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The Prometheus 1 Spacecraft Preliminary Electric Propulsion System Design

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The proposed Prometheus 1 mission is an ambitious plan to orbit and explore the Jovian moons of Callisto, Ganymede, and Europa. Such an ambitious mission is enabled by the first interplanetary nuclear electric propulsion (EP) system. This EP system pushes the state of the art in power (> 100 kW), specific impulse (> 600 s), and lifetime (> 70,000 hours). A team from the Jet Propulsion Laboratory, Glenn Research Center, Marshall Space Flight Center, and Northrop Grumman Space Technology has collaborated to complete the preliminary system design concept. The EP system consists of three different thruster subsystems and a common high pressure feed system. Primary propulsion for the cruise phase of the mission is provided by six primary and two redundant 30 kW ion thrusters. A high thrust subsystem, consisting of six 20 kW hall thrusters, is provided to allow stable trajectories during the Jovian moon transfer phases. Six primary and six redundant sub kilowatt hall thrusters are provided for attitude control. A common high pressure feed system consisting of a single 12,000 kg capacity tank, an isolation and pressure regulation module, and a xenon recovery system provide xenon propellant to the individual thruster subsystems. Planning and risk analysis activities have been performed to provide confidence in the feasibility of delivering this system in the proposed mission timeframe.

I. Introduction

The first deep space use of solar electric propulsion (SEP) on NASA's DS1 spacecraft has paved the way for applications of advanced electric propulsion on more demanding future missions[1]. This technology will be used for the first time on a dedicated NASA science mission during the Dawn asteroid rendezvous mission[2]. For more ambitious missions requiring ΔVs ranging from 40 to over 100 km/s, advanced nuclear electric propulsion (NEP) systems are required[3]. In 2003, NASA's Project Prometheus began comprehensive efforts to develop advanced technologies necessary for such ambitious NEP missions. The first proposed mission application for such technology is the Prometheus 1 spacecraft or JIMO (Jupiter Icy Moons Orbiter) with the mission objective of touring the icy moons of Jupiter[4].

II. Mission and Spacecraft Overview

According to the JIMO Science Definition Team Report, the driving goals for the Prometheus 1 mission are summarized as follows: determine the evolution and the present state of the Galilean satellite surfaces and subsurfaces and the processes affecting them; determine the interior structures of the icy satellites in relation to the formation and history of the Jupiter system and potential "habitability" of the moons; search for the signs of past and

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current life and characterize the habitability of the Jovian moons, with emphasis on Europa; determine how the components of the Jovian system operate and interact, leading to the diverse possibly habitable environments of the icy moons. The goals were summarized into an overarching statement for the JIMO mission: explore the icy moons of Jupiter and determine their habitability in the context of the Jupiter System. Within this are three well-defined, crosscutting themes including: oceans (finding their locations, studying the structure of their icy crusts, and assessing active internal processes), astrobiology (determining the types of volatiles and organics on and near the surfaces and the processes involved in their formation and modification), Jovian system interactions (studying the atmospheres of Jupiter and the satellites and the interactions among Jupiter, its magnetosphere, and the surfaces and interiors of the satellites).

The JIMO mission is planned for launch in mid to late 2015 and the proposed mission timeline is shown in Figure 1. Launches of two booster stages are scheduled to occur before the launch of the JIMO vehicle. After docking, the boosters are used to propel the JIMO spacecraft into an earth escape trajectory before separation. Once on an interplanetary trajectory, the reactor and the other systems of the spacecraft are commissioned in a thirty day period. The power cruise phase to Jupiter then commences with the interjection of several cruise phases to provide a robust trajectory against potential missed thrust periods. The resulting spiral trajectory towards Jupiter is shown in Figure 2. Ultimately, the interplanetary transfer phase results with the spacecraft capture at Jupiter approximately six years after launch.

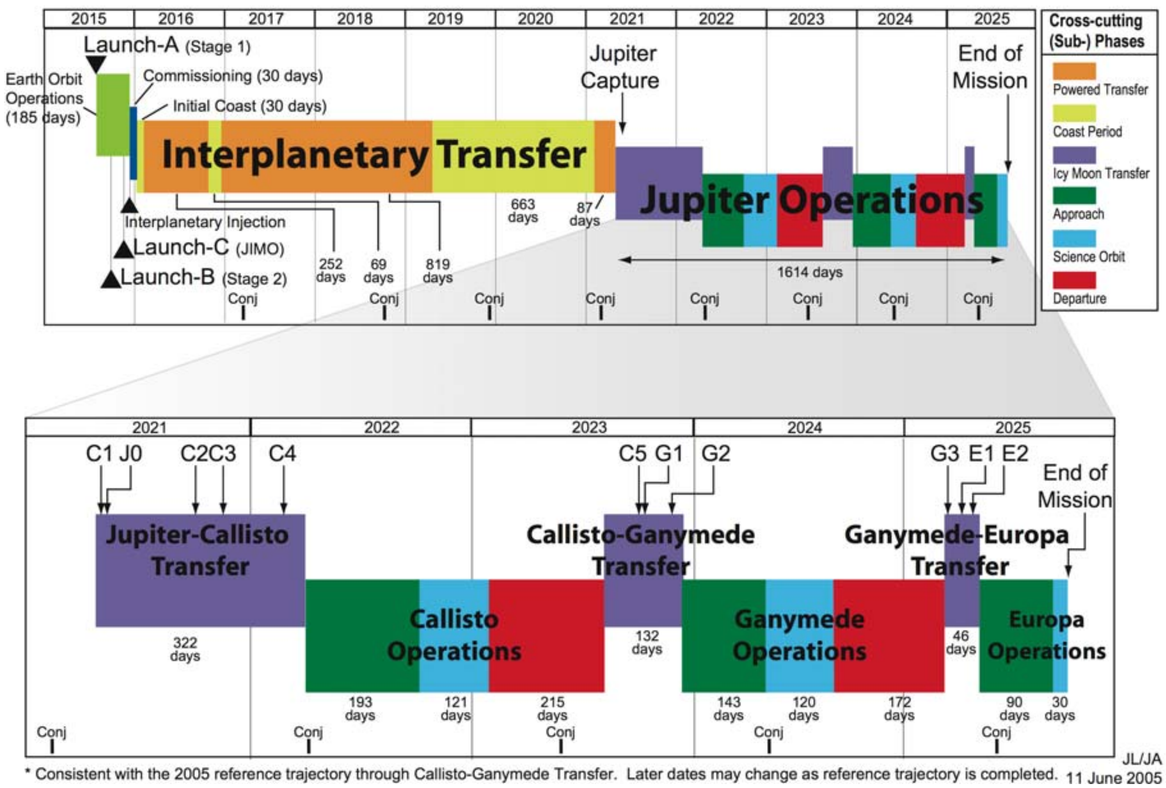

Figure 1. JIMO mission timeline.

The Jupiter operations phase begins with the approach to the moon Callisto. After the approach phase is completed, the spacecraft is reoriented to allow the aft science instruments to point towards the moon's surface. Orbital science operations are then performed with only orbit and attitude maintenance maneuvers from the propulsion system. The spacecraft is then reoriented to provide propulsion along the departure trajectory. After leaving Callisto, the spacecraft enters the transfer phase between Callisto and the next target destination, Ganymede. This process, shown in Figure 2, is again repeated at Ganymede and Europa where the mission ends. The transfer periods between the moons are subject to three body gravitational effects which make mission planning very difficult. At sufficiently low accelerations, brief potential missed thrust periods can result in unrecoverable trajectories that impact a moon's surface. Additionally, the Jovian radiation environment becomes severe as Europa's orbit is approached requiring rapid trip times during this phase of the mission to reduce the cumulative dose on sensitive spacecraft parts. These two effects have necessitated the use of a high thrust requirement during the final moon transfer phase.

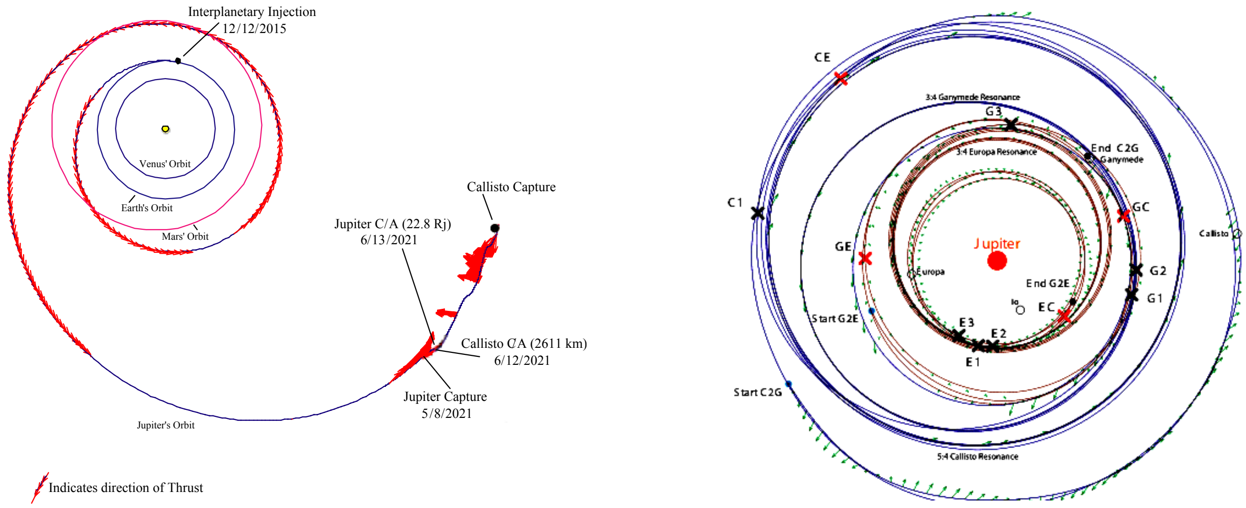

Figure 2. JIMO spacecraft trajectory.

The JIMO spacecraft configuration is shown in Figure 3. At the front of the spacecraft is a gas cooled nuclear reactor which is the ultimate power source. The thermal power created by the reactor is converted by to 208 kW of electrical power by a Brayton power conversion system. A heat rejection system, consisting of 422 m^2 of carbon-carbon panels and water filled heat pipes, is used to radiate waste heat from the reactor. The spacecraft bus provides power conditioning and distribution, radiation shielding for sensitive electronics, attitude control, command and data handling, and a 3 meter high gain antenna. Electric thrusters are distributed on two deployed aft pods with gimbals for final alignment. The mission module provides a scan platform and turn table to support various science instruments. Deployed, the JIMO spacecraft is approximately 58 meters long. At launch, the spacecraft stows in a 5 meter fairing with a mass of approximately 36,000 kg.

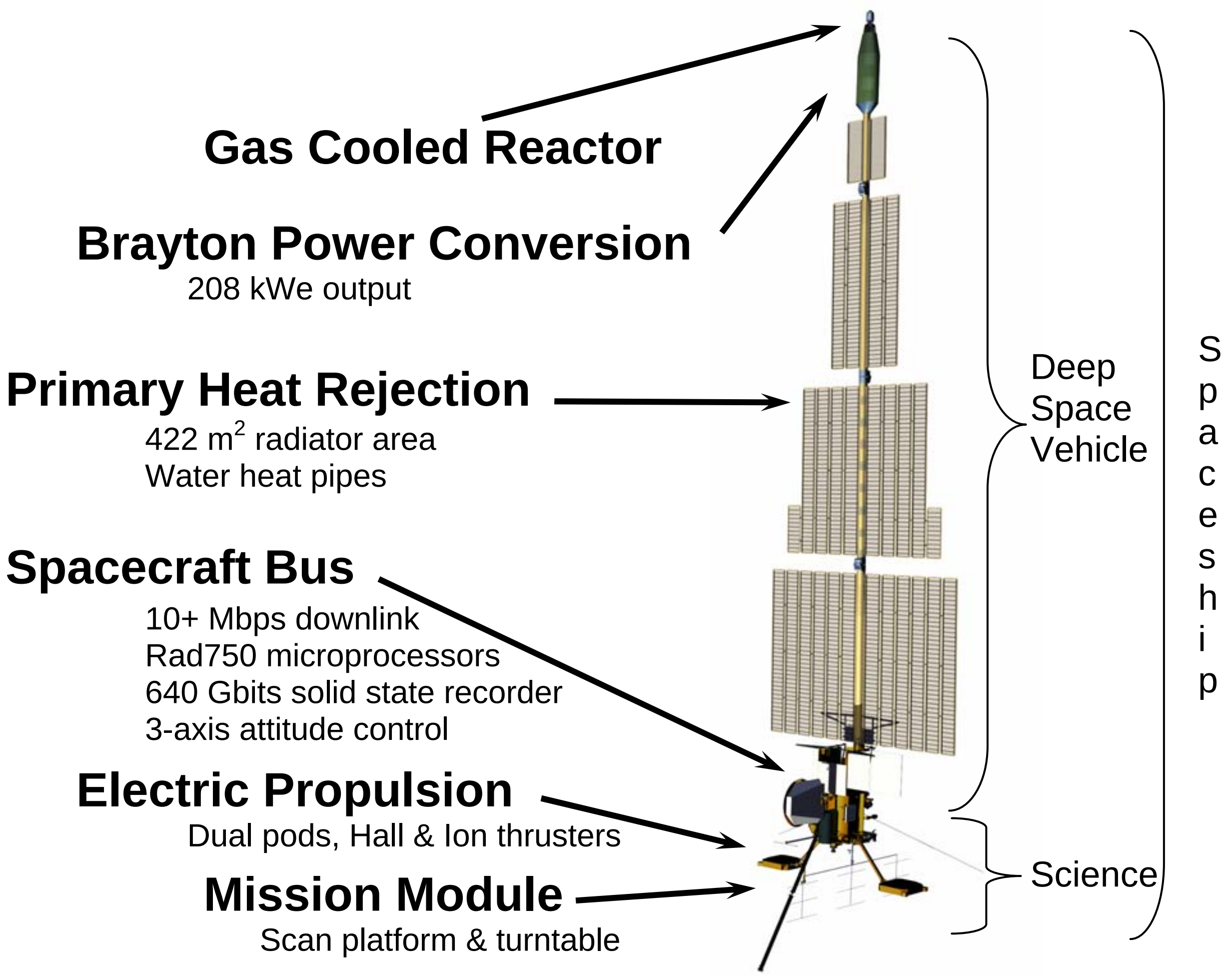

Figure 3. JIMO spacecraft configuration.

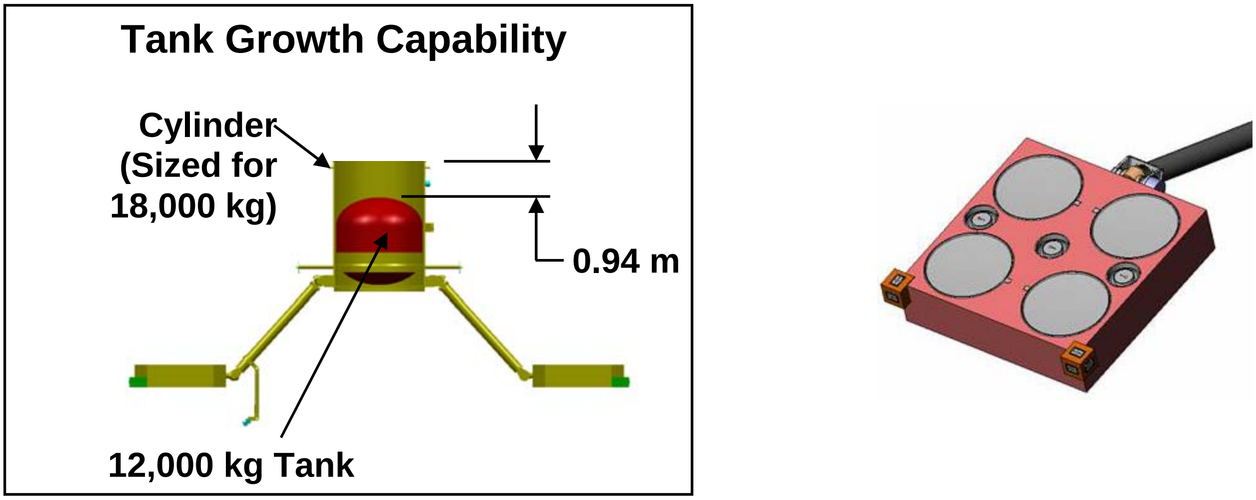

Figure 4. Electric propulsion system configuration.

III. Electric Propulsion System Architecture

The primary requirements driving the electric propulsion system architecture are listed in Table 2 along with the corresponding implementation response. These key driving requirements, in addition to the top level spacecraft level requirement for no credible single point failure modes, drove the implementation in terms of number and type of thrusters, tank configuration, and the baseline specific impulse. Optimization of the total spacecraft system mass required that trades between specific impulse and system power be performed at the spacecraft level. Specific impulse optimizations were performed to maximize the delivered mass capability of the spacecraft without paying an excessive penalty in trip time. For all but the Europa phase of the mission, optimal specific impulses ranged from 6000 sec to 8000 sec, depending on the specific trajectory. Given their maturity, efficiency, and lifetime capability, ion thrusters were selected to fulfill this mission requirement. Due to the large accelerations required during mission phases near the Europa orbit, substantial reductions in the specific impulse were required to achieve the desired thrust without exceeding the power allocation the electric propulsion system. Because it is technologically difficult to meet the ambitious lifetime requirements and throttle specific impulse substantially at fixed power for ion thrusters; an additional high power hall thruster system was added to provide the high thrust mode. Given the short duration of the high thrust mode requirement, the risk for developing such a hall thruster system was considered acceptable. Small subkillowatt hall thrusters were chosen for attitude control primary because the extra mass of a chemical propulsion system could be avoided.

Key Driving Requirement	Implementation Response
The Spaceship total propellant mass at launch shall not exceed [12,000] kg.	Single ~2m diameter, 12,000 kg capacity tank
The Deep Space System shall use a specific impulse between [6,000 - 8,000] seconds for the ion thrusters.	6 ion thrusters, nominal 7000 s Isp
The Project shall use a Deep Space Vehicle that provides jet power greater than or equal to [130] kW of primary thrust during thrust periods	6 ion thrusters, nominal 0.65 N thrust each at 7000 s Isp
The Spacecraft Module shall provide a minimum delta-V of 1.5 km/s at an acceleration of at least 0.25 mm/s2 during the Europa quasi-critical thrusting operations subphases of the mission	6 high power Hall thrusters, nominal 1.0 N thrust each (in combination with 2 ion thrusters nominal 0.65 N each)
The Spaceship will be capable of producing a minimum impulse bit of [TBD] N-s and a maximum total impulse of [1.4 x106] N-s.	12 small Hall thrusters for [non-coupled] pitch/yaw/roll control
The Electric Propulsion Segment shall receive electrical power no greater than [180] kW for electric propulsion use.	6 ion thrusters, 30 kW each, >72% total efficiency PPU and thruster

Table 1. System requirements flowdown.

The functional block diagram for the electric propulsion system is shown in Figure 5. The system is essentially broken down into three thruster subsystems with a common xenon propellant supply. The performance of these thruster subsystems is described in Table 2. Primary propulsion is provided by the ion thruster subsystem which consists of six primary and two redundant thrusters located in blocks of four thrusters on each pod per Figure 4. Each ion thruster has a dedicated power processing unit (PPU) and xenon flow control unit (XFC) with no cross strapping. Thrust augmentation is provided by the high power hall thruster subsystem which consists of six primary thrusters located in blocks of three on each pod. Each high power hall thruster has a dedicated PPU and XFC with no cross strapping. Attitude control is provided by the ACS hall thruster subsystem which consists of six primary and six redundant thrusters located in clusters of three with two clusters on each pod. Each ACS hall thruster has a dedicated XFC; but each thruster/XFC combination shares a PPU with another thruster XFC combination. The resulting six ACS hall thruster PPUs provide 5 for 6 redundancy. Xenon propellant is stored in a single tank 2 meter diameter doorknob shaped tank with a dedicated isolation and pressure regulation module. Total tank capacity is 12,000 kg and the regulated pressure is 100 psi. In addition to pressure regulators, isolation valves, and pressure transducers, the isolation and pressure regulation module contains a xenon recovery system (XRS) which provides cryogenic pumping from the tank to reduce xenon residuals at the end of the mission.

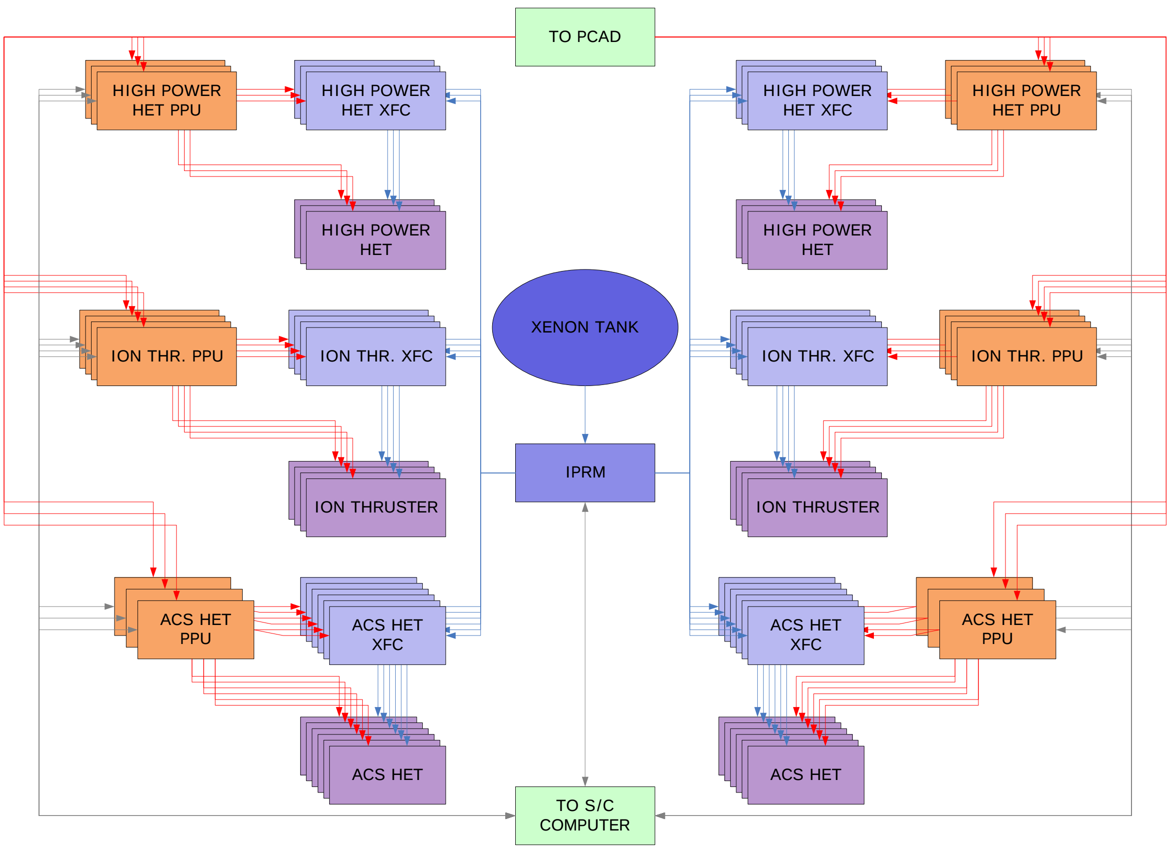

Figure 5. Electric propulsion system block diagram.

Operational modes of the electric propulsion system vary according to the needs of the mission timeline. After system initialization, six of the ion thrusters using all 180 kW of power allocated to the electric propulsion system will be used for primary thrust during the interplanetary trajectory phase. System initialization will include moving the thruster pod gimbal angle during thruster operation to determine the orientation that will minimize spacecraft torques. This gimbal angle will then be fixed for future operation. During cruise, the ion thrusters will be throttleable by 1 to 2 % to allow momentum control to reduce accumulated torques. During the cruise period; but primarily for coast periods, the ACS hall thrusters will be available for spacecraft momentum wheel unloading.

These thrusters will be fired in pairs to reduce the induction of torques in alternate axis. For transfer operations near Europa, the high power hall thrusters will be used to augment thrust. In normal operation, all six high power hall thrusters will be fired in addition to two ion thrusters; thus utilizing all 180 kW of power available for the electric propulsion system. Spacecraft reorientation operations can be accomplished by firing the desired combination of any of the thrusters. Orbit maintenance during the science mode will mostly likely be accomplished by using the ACS hall thrusters; however the high power hall thrusters can also be used when larger impulses are required.

Parameter	Ion Thrusters	High Power HET	ACS HET
Thrust (mN)	646	990	40
Specific Impulse (s)	7000	2000	1400
Thruster Throughput w/o Margin (kg)	2000	300	30
PPU Power Input (kW)	30	20	0.7
PPU Efficiency	96%	97%	93%
Primary PPU Output Voltage (V)	4500	400	300
Total Flow Rate (mg/s)	9.5	51	2.9

Table 2: Thruster subsystem performance parameters.

Many key trade studies were performed to optimize electric propulsion system performance. Six operating ion thrusters were chosen to minimize system mass and maintain reasonably low levels of system complexity. Two instead of one redundant ion thrusters were chosen to minimize the possibility of a thruster failure introducing asymmetric thrust. No redundant high power hall thrusters were added as the impact of a lost thruster could be partially made up by turning on additional ion thrusters. The resulting reduction in acceleration was deemed an acceptable degraded mission capability. PPU cross strapping was not chosen as the increased redundancy was deemed less desirable than the simplicity of a dedicated system. Multiple tank options were also evaluated; however, although they eliminated the possibility of a single point failure due to a micrometeorite strike, the resulting increased mass penalty was not deemed acceptable.

IV. Plume Modeling and Plume Analysis

The harsh plasma environment created by electric thruster operation has the potential to adversely affect the spacecraft. Figures 3 and 4 show the spacecraft configuration and the locations of the electric thrusters. Careful analysis and informed spacecraft configuration are important to ensure mitigation of these problems. There are two major categories of problem, sputtering and contamination, each having multiple sources.

Sputtering has two sources. One source is the highly energetic main beam ions which will sputter surfaces exposed to the beam. The other source is the less energetic elastically scattered and charge exchanged ions which may sputter surfaces not obviously in the plume. The thrusters carried by JIMO will have accelerating potentials hundreds of volts higher than past thrusters. With the corresponding increase in the energy of scattered ions, the potential for sputtering is also increased. Sensitive surface treatments may be stripped, optical properties altered, or surface topography changed due to sputtering.

Contamination also has two sources. The first, an unavoidable consequence of thruster operation, is sputter erosion of thruster components. For Herakles ion engines, a large fraction of this is carbon-carbon grid material. Hall thrusters tend to erode their ceramic channel walls. Material eroded from thruster components is carried away from the thruster with the plume. These thruster effluents can be a major source of contamination. The other source of contamination is frequently referred to as re-deposition. Re-deposition occurs when material sputtered from surfaces outside of the thruster is deposited on other surfaces. Surface contamination may significantly alter the properties of surfaces, possibly causing failure of sensitive surfaces such as radiators and optical components.

The plume models used for the analysis of the Prometheus One electric propulsion plume environment were all generated by SAIC in San Diego, California, or by the authors using Plumetool, an SAIC software application that generates plumes for use in the Electric Propulsion Interactions Code (EPIC). References 5 and 6 describe EPIC and its capabilities. SAIC's plume models and the models used by Plumetool are physics based, two dimensional codes that have been validated with both laboratory and flight data [7, 8, 9]. The plume codes include models of elastic scattering, main beam expansion, and neutral expansion, giving a fairly complete picture of plume physics, with the exception of thruster effluents.

Figure 6 depicts the ion density of the high power Hall thruster plume and the Herakles ion thruster plume. The figure shows an area 5 meters on a side, with the thrusters at the right edge firing to the left. The plume of the ion thruster is less dense and more tightly collimated than that of the Hall thruster. The charge exchange wings, the areas of slightly higher density at high angles from the thruster centerline, contain the greatest concentration of charge exchanged ions which potentially could be dangerous to the spacecraft. The main beam contains highly energetic ions which will severely erode materials placed in their paths. The Hall thruster produces much higher densities because of both higher flow rates and lower ion velocities than the ion thruster. It is not always clear which plume will cause the greater amount of sputter erosion, because while the Hall thruster plume is denser, the ion thruster plume carries much higher energies.

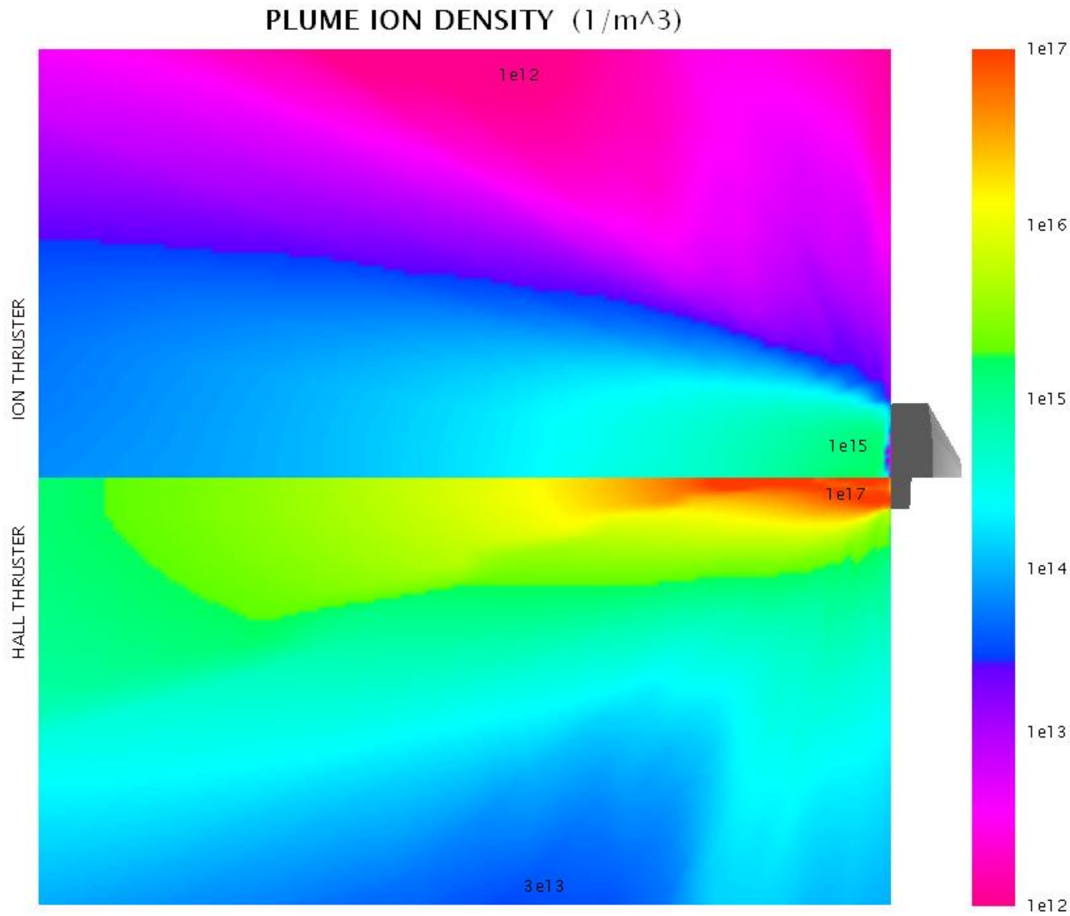

Figure 6. Plume ion density of a Herakles ion thruster (top) and a 20 kW Hall thruster (bottom). The angular shapes at the right edge of the figure represent halves of the thruster bodies approximately to scale. The figure shows an area with sides of five meters.

Despite the maturity of the physics models of the plumes, the integration of the models with tools for predicting the interaction of the plumes with the spacecraft is still in its infancy. Consequently, analysis has been rough, mostly manual calculations using data provided by the plume models. However, the plume models have helped to choose the thruster location such that obviously dangerous configurations were avoided. One of the earlier spacecraft configurations used small, bus-mounted hall thrusters for attitude control, but that approach was abandoned due to excessive plume impingement. An analysis of thruster effluents treated similarly to charge exchange ions contributed to the selection of the base-lined axial-thrust configuration rather the side-thrust configuration due to potential accumulation of carbon on the reactor surface and sputtering of the radiator panels.

Detailed sputtering and deposition analysis has not been performed as of this time. The detailed analysis is predicated on the availability of detailed instrument configurations and surface properties; as yet only a reference set of instruments exists. Sputtering and deposition in the back field of the thrusters is expected to be highly configuration dependent. Preliminary analyses show that depending on the location of instruments and their orientation, sputtering may occur to a greater or lesser degree. The analysis predicts that in 70000 hours of normal cruise mode operation, *i.e.* six Herakles ion thrusters firing, a maximum of about 4 μm of aluminum will be erode from the bare bus. In 1600 hours of high power Hall thruster operation, not including the two ion thrusters that would fire in high thrust mode, a maximum of 15 μm would be eroded. Deposition of thruster effluents is not expected to be a problem, but re-deposition of sputtered material may pose a threat. A greater amount of erosion is expected to occur on objects closer to the thrusters than the plane of the bus, for instance on bus mounted instruments. However, the problem can be mitigated through the use of sputter resistant materials, aperture covers, or shielding. One aspect of the plume analysis which has been neglected is multi-plume interactions. The effects of plume-to-plume interaction are not well understood. It is expected that there will be charge-exchange enhancement due to greater path lengths for neutrals before they escape the beams, but extent of this effect remains to be investigated. Some work has been done on plasma properties of multi-plume environments, *c.f.* Reference 10, but the body of work is insufficient to-date to allow high confidence analysis.

The electric thruster plume environment created by the simultaneous operation of as many as eight high-power thrusters poses many threats to the spacecraft. Only through careful configuration and detailed analysis can all likely risks be mitigated. Preliminary analyses have shown that the problems posed by the electric thruster plumes on the Prometheus One spacecraft configuration are tractable. However, it remains to actually find solutions to the problems presented.

V. Conclusion

Significant work remains for the complete definition of the electric propulsion system architecture for the Prometheus 1 spacecraft. Certain trades need further definition such as ACS hall thruster versus a chemical propulsion system for attitude control, detailed feed system trades, and centralized or distributed controller functionality. Also most of the detailed analysis still needs to be performed such as thermal, dynamic, EMI, and more detailed plume analysis. Although much work remains, the Prometheus 1 electric propulsion system engineering work remains the best current attempt and sufficiently defining an architecture for realistic cost, mass, and schedule estimates.

Acknowledgments

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