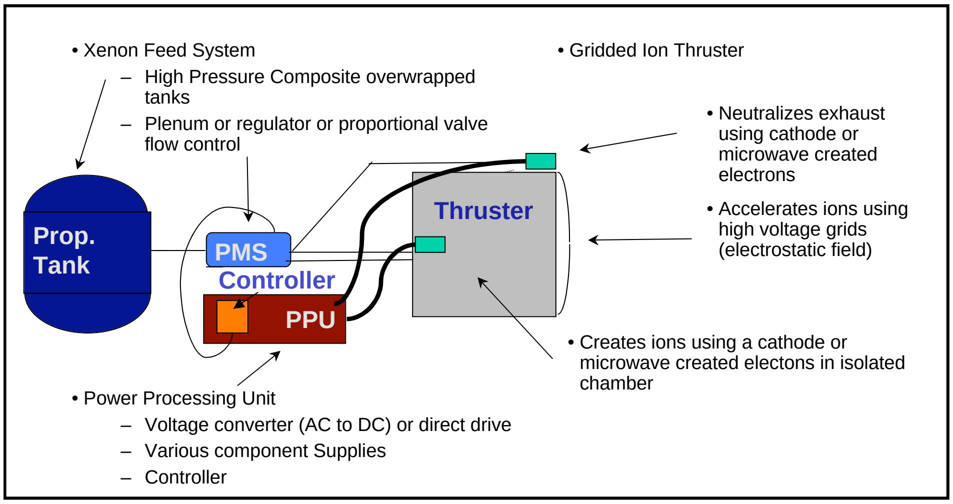


Figure 4: JIMO Electric Propulsion System [8]

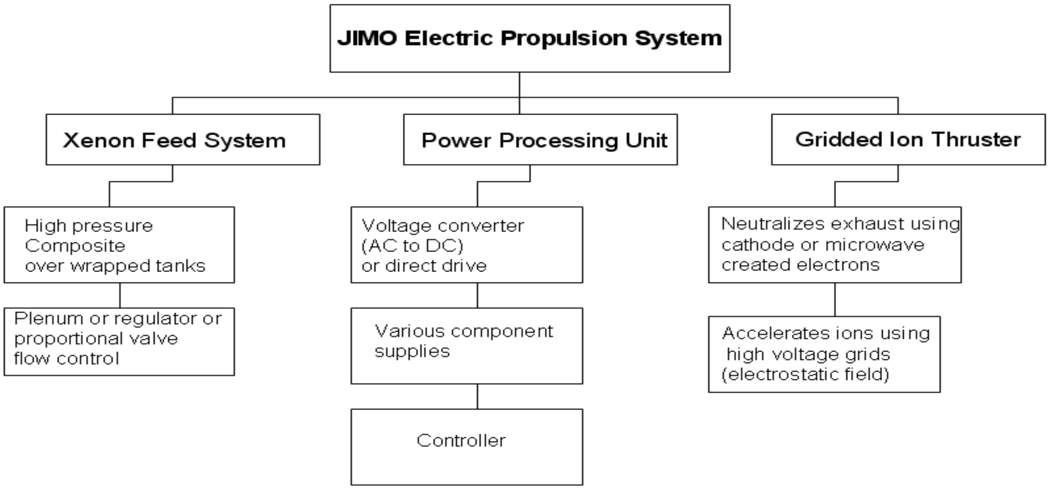


Figure 5: JIMO Electric Propulsion System Functions

5.2.1 Xenon Feed System

Due to the long lifespan of the JIMO mission, the propellant must be stored for very long periods of time. State of the art xenon storage systems, using compact and very light tanks, are used to store the required propellant loading of approximately 8000 kg to 12000 kg. The tanks are carbon overwrapped pressure vessels (COPV), storing propellant at very high pressures ($\sim$ 2000) psi. In order to survive Jupiter/s radiation environment, a radiation qualification level greater than 5000 kRad is required.

5.2.2 PPU

A power processor unit (PPU) is necessary to convert the power from the spacecraft nuclear reactor to the various voltages and currents required by the ion thruster components. Most of the power is needed for the beam power supply, which powers the acceleration of the ions. Beam voltages usually vary from 1000 to 7000 Volts depending on the exhaust velocity desired. The other power supplies are at lower voltages and include the acceleration grid, the cathode, and the microwave supplies. The biggest challenge for the power processor is to raise the voltage from the bus to the high beam voltage. The bus voltage has two types, AC or DC, and a voltage level of 100 to 400 Volts or more. The voltage level determines the applicable conversion approach.

5.2.3 Gridded Ion Thruster

At the center of an ion propulsion system is the ion thruster shown in Figure 6. It produces ions, which are used to provide the thrust, in the main chamber through collisions between electrons, provided by either a hollow cathode or from a microwave source, and a neutral gas from the anode. For the JIMO mission, xenon is used as neutral gas. The chamber is lined with magnetic rings that confine the electrons, enhancing the chance of collision with the neutral atoms. At the exit of the chamber are two grids. The inner grid is at the same high voltage as the discharge chamber cathode and is called the screen grid. The outer grid is set to a negative voltage, ranging form -200 to -800 Volts relative to spacecraft potential and dependent on the desired performance. This outer grid is called the acceleration grid. The ions are accelerated between the two grids and are focused to not collide with the grids. They are then expelled through circular apertures out of the thruster. The final component of the thruster is the neutralizer, a hollow-cathode or microwave source that provides electrons to neutralize the ion beam. This prevents the development of a charge on the spacecraft, allowing continued usage of the ion thruster.

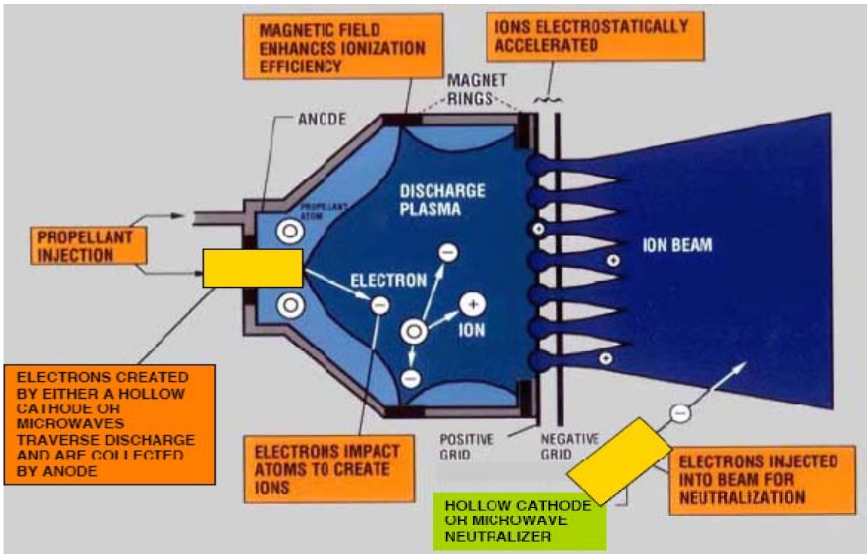
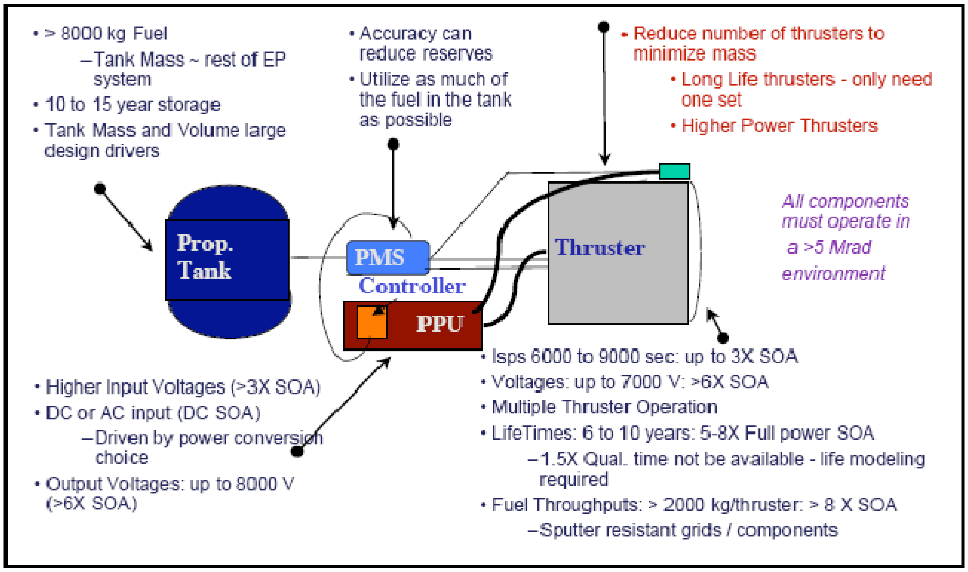


Figure 6: Xenon ion thruster operation [8]



- > 8000 kg Fuel
  - Tank Mass ~ rest of EP system
- 10 to 15 year storage
- Tank Mass and Volume large design drivers

- Accuracy can reduce reserves
- Utilize as much of the fuel in the tank as possible

- Reduce number of thrusters to minimize mass
  - Long Life thrusters - only need one set
  - Higher Power Thrusters

All components must operate in a >5 Mrad environment

- Higher Input Voltages (>3X SOA)
- DC or AC input (DC SOA)
  - Driven by power conversion choice
- Output Voltages: up to 8000 V (>6X SOA)

- Isps 6000 to 9000 sec: up to 3X SOA
- Voltages: up to 7000 V: >6X SOA
- Multiple Thruster Operation
- LifeTimes: 6 to 10 years: 5-8X Full power SOA
  - 1.5X Qual. time not be available - life modeling required
- Fuel Throughputs: > 2000 kg/thruster: > 8 X SOA
  - Sputter resistant grids / components

Figure 7: JIMO Electric Propulsion System Challenges [8]

5.3 Why NEP

A good summary of driving requirements is illustrated in Figure 7. The technology available today is not adequate to meet these requirements, but performance and power requirements can only be satisfied with a nuclear electric propulsion system. Solar panels, as used on Deep Space 1, would not produce enough power for a Prometheus mission. The Nuclear Electric Xenon Ion System (NEXIS) is a good example of a system specifically designed to meet the requirements of Prometheus. The goal is to develop ”an ion engine capable of operating at an input power of 20 kW, an Isp of 7500 sec and have a total xenon throughput capability of 2000 kg” [9]. These specifications are in the range of JIMO requirements.

6 Conclusion

Deep space exploration clearly dictates new requirements for spacecrafts, many of which are mentioned above. Due to the immense amount of propellant required by chemical propulsion systems and the large distance to the sun, for the option of solar sails, Nuclear Electric Propulsion systems are the only option for long lasting deep space voyages. Even though there are still numerous challenges to be addressed, the concept seems to have the possibility of great progress and of providing the link to the future. The Vision for Space Exploration, with its mission to extend the presence of humans across the solar system, demands the technologies developed in the Prometheus project. Someday, hopefully, the appropriate funds will be reallocated to advance the development and carry out missions such as JIMO.

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