

Results of the JIMO Follow-on Destinations Parametric Studies

Muriel A. Noca¹, Kurt J. Hack²

¹*Deep Space Mission Architecture Group, Jet Propulsion Laboratory,
California Institute of Technology, Pasadena, CA 91109*

²*Space Propulsion and Mission Analysis Office, NASA Glenn Research Center, Cleveland, OH 44135*
¹*muriel.noca@jpl.nasa.gov*

Abstract. NASA's proposed Jupiter Icy Moon Orbiter (JIMO) mission currently in conceptual development is to be the first one of a series of highly capable Nuclear Electric Propulsion (NEP) science driven missions. To understand the implications of a multi-mission capability requirement on the JIMO vehicle and mission, the NASA Prometheus Program initiated a set of parametric high-level studies to be followed by a series of more in-depth studies. The JIMO potential follow-on destinations identified include a Saturn system tour, a Neptune system tour, a Kuiper Belt Objects rendezvous, an Interstellar Precursor mission, a Multiple Asteroid Sample Return and a Comet Sample Return. This paper shows that the baseline JIMO reactor and design envelop can satisfy five out of six of the follow-on destinations. Flight time to these destinations can significantly be reduced by increasing the launch energy or/and by inserting gravity assists to the heliocentric phase. This paper summarizes the findings of these high level parametric studies. The conclusion will outline the requirements for JIMO to be planned as a multi-mission capability.[†]

DEFINITIONS AND NOMENCLATURE

P_{ppu} :	Total electrical power level input to the EP Power Processing Units (PPUs).
P_o :	Total electrical power used by the PPU's and the balance of the Space System.
M_o :	Total launch mass (wet), also called injected mass (does not include launch vehicle, nor chemical stages).
M_{com} :	Total mass at the end of the mission, or in other terms total wet launch mass minus propellant mass used for main thrusting only (deterministic propellant mass). This mass includes residuals and other non main-thrust propellant.
M_{dry} :	Total dry mass at the end of the mission.
Isp:	Thruster specific impulse.
TTth:	Total time of thrust, total time when thrusters are on to provide main thrust.
TTF:	Total time of flight, total time of travel from departure to final science orbit.
TMT:	Total mission time, total time of flight plus science duration.
TFS:	Time of first science return, time of first encounter of a scientifically targeted body.
KBO:	Kuiper Belt Objects.
IP:	Interstellar Precursor.
MASR:	Multiple Asteroid Sample Return.
CSR:	Comet Sample Return.

INTRODUCTION

The proposed JIMO project would be the first in a series of expected strategic exploration applications based upon a common line of technologies. Six follow-on applications that meet certain criteria were identified and investigated. The objective of the study was to investigate a set of potential JIMO follow-on applications to assess the applicability of JIMO-developed technologies for these applications. For each proposed follow-on application, three parametric study cases were performed:

[†] The work discussed in this paper was conducted without the involvement of DOE Naval Reactors (who is assigned responsibility on spacecraft reactor and nuclear power plant matters for the Prometheus 1 project). The views expressed in this document do not represent or imply an official Government position or decision, and do not necessarily reflect agreement by the Government.

1. Analytical and parametric studies of the selected set of destinations employing the baseline JIMO current technologies directly.
2. Analytical and parametric studies of the selected set of destinations employing JIMO technologies and assumed pre-planned product improvements in one or more technology areas. Improvements were defined by the JIMO project in conjunction with the Prometheus technology community.
3. Analytical and parametric studies of the selected set of destinations according to a set of programmatic guidelines specified by NASA and the Nuclear Systems Program Office. The intent of this task was to determine what the technology requirements are based upon imposed programmatic goals and constraints. The Nuclear Systems Program Office established the following guidelines for reasonable performance of potential follow-on applications (*threshold/goal flight time to first science return*):
 - Saturn/Titan/Rings: *8/6 years to the Saturnian system*
 - Neptune/Triton/Rings: *15/10 years to the Neptunian system*
 - Kuiper Belt Object: *15/10 years to the target*
 - Interstellar/Heliopause: *20/15 years to the target*

The study approach was to perform a 'broad but thin' investigation of all potential applications to develop favorable architectures. The analysis used the multi-mission system model and other modeling tools and techniques. To accommodate the wide range of varying parameters, we developed trajectory databases for selected ΔV -driven destinations, applied the baseline JIMO range of application (Isp, launch mass, power levels) or other technology choices, and looked at resulting flight times and other mission parameters. This document provides the assumptions, analysis process and results of the JIMO follow-on destinations parametric study.

CAVEATS AND UNCERTAINTIES

The trade space analysis described herein includes elements related to mission design (trajectories, flight time, propellant mass, etc.), technology (power level, Isp...), and hardware constraints (launch vehicle, space system dry mass). Since the effort was focused on evaluating the trade space, all of these elements were modeled parametrically. These results are therefore qualitatively accurate representations of the trade space, but do not represent all possible options for mission design, technology, or hardware. The results are qualitatively and quantitatively correct for the set of approximations assumed. The process by which the results are obtained is exact and reproducible with any new set of data/model/assumptions. This analysis is a work in progress, based on a set of assumptions that will vary over time. Similar analysis will be done again as the collective understanding and assumptions evolve. At the start of the task several decisions were taken to either simplify the analysis or, by lack of information, to provide inputs to define the needs for the program. The two major decisions were the following:

- No gravity assist were assumed for the *heliocentric* parts of the trajectories; gravity assists are very hard to introduce in a parametric fashion as they are difficult to compute. However, gravity assists would certainly be taken into account in an actual mission design as they offer many advantages. Thus, the results presented here would be improved if gravity assists would be inserted. Gravity assists were used for the calculation of the moon tour ΔV s.
- No launch vehicle constraint. At the time of the analysis, no launch vehicle was defined, so there are no launch vehicle assumptions in the analysis. The analysis represents the required launch mass as a function of the trajectory and other parameters. On-orbit assembly is a likely option, making it possible to launch one to several chemical stages to increase launch energy. This scenario substitutes the number of launches as a performance metric, instead of a fixed launch vehicle constraint.

The uncertainties that have the potential to impact this analysis lay in three areas:

- Process: Models of models: The analysis is based on a system model that includes curve fits and approximations. Models of more detailed models have been included for simplicity and effectiveness. The models are also tied to a configuration of the space system. This configuration becomes less accurate for power levels that are limited by the launch vehicle fairing dimensions. This was about 100 kWe at JIMO start, was increased to the 130 kWe assumed in this document, and may be up to 200 kWe for JIMO with enhanced launch vehicle fairings.

- Trajectories. Results are based on simplified trajectory models and should be used to gauge relative performance. Results shown here do not represent all possible mission architecture or mission design options and should only be used for preliminary trade studies.
- Space system design. The Space System Design is based on the Government Technical Baseline 2 (TB2) studies. The mass of the Space System local radiation shielding has not been assessed in detail for each of the destinations.

JIMO POTENTIAL FOLLOW-ON APPLICATIONS

The JIMO follow-on applications initial study list was provided by NASA HQ and included the following destinations: Saturn and its moons, Neptune and its moons, Kuiper Belt Objects Rendezvous, Interstellar Precursor, Comet Cryogenic Sample Return, and Multi-Asteroid Sample Return. Representative mission architectures were selected and are summarized in Table 1. As previously mentioned, these architectures are representative of a range of possible options. The ΔV s associated with each destination highly depend on the architecture and can vary significantly. They were chosen rather conservatively as they did not exclude any possible science (the moon tours of Saturn and Neptune includes encounters with several moon and orbiting bodies). The transfer ΔV s vary also significantly with flight time and the ones quoted represent the most likely range for a JIMO type vehicle.

Databases of trajectories were generated in a parametric fashion for Saturn, Neptune, KBO, and the Interstellar Precursor destinations. All trajectories started from $C3 = 0 \text{ km}^2/\text{s}^2$. Also these databases were generated using the optimum Isp. Positive C3 databases were also generated for Saturn and Neptune (at C3 of 10 and 20 km^2/s^2).

TABLE 1. Representative Mission Architectures for the JIMO follow-on potential destinations.

Saturn and Titan	Spiral down to Rendezvous with Iapetus, Hyperion and Titan Spiral out of Titan's orbit, perform a plane change and a Saturn ring jump Polar orbit at Saturn (periapsis at 1.01 R_{Saturn}) Requires 4 years, not including time for science	Transfer ΔV : ~ 22–23 km/s Tour ΔV : ~ 12 km/s
Neptunian System	Rendezvous with Triton and science at Triton Escape Triton, orbit transfer via NEP and multiple Triton gravity assist to a 15-day science polar orbit around Neptune (periapsis at 1.2 R_{Neptune}). Ring jump performed with NEP system.	Transfer ΔV : ~ 38–40 km/s Tour ΔV : 3.5 km/s
Kuiper Belt Objects (KBO)	Rendezvous with 3 KB Objects ~ 1-2 AU apart	Transfer ΔV : ~ 40–44 km/s Tour ΔV : 8 km/s
Interstellar Precursor (IP)	Reach 200 AU in the direction of the heliopause "nose"	Transfer ΔV : ~ 54–60 km/s
Multiple Asteroid Sample Return (MASR)	Acquire samples from four asteroids classes + return to Earth 500 kg daughter spacecraft deployed at each asteroid	Total ΔV : ~ 29 km/s
Comet Sample Return (CSR)	Rendezvous with a short-period comet + return to Earth 500 kg daughter spacecraft deployed at the comet	Total ΔV : ~ 21–25 km/s

For the Comet Sample Return and Multiple Asteroids Sample Return, sample trajectories using JIMO parameters (Isp fixed not optimized) were computed and used. Assessing multiple specific targets in a parametric or trade-space fashion is impractical, as the initial acceleration changes arrival at first body and continually varies mission geometries to subsequent targets.

JIMO SPACE SYSTEM ASSUMPTIONS AND POTENTIAL PRE-PLANNED PRODUCT IMPROVEMENT

The JIMO space system assumed is based on and limited to the TB2 Liquid Metal reactor concept with Brayton (Br) power conversion. As a preliminary estimate of the potential follow-on applications for JIMO, the propellant tank capacity was designed for 14,000 kg of Xe and the JIMO reactor size was set at 15 MWth-yrs with a full thermal power capability of 1.2 MWth for the Brayton option. Subsequent to the final TB2 design and in light of the preliminary results of this analysis (March '04), the JIMO project decided to increase the baseline power to 130 kWe and the tank capacity to 18,000 kg.

The electric propulsion (EP) model used in these results is representative of the two electric thruster technologies being developed at the time for JIMO (HiPEP and NEXIS). To reduce technical risk associated with development of these thrusters, the specific impulse has been limited to the 5,500–8,000 second range. A total EP system efficiency of 0.7 was assumed. Minimizing the flight time will minimize the specific impulse; the lowest value now assumed is 5,500 seconds and is based on practical limitations of maintaining adequate thruster throughput.

A ΔV of 1 km/s was added to all trajectories to include propellant for navigation, attitude control, additional EP propellant needs and uncertainties, and mission design margins.

The JIMO “Mission Module” mass was assumed to be an acceptable mass allocation for the follow-on destinations (1,500 kg).

In agreement with the JIMO project and technologists, we identified a list of the potential JIMO Pre-planned product improvement (PPPIs) as summarized in Table 2 (more details on these technologies can be found in the “Detailed Investigations” section).

TABLE 2: JIMO potential pre-planned product improvements.

Subsystem	Technology improvement	Assessed in the study?
Power conversion	Refractory Brayton (27% efficient)	Assessed
Power conversion	High Power Brayton engines*	Assessed
Electric Propulsion	High power version of NEXIS/HIPEP	Assessed
Feed System - Tank	Multiple COPV	Not assessed (no data available)
PMAD	DC distribution	Not assessed (no data available)

*May or may not be a PPPI, significant system, or architecture issue.

PROMETHEUS MASS MODELS

To perform the analysis, mass models of the Space System are needed to select only the trajectories that deliver the required dry system masses. For power trades, the mass models includes a power component. Several mass models were elaborated for JIMO and for this Prometheus activity. The JIMO models are applicable ONLY for the JIMO TB2 planned space system configuration and mission architecture. The Prometheus models are applicable for the JIMO follow-on destinations only. Figure 1 shows the Space System dry masses as a function of power for each model.

All the mass models were elaborated starting with the *JIMO TB2* (Technical Baseline 2, Feb. 29, 2004) Mass Equipment List (MEL) modified for known subsequent changes near 100 kWe and estimated changes required to obtain higher power levels. The model provides an approximation to the variation of the JIMO vehicle mass as a function of power over the range from 80 to ~130 kWe, with decreasing fidelity above 130 kWe. Subsequent changes to this mass model were implemented during the Exploration Architecture Synergy task¹. A new mass model, *JIMO TB2+*, was generated. It includes updated technical mass margins, and better uncertainty allocations

for the reactor and Space System radiation shielding. This model also provided a better assessment, although very preliminary, of power level above 150 kWe.

Subsequently, a Prometheus specific mass model had to be elaborated to take into account the different environment and requirements imposed by the follow-on destinations. The first effort in that direction started during the Prometheus Saturn in-depth study led by Team Prometheus in June 2004². A *Team Prometheus* JIMO “light” mass model was worked out that was more reflective of the JIMO follow on applications, as it accommodated for a less stringent radiation environment, less stringent planetary protection requirements, a change in Brayton architecture (from four to two Brayton engines), a change in Electric Propulsion (EP) architecture (from 2 to 1 redundant engine), a resizing of the Primary Heat Transfer (PHT) system to the actual (lower) thermal output and formally included the JIMO space system margin policy (43% overall system contingency) and mission design margin. This mass model was also based on the Brayton configuration.

The JIMO project accepted the change in mass due to reduced radiation and resizing of the Primary Heat Transfer, but had serious concerns about the change in Brayton architecture and concerns about change in EP architecture. Based on these concerns, the *Prometheus* mass model was elaborated (at two different Isp, Brayton configuration), taking into account the reduction in radiation and resizing of the PHT, and recent changes on the attitude control thrusters configuration. The Prometheus mass model assumes the JIMO fixed size reactor and an 18,000 kg tank. Previous analysis showed that optimizing the reactor size had a small mass benefit compared to the fixed reactor, and is well within the uncertainties of this analysis.

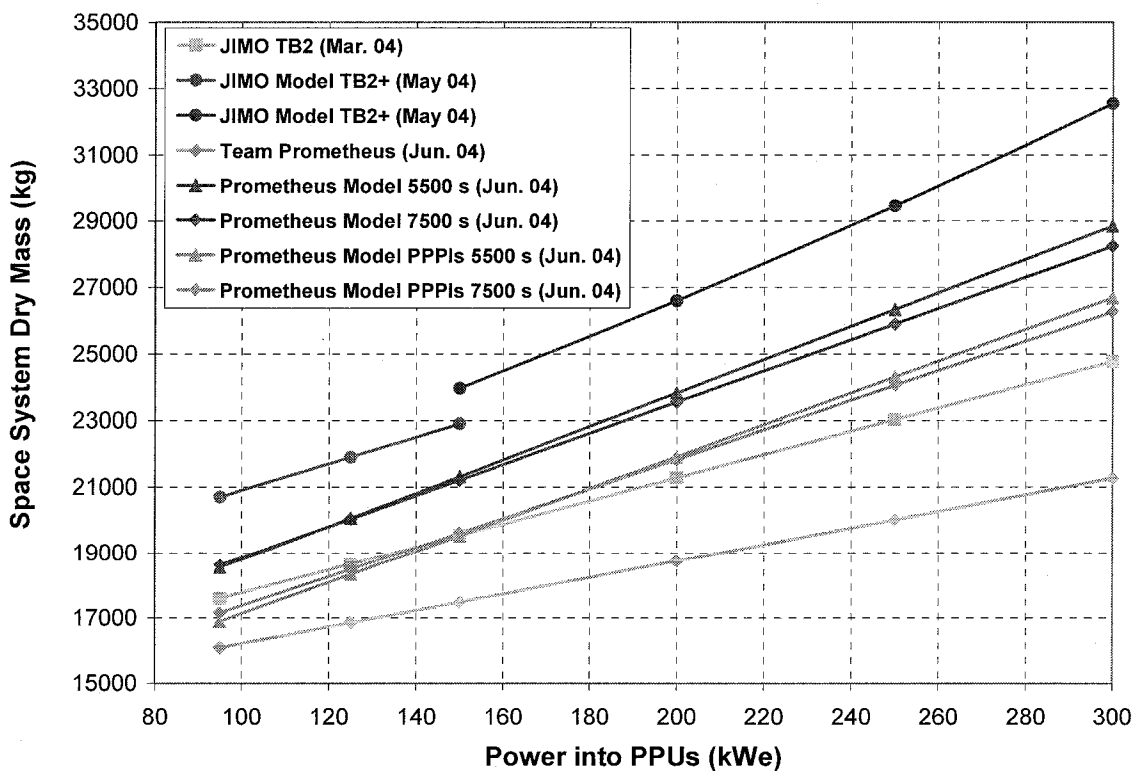


FIGURE 1. Representation of the mass models elaborated for JIMO and Prometheus parametric studies (Brayton configuration).

Finally, the mass savings provided by the PPPIs (masses include margins) were assessed during the Saturn In-depth Study. The *Prometheus PPPIs* model takes into account high power Brayton and high power EP. The high power Brayton PPPI, which consisted in reducing the number of Brayton converter and increasing their respective power to the full power, had the most impact on the dry mass of the system. However, this architecture has consequences on the system that have not been quantified and therefore are probably optimistic.

RESULTS OF THE PARAMETRIC ANALYSIS

With the trajectory databases and Prometheus space system mass models, one can create trade space plots representing the trade between launch mass (or other parameters such as propellant mass or reactor energy requirement), flight time at various fixed power levels and I_{sp} ³. In cooperation with the JIMO project, two representative data points (130 kW_e and 175 kW_e) were selected on these trade space plots as representative of the JIMO current power level and of a potential high power JIMO system. This process was applied to all destinations and combined in ΔV charts. The resulting ΔV charts gather the information for each destination onto one figure. Figure 2 through 7 summarize the results. Each figure represents a different parameter that can be translated as a requirement.

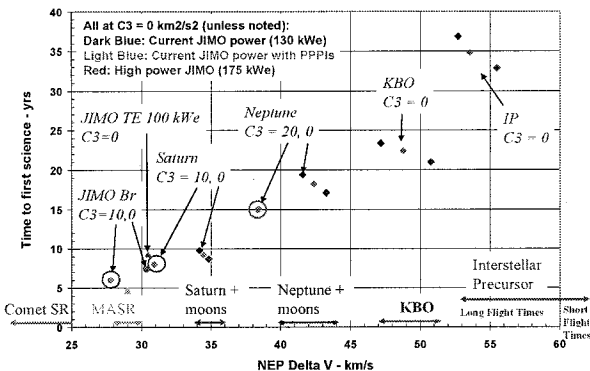


FIGURE 2: Time to first science results.

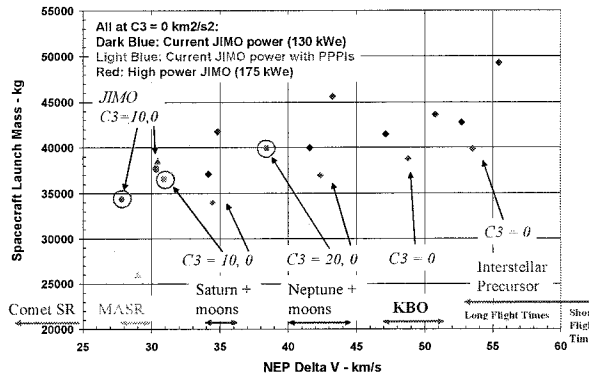


FIGURE 3: Required launch mass results.

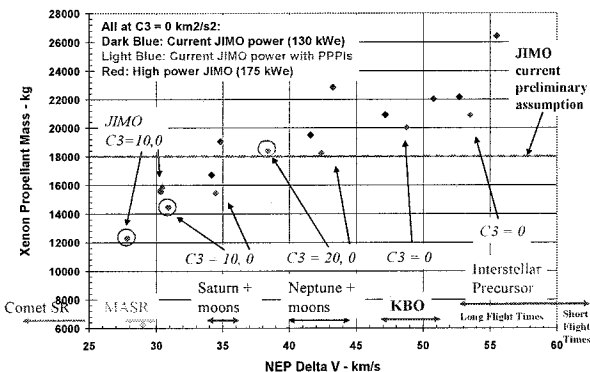


FIGURE 4: Required Xe propellant mass (incl. ΔV margin).

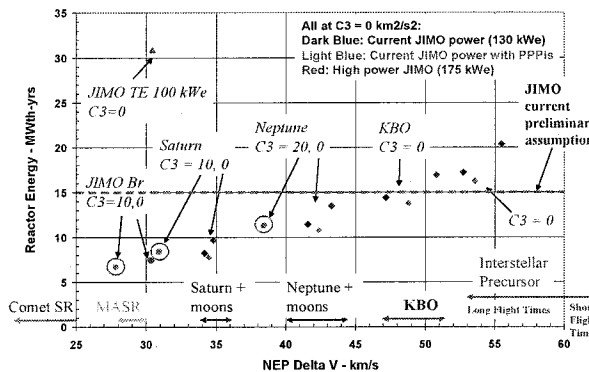


FIGURE 5: Required reactor energy results.

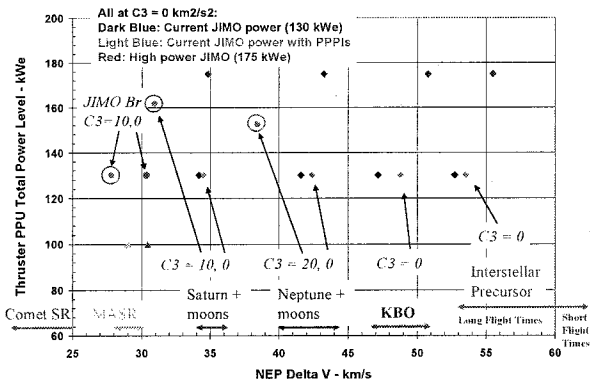


FIGURE 6: Power to the PPUs results.

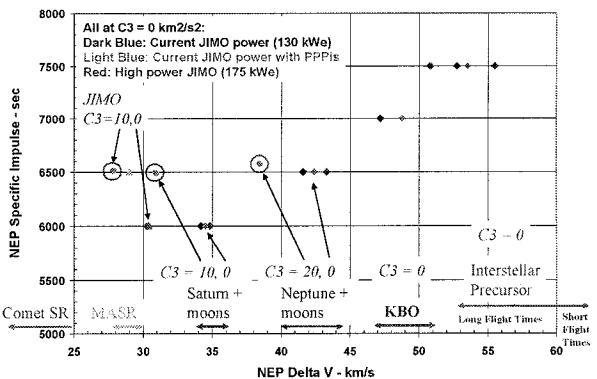


FIGURE 7: Assumed I_{sp} results

The reactor energy requirements were calculated assuming two years of science (no thrusting) at Saturn and Neptune, and a few months at each KBO (not applicable for the IP destination). This requirement also assumed that:

- the reactor would be turned down to 30% of its maximum power during non thrusting periods,
- the Space Reactor and Power System (SRPS) efficiency was 22%,
- in addition to the PPU power, the bus power was fixed to 5 kWe,
- the SRPS auxiliary power was 5% of the maximum power.

1. Assessment of the JIMO System.

Figure 2, 4, 5 and 7 particularly assess this task. They show the Time to First Science (TFS), Xenon propellant mass (includes ΔV margins), reactor energy requirement, and Isp for the current 130 kWe JIMO power (P_{PPU}) and for a high-power version of JIMO (the JIMO project does not preclude the possibility of utilizing higher power than the one needed for JIMO for other destinations if the key technologies developed for JIMO, especially the reactor and the basic space system and configuration, remain the same). Table 3 and 4 summarize the values. As shown, the MASR and CRS are not driving destinations for the JIMO system.

TABLE 3: Tabulated results for the 130 kWe (or otherwise noted) JIMO system.

	TFS (yrs)	Xe mass (kg)	Reactor energy (MWth-yrs)	Isp (s)	Required launch mass (kg) @ C3=0
Saturn & moons	9.8	16,704	8.2	6,000	37,100
Neptune & moons	19.4	19,491	11.5	6,500	40,000
KBO	23.4	20,915	14.4	7,000	41,450
IP	36.9	22,164	17.2	7,500	42,750
MASR (95 kWe)	4.7	6,390	<< JIMO	6,500	26,000
CSR (95 kWe)	5.5	7,830	<< JIMO	6,000	26,000

TABLE 4: Tabulated results for the 175 kWe high power JIMO system.

	TFS (yrs)	Xe mass (kg)	Reactor energy (MWth-yrs)	Isp (s)	Required launch mass (kg) @ C3=0
Saturn & moons	8.7	19,046	9.7	6,000	41,750
Neptune & moons	17.1	22,858	13.5	6,500	45,600
KBO	21	22,032	16.9	7,500	43,600
IP	32.9	26,426	20.4	7,500	49,300

Given no programmatic requirements, assuming no heliocentric gravity assists and no launch vehicle mass constraints, the current JIMO reactor and design envelope can accommodate five out of the six potential JIMO follow-on destinations (not Interstellar Precursor) with varying ranges of flight times. The reactor energy level is appropriate; the tank size could be increased slightly to fit the requirements.

2.0 Assessment of the JIMO System assuming Pre-Planned Product Improvement.

The same figures allow for an assessment of the benefits of pre-planned product improvements for a power level of 130 kWe (P_{PPU}). Table 5 summarizes the results. The PPPIs typically provided a reduction in dry mass of ~ 2,000 kg compared to the JIMO 130 kWe total dry mass, although full system implications of their implementation were not assessed in detail, thus this mass saving might be optimistic.

TABLE 5: Tabulated results for the 130 kWe JIMO system with PPPIs.

	TFS (yrs)	Xe mass (kg)	Reactor energy (MWth-yrs)	Isp (s)	Required launch mass (kg) @ C3=0
Saturn & moons	9.2	15,410	7.7	6000	34,000
Neptune & moons	18.3	18245	10.8	6500	36,950
KBO	22.4	20009	13.8	7000	38,750
IP	34.8	20871	16.2	7500	39,850

As the figures and the table show, the PPPIs provide a decrease of ~ 6 months to 1 year in flight time, a decrease in Xe propellant mass of about 1,000 kg, a decrease in reactor energy requirement of ~ 0.5–0.7 MWth-yrs, and a launch mass decrease of ~3,000 kg.

However, neither current nor high power JIMO, nor the PPPIs are sufficient to provide the programmatic goals in flight time. The next paragraph assesses what is needed to significantly reduce flight times.

3.0 Assessment of the application requirements based upon program goals and constraints.

Again, the Nuclear Systems Program Office established the following guidelines for reasonable performance of potential follow-on applications (*threshold/goal to first science return*): 8/6 years to the Saturnian system, 15/10 years to the Neptunian system, 15/10 years to the target, 20/15 years to the target. A significant reduction of flight time can be achieved in several ways. As shown in Figure 2, increasing the power level or introducing PPPIs does help, but does not provide sufficient flight time reduction. Two other ways to reduce flight time are to increase launch energy (C3) and/or to introduce gravity assists during the heliocentric phase of the flight.

Table 6 and previous figures provide an assessment of the C3 needed for the current JIMO system, as well as the launch mass required at a C3 = 0 to reach the threshold TFS. The positive C3 assessment is only provided for the Saturn and Neptune destinations as time and funding permitted the elaboration of complementary trajectory databases at a C3 of 10 and 20 km²/s². Since no launch vehicle were assumed in this study’s approach, mass could always be added to the capability of the launch vehicle to find a solution for the given flight times. One can safely infer that goal flight times will require the addition of gravity assist(s) to be reached.

TABLE 6: Tabulated results to reach threshold TFS for JIMO system at positive C3.

	TFS (yrs)	PPU power (kWe)	Xe mass (kg)	Reactor energy (MWth-yrs)	Isp (s)	Required launch mass (kg) @ C3
Saturn & moons	8	160	12265	6.7	6,500	34,350 @ C3=10
Neptune & moons	15	155	14425	8.4	6,500	36,550 @ C3=20

Note that increasing the C3 implied a launch mass approximately equivalent to the launch mass required for the 175 kWe cases at C3=0, but had the benefit of reducing the power needed (thus relaxing some of the system issues), of reducing the propellant mass required down to the current JIMO levels, and also reducing the reactor energy requirements.

CONCLUSION

Jupiter Icy Moon Orbiter (JIMO) is under consideration to be the first in a series of missions that uses a common set of new space technologies defined by the Prometheus Program. In this paper, follow-on missions to JIMO are identified. These missions are a Saturnian system tour, a Neptunian system tour, a Kuiper Belt object rendezvous, a 200 AU mission at the nose of the Heliopause (Interstellar Precursor), a Comet Cryogenic sample return, and a Multiple Asteroid sample return. These missions were investigated to determine which technologies would provide the broadest applicability to the greatest set of potential follow-on destinations. The principal findings of this study are:

1. The currently proposed JIMO reactor and design envelope can be used for five out of six potential follow-on missions (not applicable for the Interstellar Precursor application).
2. With the implementation of Pre-Planned Product Improvements (PPPIs) in key technology areas, the space system dry mass, flight time, Xenon propellant load, reactor energy, and a launch mass could be reduced but:
3. Programmatic flight time goals to follow-on destinations could not be met neither with the implementation of PPPIs, nor with current or high-power JIMO power system designs. However, significant flight time reductions could be achieved with increases in launch energy (C3) or with the use of gravity-assist maneuvers in the heliocentric phase of the missions.

This analysis is work in progress and should be continued as the design of the JIMO system evolves. More needs to be done, especially in the areas of launch vehicle definitions, positive C3 analysis and insertion of gravity assists in the heliocentric phases.

ACKNOWLEDGMENTS

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

The authors gratefully acknowledge the work and contribution of all the JPL and NASA-GRC team members that participated in this study: Jon Sims (mission design), Daniel Parcher and Try Lam (Saturn and Neptune trajectory databases), Anastassios Petropoulos and Greg Whiffen (Saturn and Neptune moon tours), Robert Falck (Kuiper Belt Object and Interstellar Precursor mission design and trajectory databases), Melissa McGuire (Multiple Asteroid Sample Return trajectories), Ian Dux (Comet Sample Return trajectories), and Stephanie Leifer (analysis and data processing).

The authors wish to especially thank Leonard Dudzinski (NASA HQ) and Erik Nilsen (JPL) for making the funding available for this work.

REFERENCES

- [1] "JIMO System Analysis for JIMO Exploration Architecture Synergy Task", JIMO document number 982-R05198.
- [2] Team Prometheus, "JIMO Follow-on Mission Studies, Saturn/Titan Mission", Final Report, July 9, 2004
- [3] M. Noca, R. Moeller, T. Spilker, "Reaching the Outer Planets with Nuclear Electric Propulsion: Trades, Sensitivities and the Case for a Neptune System Explorer", 20th Symposium on Space Nuclear Power and Propulsion, STAIF Conference, February 2003, Albuquerque, New Mexico.