

JIMO Follow-On Mission Studies

Celeste M. Satter

*Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91001
Tel. (818) 354-9246; Email, Celeste.M.Satter@jpl.nasa.gov*

Abstract. Team Prometheus is a geographically-distributed, collaborative engineering team composed of representatives from several NASA centers and the Department of Energy (DOE). During the months of April through September 2004, Team Prometheus performed studies of representative Saturn/Titan and Neptune/Triton science missions based on proposed Jupiter Icy Moons Orbiter (JIMO) technology. The principal objectives of these studies were: 1) to assess the feasibility of using direct copies of the baseline JIMO flight system designs to perform these follow-on missions, and 2) to identify and assess technologies or potential enhancements or alterations to the baseline JIMO designs which could reduce the cruise durations to meet NASA Headquarters-specified programmatic goals. A tertiary objective was to provide feedback to the JIMO Project on the suitability of the JIMO reference designs for potential follow-on applications.

STUDY OBJECTIVES

The objectives of the JIMO follow-on mission studies were 1) to assess the feasibility of performing follow-on missions (Saturn/Titan and Neptune/Triton) using exact duplicates of the baseline JIMO government study team spacecraft designs, and 2) to investigate enhancements which could make the designs more optimal for the mission applications studied.

Each design was assessed on a subsystem-by-subsystem basis to determine whether the design was capable of performing the mission, and to identify any design modifications, which were necessary to meet the mission application requirements. Subsequently, design enhancements that could make the designs more optimal for the subject mission applications were investigated. These ranged from minor changes such as removing unnecessary radiation shielding to major changes such as changing reactor power levels and launch architectures.

An additional objective in both studies was to investigate the feasibility of achieving NASA Headquarters-specified trip time objectives. Headquarters specified an 8-year (threshold) trip time to the Saturn system with a 6-year (goal), and a 15-year (threshold) trip time to the Neptune system with a 10-year (goal).

APPROACH

In both the Saturn/Titan and Neptune/Triton studies, the first step was to perform a direct assessment of the suitability of the unaltered JIMO government team reference designs to the proposed mission application.

At the time of the start of the Saturn/Titan mission study, the JIMO government design team had just completed a reference design referred to as Technical Baseline 2.0 (TB2). TB2 was a fairly complete, well-documented, and self-consistent design which served as a good starting point for the Saturn/Titan study. While two major power conversion options were being considered for the JIMO TB2 reference mission (Brayton and Thermo-Electric), the Brayton option was used in these studies because the system-level designs for that option were more complete than those for the Thermo-Electric option. The JIMO TB2 baseline design is shown in Figure 1.

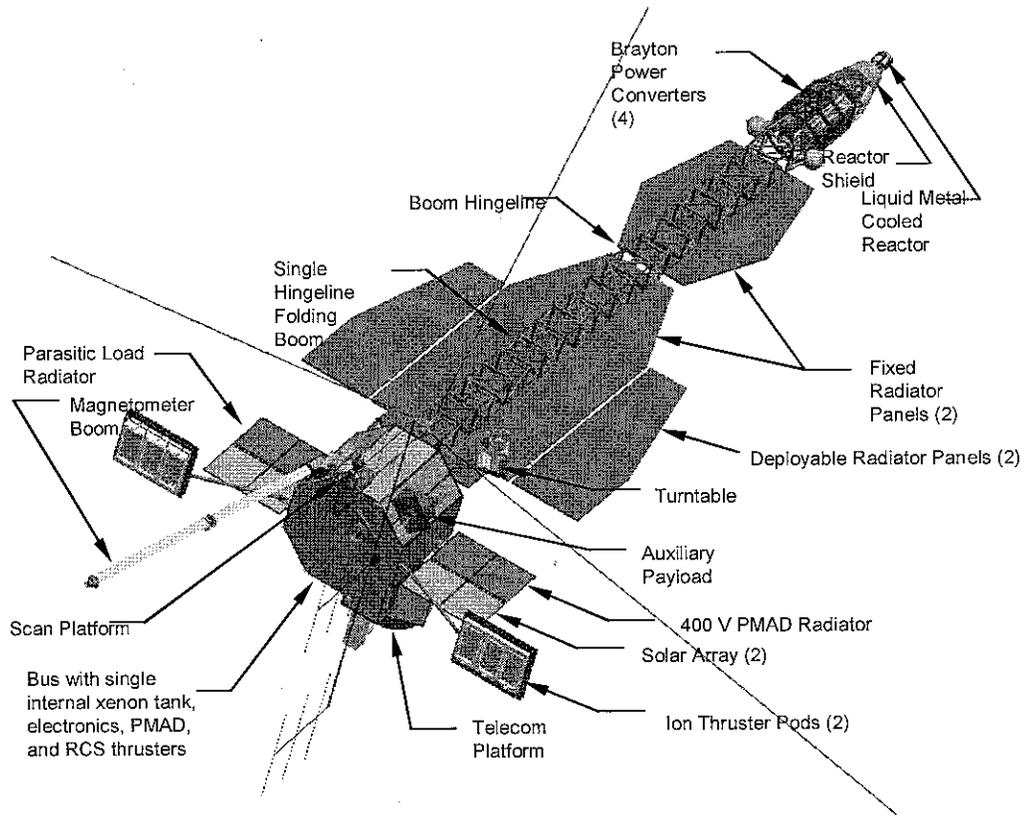


FIGURE 1. JIMO TB2 Reference Design Concept

Key top-level design parameters for the JIMO TB2 reference design were:

- 1.2 MWth Liquid-Metal reactor (operating at ~520 kWth output)
- 95 kWe to PPUs
- 22% efficient Brayton Power conversion
- High-power ion thrusters operating at 6500 sec Isp

By the time of the start of the Neptune/Triton study, however, the JIMO government study team reference design had evolved substantially from the TB2 baseline. The then current reference design was referred to as Technical Baseline 2.5 (TB2.5). However, this reference design did not yet exist in a complete, self-consistent form which could be used by Team Prometheus. Therefore, the first step in the Neptune/Triton study was the generation of a "Team Prometheus version" of the JIMO TB2.5 reference design. This design was created by starting with the JIMO TB2 reference design used in the Saturn/Titan study, and updating it with all the major design changes between the JIMO TB2 and TB2.5 baselines. These major design changes are summarized in Table 1.

TABLE 1. Major Design Changes Between the JIMO TB2 and TB2.5 Baselines

Key Elements (Common to all options)	TB2 Characteristics	TB 2.5 Characteristics	Comments
Launch Vehicle	Existing HELV	Phase 1 HELV; multiple launches/ on-orbit assembly	
JIMO Launch Envelope	5 m × 19 m	6 m × 20 m	
Reactor			
Energy	6.2 MWth-yrs	15.0 MWth-yrs	
Max Power		1.2 MWth	
Lifetime		14 years	JIMO only. Follow on missions for 20 years will not be at full power.
Minimum operating power	30% of full pwr	100% of full pwr	
Configuration			
Main boom length	21.5 m	28.0 m	
AACS			
Ion engine articulation range		±15°	
Solar array articulation	1-axis	Fixed	Trade study to be performed.
Telecom			
HGA configuration	Single dish	tetra-Gregorian	
HGA pointing control	3.0 mrad	1.0 mrad	monopulse tracking and electronic beam steering
EP			
Number of "small" Hall thrusters		12	Body-mounted; used for RCS after EP startup
Propellant			
Xenon tank capacity	14,000 kg	18,000 kg	
Docking Adapter			
Solar panel size	N/A	1.5 kW	
Power Conversion			
Total electrical output	110 kWe	146 kWe	Brayton
Shunt Regulator			
Power	110 kWe	146 kWe	
Radiator size	7.4 m ²	TBD	
Electric Propulsion			
ISP	6,500 sec	6,000 sec	
PPUs			
Input power	95 kWe	130 kWe	
Startup Power			
Energy storage required	2.0 kWh	3.0 kWh	
Bus segment solar panel size	6.0 kW	3.0 kW	Trade-off between solar array and battery sizing
Power Conversion Radiator			
Temperature	475 K	415 K	
Required area	153 m ²	261 m ²	
Actual area in configuration	170 m ²	346 m ²	
Secondary EM pump and NAK tank location	forward end	aft end	

The resulting "Team Prometheus version" of the reference JIMO TB2.5 design is shown in Figure 2.

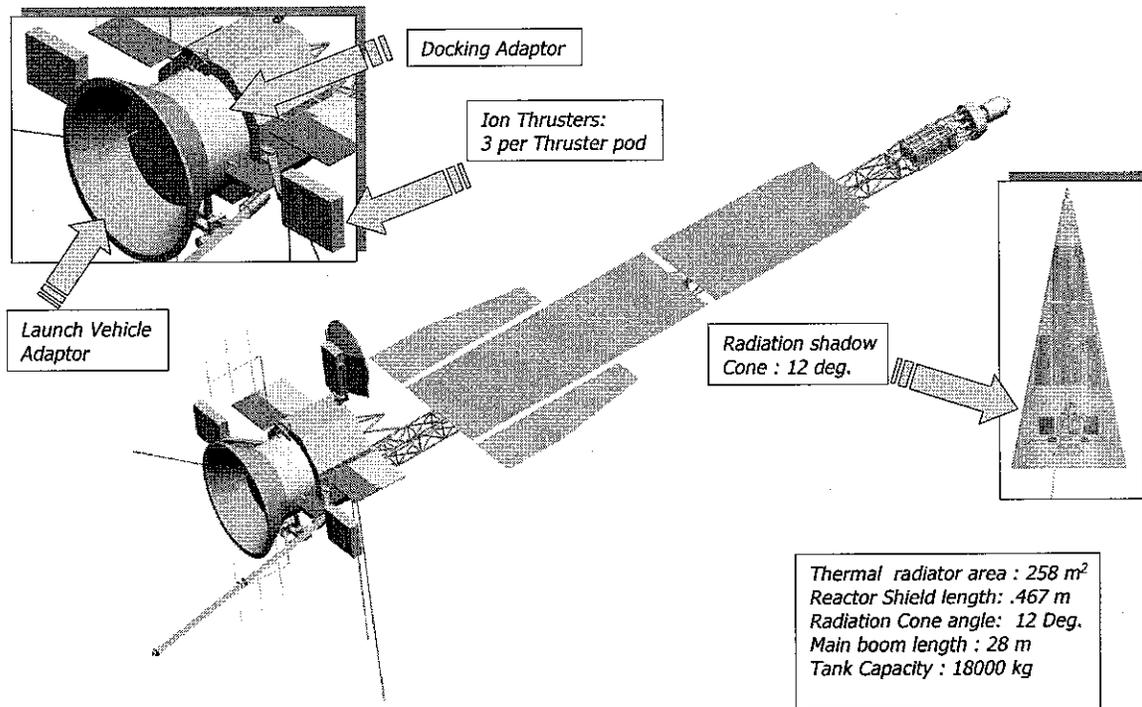


FIGURE 2. "Team Prometheus version" of the JIMO TB2.5 reference design

Subsequent to the direct assessment of the JIMO reference designs "as-is", both studies progressed through a sequence of cumulative mass reductions, and then through a number of mission architecture variations to achieve the trip time goals. These included variations in reactor power level, thruster specific impulse, launch C3, gravity assist options, and consideration of advanced technologies. The Neptune study also included one case where the system mass was increased to provide additional payload capability and potentially reduced risk through the use of increased redundancy.

TEAM DESCRIPTION

The core participants in the Team Prometheus studies were the Jet Propulsion Laboratory (JPL), Glenn Research Center (GRC), Marshall Space Flight Center (MSFC), and the Department of Energy's (DOE's) Oak Ridge National Laboratory (ORNL).

JPL was the Study Lead, and was responsible for mission design (together with GRC) and issues of payload accommodation. GRC had responsibility for power conversion and electric propulsion technologies, and shared responsibility for mission design with JPL. MSFC was responsible for CAD/CAM and Configuration, structures and mechanisms, and also provided information on Advanced Launch Vehicle capabilities. ORNL provided reactor module design expertise, including the reactor, reactor shield, heat exchangers, and control elements.

In addition to the core Team participants, Kennedy Space Center (KSC) provided information on current generation launch vehicle capabilities, and Ames Research Center (ARC) provided support in the areas of aeroshell design and collaborative engineering.

SCIENCE ASSUMPTIONS

The Team was directed to make no assumptions about the science which might be performed in these missions, but also to make sure that the resulting mission architectures did not preclude potential science. Effort was made, therefore, to ensure that the resulting designs enabled the broadest possible spectrum of science investigations

within practical Delta-V limits. As the Neptune/Triton study took place after the June 2004 Outer Planets Science Working Group meeting in Pasadena, California, the Team also endeavored to ensure that the science goals of the Neptune splinter group at that meeting were accommodated in the Neptune/Triton mission and system designs.

For both studies, a generic "Black Box" payload corresponding to JIMO Payload Accommodation Envelope (PAE) was initially assumed. The JIMO PAE is described in Reference 1. In the latter part of the Neptune/Triton study, an enhanced launch architecture using assumed advanced launch vehicle capabilities enabled an expansion of the JIMO PAE.

For the Saturn/Titan mission, two potential science tour trajectories were analyzed to scope the associated Delta-V requirements. In order to maintain the broadest possible science capability, the more demanding of these two tours was chosen for sizing analyses. For the Neptune/Triton mission, only a single representative science tour was analyzed.

BASELINE MISSION DESIGN

The Saturn/Titan mission study assumed the baseline JIMO launch architecture at the time of the study, which consisted of a single launch to a C3 of $0 \text{ km}^2/\text{s}^2$ and no gravity-assists. Nuclear Electric Propulsion (NEP) was then used for the trajectory to the Saturn system.

Two different representative moon tours were considered for the Saturn study. The first tour captured directly into a highly-elliptical Saturn orbit with a periapsis inside the rings (1.01×20 Saturn radii- R_S) initially. Once the science in that orbit was complete, the spacecraft began an inclination change from 90 degrees to about 15 degrees, increased the apoapsis to $70 R_S$, and then performed a "ring jump" in a single revolution around Saturn by performing a long, low-thrust propulsive maneuver around apoapsis. This ring jump increased the periapse from a radius of $1.01 R_S$ (inside the rings) to a radius of $2.3 R_S$ (outside the rings). The spacecraft then finished the inclination change to get into the orbit plane of Titan. Once the spacecraft spiraled out to Titan, it then spiraled down to a science orbit of 1700 km altitude. This first tour option required a total of 3 years (not including science observation time), and a Delta-V of 7 km/sec.

The second moon tour started out with a spiral about Saturn down to Titan's range from Saturn at which point it spiraled in to a Titan orbit of 1700 km altitude. It also included Delta-V required to flyby Iapetus and Hyperion. After the Titan science orbit was complete, the spacecraft spiraled away from Titan and then began to spiral down to the $1.01 \times 20 R_S$ Saturn orbit by reversing the process described in the first tour option. The spacecraft first spiraled down to a $70 \times 2.3 R_S$ orbit, then performed the ring jump to a $70 \times 1.01 R_S$ orbit, then lowered the apoapsis to $20 R_S$. The total time required for this tour was 4 years (not including science time), and required a Delta-V of approximately 12 km/sec.

The second tour was assumed for the Saturn/Titan study for conservatism, because of its more demanding requirements. Providing the higher Delta-V capability would enable a broader range of actual science tours for the mission.

It was decided that the Neptune/Triton science tour should spiral down to Triton and place the spacecraft into a 700 km (4.3-hour period) circular orbit with an inclination of 90 degrees. After the Triton orbit, the spacecraft would then transfer into a polar elliptical orbit around Neptune. The periapse would have an altitude of 0.1 Neptune radii (~2,400 km), and the apoapse would have an altitude of about 500,000 km. The Team decided that there was no need for a single ring jump, since there are enough gaps in the rings that the spacecraft could "skip" through them as the periapse is reduced. The total tour time from Neptune capture to the end of science activity was 5 years. The total Delta-V required for this tour was 10 km/sec.

RADIATION ENVIRONMENT

One of the most significant differences between the JIMO mission and the Saturn/Titan and Neptune/Triton missions is their ambient radiation environment. The anticipated environmental ionizing radiation dose for both the

Saturn and Neptune missions is approximately three orders-of-magnitude less than that anticipated for the baseline JIMO mission.

What this means is that much of the local radiation shielding carried in the JIMO reference design for protection from the heavy radiation dose in the Jovian system is not needed for either the Saturn or Neptune missions. Additionally, since the environmental radiation dose was lower, the allowable dose coming from the reactor could be increased (assuming re-use of the same JIMO radiation-hardened parts), thereby enabling a reduction in the mass of the reactor shield as well.

PLANETARY PROTECTION

At the time of these studies, both the Saturn/Titan mission and the Neptune/Triton missions would have been classified as Category II missions according to the official NASA Planetary Protection guidelines [Ref. 2]. This classification requires that the likelihood of accidental impact with Titan or Triton should be minimized, and some contamination control measures would be required for possible probes or landers. The mission architecture implications of this are significant, because at the time of these studies it was expected that the JIMO reference mission would have to meet much more demanding Category IV requirements for Europa. These Planetary Protection requirements drove the original baseline JIMO TB2 and TB2.5 designs to dual-fault tolerance (i.e., extra redundancy) in some subsystems in order to ensure that the vehicle could achieve an assumed quarantine orbit at Europa at end-of-mission.

RESULTS

Saturn/Titan Mission Study Results

The results of the initial assessments were that an exact copy of the baseline JIMO TB2 design would be capable of performing a Saturn/Titan mission. It would return a reduced data rate due to longer link distance, but this data rate would still be more than an order of magnitude greater than Cassini's (~3-4 Mbps vs. ~125 kbps). It would, however, take 13.8 years to reach the Saturn system.

A lightweighted version of the baseline JIMO TB2 design (dubbed "JIMO Lite"), which had been made more optimal for the Saturn/Titan application by removal of unneeded radiation shielding mass and extra redundancy achieved a trip time of 7.3 yrs to the Saturn system by launching to a C3 of 10. Adding a Mars gravity assist to this design could potentially yield an additional ~ 1 year reduction in trip time.

A number of advanced technologies were considered to potentially provide further system mass reductions. Due to time constraints, the Team was only able to assess the system-level impact of one of these changes, so a hypothetical increase of Brayton power conversion efficiency from 22% to 27% was chosen as potentially offering the biggest mass payoff. However, this change provided only a small additional improvement in overall system mass or resulting trip time. It should be noted, however, that all of the design modifications in this study were undertaken sequentially, and that the mass reduction due to individual advanced technologies could potentially be much greater if utilized in the original baseline design rather than after all other mass reduction options had already been incorporated.

Neptune/Triton Mission Study Results

One of the conclusions of the Saturn/Titan study was that all the options for system mass reduction studied provided only limited trip-time reductions. Therefore, during the course of the Neptune/Triton studies, the Team quickly examined the previously identified mass reduction options, and then focused on launch vehicle and launch architecture options together with gravity assist options to achieve more substantial trip time reductions. In addition to the reduced flight time options examined, a latter case investigated a significant alternative trade space option addressing increased payload allocations and risk mitigation to determine potential impact on the JIMO reference architecture. The cases studied were:

- Case 1: Created baseline JIMO TB2.5 design
- Case 2: Evaluated direct application of JIMO TB2.5 design (from Case 1) to Neptune/Triton mission
- Case 3: Reduced radiation shielding and redundancy not needed for this mission
- Case 4: Increased power and ISP to reduce trip time
- Case 5: Incorporated Earth Gravity-Assist to reduce trip time
- Case 6: Change launch architecture from multiple-launch/on-orbit assembly to direct launch using Advanced Launch Vehicle
- Case 7: Use Advanced Launch Vehicle in a multiple-launch/on-orbit assembly scenario to enable launch to much higher C3 and reduced trip time (includes Jupiter gravity-assist)
- Case 8: Use Advanced Launch Vehicle in a multiple-launch/on-orbit assembly scenario to enable higher payload allocations and possibly reduced risk

The design changes were applied incrementally, with each of the above eight cases building upon the results of the previous case, except for Case 8 which was based upon Case 6.

Table 2 summarizes the study results for all eight Cases. The JIMO TB2.5 reference design (Team Prometheus version) required in excess of 30 years trip time to reach the Neptune system, so was deemed impractical. Trip times range from 17.3 years for JIMO TB2.5 "Lite" (Case 3), to as low as 13.5 years for a 200 kW design using an Earth gravity-assist (Case 5). These cases all assume the JIMO TB2.5 launch architecture, which utilizes three launches and a Phase I HELV. Assuming a more capable Advanced Launch Vehicle, Case 6 showed a direct launch with no on-orbit assembly appears feasible, yielding a trip time of 12.6 years with an Earth gravity-assist. Assuming the JIMO TB2.5 baseline three-launch/on-orbit-assembly architecture, but using the more capable Advanced Launch Vehicle instead of the HELV1, an Earth orbit escape C3 of $55 \text{ km}^2/\text{s}^2$ appears achievable, yielding a trip time of approximately 10 years with a Jupiter gravity-assist as shown in Case 7. All of these trajectories remain within the capability of the JIMO TB2.5 flight system, except for Case 6 which exceeds the JIMO TB2.5 Total Reactor Energy MWth-years slightly (16.3 required vs. 15 capability of TB2.5), although reactor power level was not exceeded.

The final Case studied, Case 8, requires both a higher reactor power and higher total Reactor Energy (MWth-years) than the JIMO TB2.5 baseline reactor can provide. Case 8 could still achieve a flight time lower than the 15-years to Neptune programmatic threshold by providing 275 kWe to the PPU's. However, this mission architecture and vehicle design demonstrate the potential to deliver significantly higher science payload and potentially reduce overall mission risk through higher mass margins, added redundancy, and risk-mitigating design changes. The Case 8 design required the same highly-advanced launch architecture capability assumed in Case 7. However, despite significant increases in mass, radiator area, and boom length, the overall spacecraft architecture remained unchanged.

CONCLUSIONS

All of the options for system mass reduction and improved performance considered in both the Saturn/Titan and Neptune/Triton studies yielded only limited trip-time reductions. These options included removal of radiation shielding mass, reductions in hardware redundancy, and introduction of pre-planned product improvements. It appears that combinations of more capable launch vehicles, on-orbit assembly, and gravity assists yield greater "payoff" in terms of trip time reduction. These mission architecture options provide the potential to launch greater mass to higher C3s and carry more propellant, enabling the use of higher-power and higher-thrust systems -- needed to provide shorter trip times. If trip time reduction is a driving requirement, then this region of the mission architecture trade space should be given careful consideration in the overall Prometheus program architecture.

TABLE 2. Summary of Neptune/Triton Study Design Cases

Study Case:	Case 1 JIMO TB2.5 Transition	Case 2 Assess JIMO TB2.5 for Neptune/Triton	Case 3 JIMO Lite	Case 4 High Power	Case 5 Earth Gravity Assist	Case 6 Advanced LV; Single Launch	Case 7 Advanced LV; Multiple-Launch	Case 8 Heavy w/ Redundancy
Case Description:	NEP	NEP	NEP	NEP	NEP w/ EGA	NEP w/ EGA	NEP w/ JGA	NEP w/ EGA
Trajectory	N/A	30-35 (est.)	17.3	16.3	13.6	12.6	10.0	14.0
Flight Time (yrs)	Multiple Launches; On- Orbit Assembly	Multiple Launches; On- Orbit Assembly	Multiple Launches; On- Orbit Assembly	Multiple Launches; On- Orbit Assembly	Multiple Launches; On- Orbit Assembly	Single Launch	Multiple Launches; On- Orbit Assembly	Multiple Launches; On- Orbit Assembly
Launch Architecture	Phase 1 HELV	Phase 1 HELV	Phase 1 HELV	Phase 1 HELV	Phase 1 HELV	Advanced LV	Advanced LV	Advanced LV
Launch Vehicle	36,000	36,000	36,000	36,000	36,000	N/A*	68,500	68,500
Launch Vehicle Capability (kg to LEO)	10	10	10	10	10	5.2	55	3.4
C3 (km ² /s ²)	N/A	N/A	35,000	35,000	35,000	46,078	37,100	61,213
Trajectory Convergence Mass at Chosen C3 (kg)	22,614	22,614	18,775	21,258	21,064	22,773	22,200	36,051
Total Dry Mass (kg)	30	N/A	44.1	37.6	37.5	50.5	43.2	43.2
Post-Launch Delta-V (km/s)	6,000	6,000	7,473	8,000	8,000	7,350	7,500	8,000
Ion Thruster Specific Impulse (s)	130	130	130	200	200	200	200	275
Power to the PPU's (kWe)	9	N/A	10.6	14.5	13.5	16.3	12.2	23.1
Reactor Energy Required (MWh-yrs)	14	N/A	16.8	12.8	11.9	14.4	10.8	14.5
Full Power Reactor Life (yrs)	28	28	28	28	28	24.1	28	46
Boom Length (m)						* This case did not go to LEO, LV capability to C3=5.2 approximately 46MT		

NOMENCLATURE

AACS	= Attitude Articulation and Control System
ARC	= Ames Research Center
CAD	= Computer-Aided Design
CAM	= Computer-Aided Manufacturing
C3	= Trajectory energy parameter, in km^2/s^2
Delta-V	= Velocity increment
DOE	= Department of Energy
EGA	= Earth gravity-assist
EP	= Electric Propulsion
GRC	= Glenn Research Center
HELV	= Heavy Expendable Launch Vehicle
HELV1	= Phase 1 HELV
Isp	= specific impulse
JGA	= Jupiter gravity-assist
JIMO	= Jupiter Icy Moons Orbiter
JPL	= Jet Propulsion Laboratory
kbps	= kilobits per second
KSC	= Kennedy Space Center
kWe	= kilo-Watts electric
kWth	= kilo-Watts thermal
Mbps	= Megabits per second
MSFC	= Marshall Space Flight Center
MT	= metric ton (1000 kilograms)
MWth	= Mega-Watts thermal
NASA	= National Aeronautics and Space Administration
ORNL	= Oak Ridge National Laboratory
PAE	= Payload Accommodation Envelope
PMAD	= Power Management and Distribution
PPU	= Power Processing Unit
RCS	= Reaction Control System
Rs	= Saturn radii
TB2	= Technical Baseline 2
TB2.5	= Technical Baseline 2.5

ACKNOWLEDGEMENTS

The work described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The study results reported herein, however, reflect the outstanding efforts of the entire Prometheus Team, including members at JPL, GRC, MSFC, KSC, ARC, and DOE/ORNL. The JIMO Follow-On Mission Studies are an excellent example of the "One NASA" spirit (and DOE/ORNL, too!)

Special recognition is due the Information Technology infrastructure personnel at all the participating centers who truly enabled this collaborative effort.

REFERENCES

1. "Report of the NASA Science Definition Team for the Jupiter Icy Moons Orbiter (JIMO)," Table 4.1 - JIMO Proposed Payload Accommodation Envelopes, Parts 1 and 2.
2. "NPG 8020.12B Planetary Protection Provisions for Robotic Extraterrestrial Missions."