Atmospheric Mining in the Outer Solar System: Interplanetary Transfer Vehicles, In-Situ Resource Utilization, and Moon Mining Issues

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Atmospheric mining in the outer solar system (AMOSS) has been investigated as a means of fuel production for high energy propulsion and power. Fusion fuels such as Helium 3 (3He) and deuterium can be wrested from the atmospheres of Uranus and Neptune and either returned to Earth or used in-situ for energy production. Helium 3 and deuterium were the primary gases of interest with hydrogen being the primary propellant for nuclear thermal solid core and gas core rocket-based atmospheric flight. A series of analyses were undertaken to investigate resource capturing aspects of atmospheric mining in the outer solar system. This included the gas capturing rate, storage options, and different methods of direct use of the captured gases. While capturing 3He, large amounts of hydrogen and 4He are produced. With these two additional gases, the potential for fueling small and large fleets of additional exploration and exploitation vehicles exists. Analyses of orbital transfer vehicles (OTVs), landers, and in-situ resource utilization (ISRU) mining factories are included. Preliminary observations are presented on near-optimal selections of moon base orbital locations, OTV power levels, and OTV and lander rendezvous points. Aerospacecraft with closed cycle gas core propulsion are used to capture the 3He and deuterium from the outer planet atmospheres. Water ice on the outer planet moons has been identified as critical resources for refueling the moon landers and the nuclear electric propulsion (NEP) OTVs. The numbers of interplanetary transfer vehicles (ITVs) and the launch vehicles will be presented. Preliminary design parameters for the ITVs and their payload limits will be assessed. The number of mining machines and their associated issues are addressed.

I. Atmospheric Mining in the Outer Solar System

Atmospheric mining of the outer solar system is one of the options for creating nuclear fuels, such as 3He, for future fusion powered exploration vehicles or powering reactors for Earth's planetary energy. Uranus' and Neptune's atmospheres would be the primary mining sites, and robotic vehicles would wrest these gases from the hydrogen-helium gases of those planets. While preliminary estimates of the masses of the mining vehicles have been created (Refs. 1-13), additional supporting vehicles may enhance the mining scenarios. Storing the mined gases at automated bases on outer planet moons was conceived to ease the storage requirements on interplanetary transfer vehicles (that would return the cryogenic gases to Earth).

II. Resource Capturing Studies

Studies of the gas capture rate and its influence on mining time in the atmosphere were conducted. Aerospacecraft cruisers have been identified as a "best" solution for atmospheric mining (Ref. 1-13). To power these vehicles, atmospheric hydrogen gas would be liquefied and used a rocket propellant for the ascent to orbit. A gas core rocket is a likely candidate. Gaseous or liquid hydrogen would be used to power the engines during atmospheric mining operations. Helium 3 (3He) would be separated from the atmospheric hydrogen and helium (4He) captured, liquefied, and stored as a payload that would be returned to orbit. A 500-kg payload of 3He is captured during the mining time. Table I provides the amount of 3He in the outer planet atmospheres.

Table I. Fraction of helium 3 in outer planet atmospheres

	Uranus	Neptune
Amount of 3He in 4He	1.00E-04	1.00E-04
Amount of 4He in atmosphere	0.152	0.19
Amount of 3He in atmosphere	1.52E-05	1.90E-05

III. Orbit Transfer Vehicle Operations and Analyses

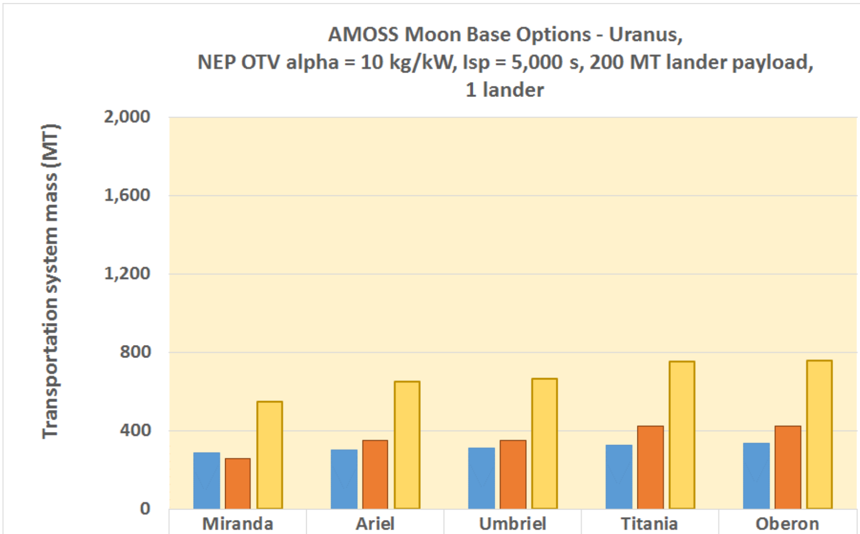
Selecting the appropriate moon for OTV propellant factories is a primary focus of the paper. An example of the OTV and lander flights' delta-V values needed for OTV refueling is presented in Appendix A, Tables A-I through A-IV. The OTVs mission design was planned with a rendezvous with the AMOSS mining aerospacecraft (ASC), departure from the rendezvous point near the cloud tops (800 km above the planet), low thrust transfer to the moon base (that base is located on Titania, in orbit around Uranus), and then rendezvous with the moon base lander. The lander delivered the propellant to the OTV for the round trip from the moon to the 800 km altitude above the planet. References 14 through 35 provide the supporting data for vehicle design and outer planet physical characteristics and resources.

Establishing an optimum transportation system will be influenced by many factors: the OTV mass and power level, the payload mass of the lander and the selection of the moon for the mining factories. Several optima will be created based on the size and mass of the moon selected. The moon's mass will strongly influence the propellant mass needed for the refueling of its oxygen/hydrogen propulsion system and the time needed for creating the fuel for the OTV.

Figures 1 and 2 provide the initial masses of the OTV and landers, for landers based at the moons of Uranus and Neptune, respectively. Using the landing and ascent delta-V values for various moons of Uranus and Neptune, the "best" moon base location will be estimated. The largest moons may be less attractive as their orbital and escape velocities are higher, requiring larger and more massive landers.

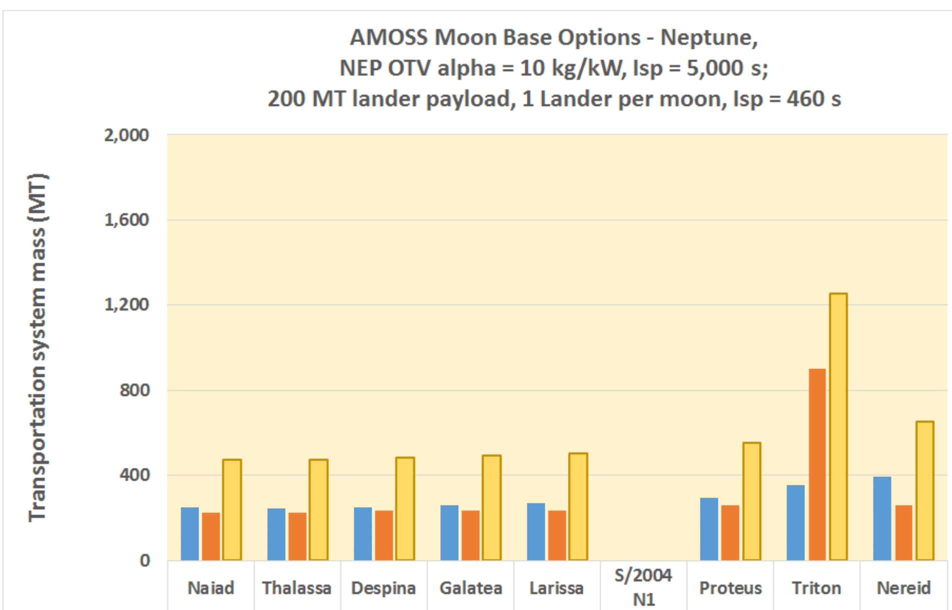
Two examples of the estimated transportation system masses are presented in Figures 1 and 2 (Ref. 3); Figure 1 shows the transportation system mass for Uranus' moons and Figure 2 depicts that transportation mass for the moons of Neptune. As shown in Tables A-I and A-II, these moons represent the moons with the smallest and largest delta-V values required for moon landing operations at each planet. The NEP OTV operated with an Isp of 5,000 s and a reactor alpha of 10 kg/kW. The OTV delta-V values are presented in Tables A-III and A-IV. The power level was 10 MWe. For all cases, a lander Isp value of 460 s was selected for the comparison. The lander payload masses were 200 MT. While the smallest moons require the lowest overall transportation system mass, the moon low gravity may be too low for efficient propellant processing. Such processing may be possible aboard an artificial gravity in-space base. Additional OTV and lander analyses for the wide range of moons will be presented. The influence of in-space processing, in orbit about the planets' moons, will also be investigated.

Figure 3 shows the range of masses for potential orbital factories for ISRU processing (Refs. 37 and 38). The gravity levels of the outer planet moon are sufficiently low to require artificial gravity for the processing of the water ice for the lander and OTV propulsion, as well as the 3He and deuterium for the AMOSS fusion fuels.



	Miranda	Ariel	Umbriel	Titania	Oberon
OTV	287.1	301.3	312.8	326.8	334.1
Lander (460 s)	258.0	351.1	351.1	424.0	424.0
Total	545.1	652.4	663.9	750.8	758.1

Figure 1. Uranus - Transportation System Mass – NEP alpha = 10 kg/kW, Isp = 5,000 s, Lander Isp = 460 s (one lander included in each case).



	Naiad	Thalassa	Despina	Galatea	Larissa	S/2004 N1	Proteus	Triton	Nereid
OTV	247.7	246.1	248.8	259.2	269		293.5	355.5	392.1
Lander (460 s)	226.0	226.0	233.5	233.5	233.5		257.9	900.0	257.9
Total	473.7	472.1	482.3	492.7	502.5	0.0	551.4	1,255.5	650.0

Figure 2. Neptune - Transportation System Mass – NEP alpha = 10 kg/kW, Isp = 5,000 s, Lander Isp = 460 s (one lander included in each case)

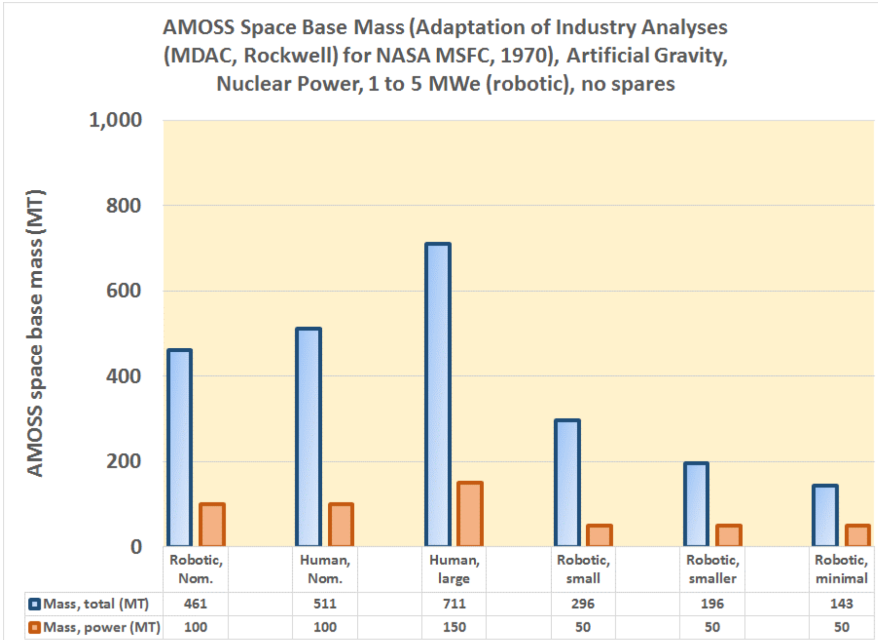


Figure 3. Space base mass estimates (based on extrapolations of data in Ref. 37 and 38)

IV. Overall Architecture Masses

Analyses were conducted to estimate the AMOSS on-orbit mass requirements for 10 years of operations. Table II shows the AMOSS vehicle lifetime and replacement schedules. Figures 4 and 5 shows the mass delivery schedule for Miranda based AMOSS systems (Ref. 3). Using nominal masses for each of the transportation and factory systems, the total mass for the initial deliveries was approximately 22,000 MT (Ref. 3). The NEP OTV lifetimes were also assessed for 7 and 10 year lifetimes (Ref 3). The smaller moons closer to both Uranus and Neptune required shorter trip times and hence allowed for more OTV flights for a given OTV lifetime. Figure 6 shows the ASC fleet mass reductions that are possible with increasing ASC payload mass. By increasing the ASC payload from 1 MT to 100 MT, the total ASC fleet mass is reduced from 100,000 MT to 1,350 MT. With this improvement, the overall architecture mass is reduced from 112,000 MT to 22,000 MT.

Mining time and propellant masses:

In all previous AMOSS analyses, the moons closer to the target planet reduced the mining system mass and are the most attractive. The minimal AMOSS OTV fleets mass uses Miranda at Uranus and Naiad or Thalassa at Neptune. The OTV and lander propellant masses for Uranus and Neptune moon operations are shown in Figure 7 and 8, respectively. As an example, the minimal OTV and lander propellant masses for Miranda are 82.1 and 27.1, respectively. The OTV and lander propellant values for Thalassa are 43 and 4, respectively.

For Miranda, using the MF of 1x10^-1, the mining time is approximately 7.7 days. With a MF of 1x10^-2, the mining time is 77 days, shown in Figure 9A.The capture bag for the mined material is also presented in Figure 9B. For a 100 MT water mass and the MF of 1x10^-2, the capture bag radius is 12.3 meters. Maintaining the integrity of the capture bag will be a major challenge. The water and the other regolith components will be gases and rock. A water-rock separation system will likely include some centripetal acceleration. Purification of the water will be another challenge. Once the water is captured, it must be separated into oxygen and hydrogen.

Table II. AMOSS vehicle lifetime and replacement schedules

Table I. AMOSS vehicle lifetime and replacement schedules

ASC lifetime = 100 to 1,000 flights per ASC; a total of 10,000 flights needed.
This translates to 10 to 100 ASCs.

OTV lifetime = 7 years.
This translates to 11 OTVs for Miranda.
This translates to 4 OTVs for Thalassa.

Lander lifetime = 5 to 10 flights per lander; for a total of 77 OTV refueling flights.
This translates to 8 to 16 landers.
5 flights per lander = 16 landers
10 flights per lander = 8 landers

Factory lifetime = 5 to 10 years.
This translates to 2 to 6 factories.
10 years = 1 or 2 factories
20 years = 2 or 4 factories
30 years = 3 or 6 factories

Add a specific fraction for the replacement masses: 10% replacement mass.

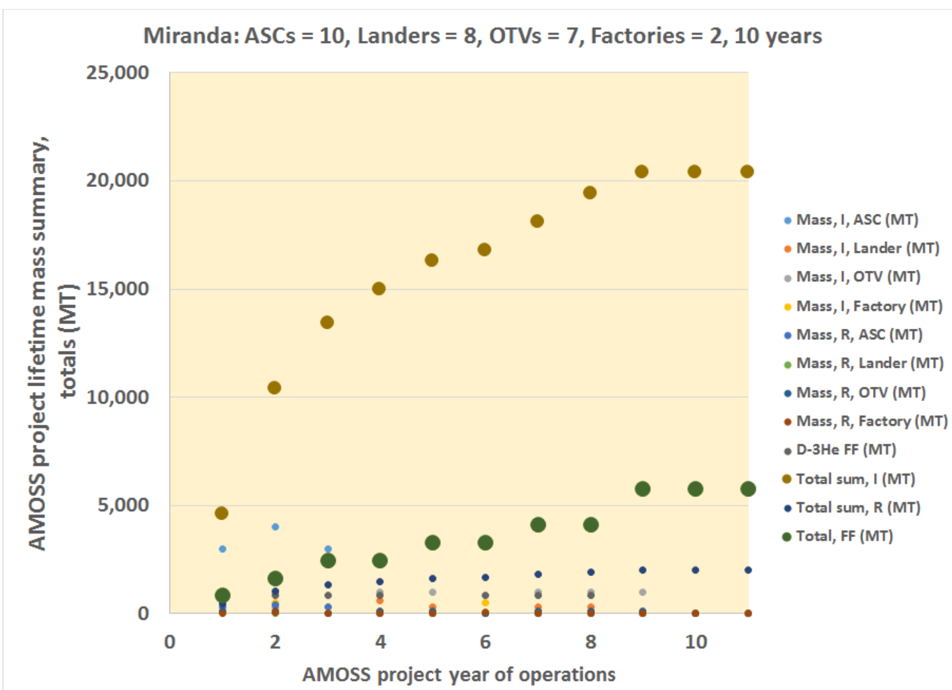


Figure 4. AMOSS – Miranda project lifetime mass requirements

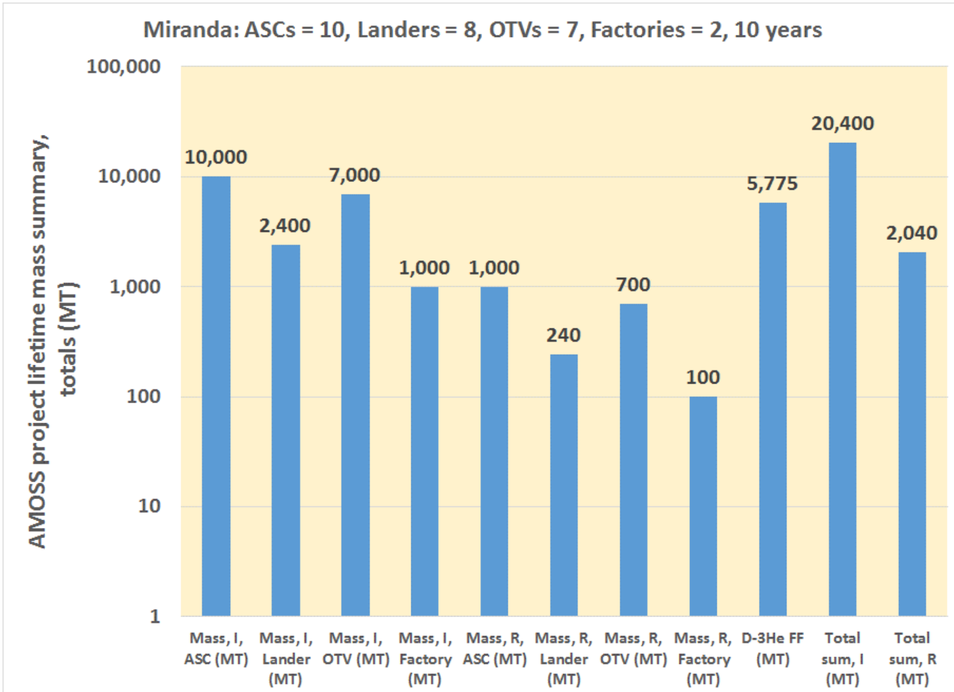


Figure 5. AMOSS – Miranda project lifetime mass elements

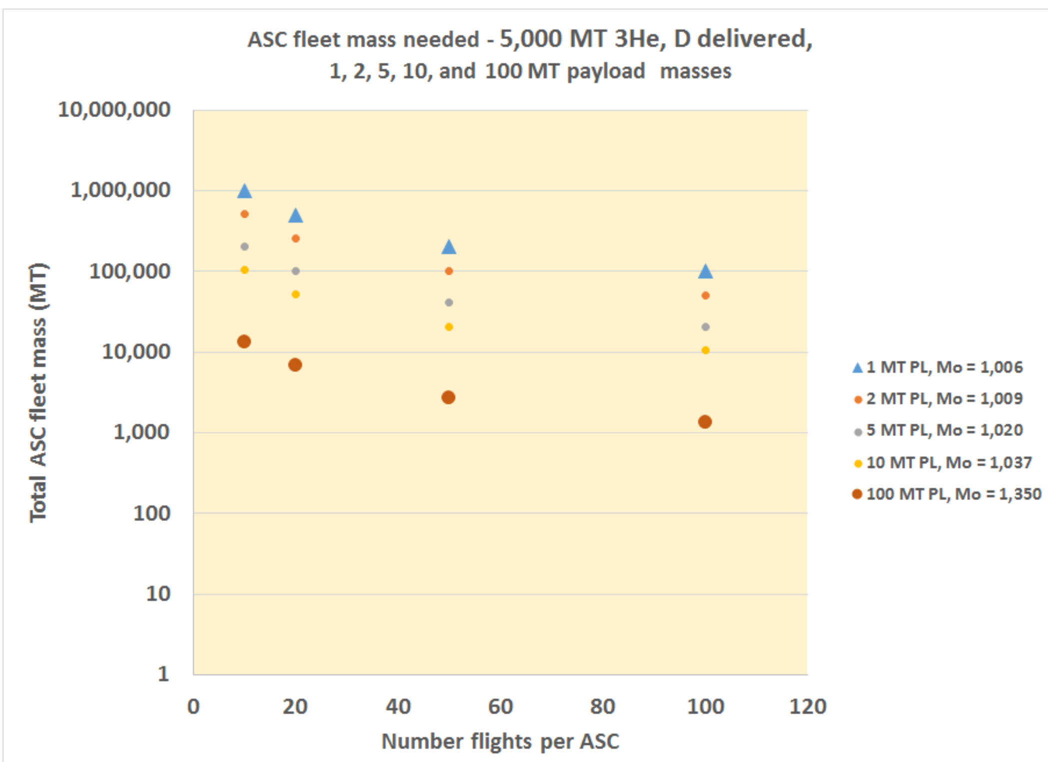


Figure 6. Aerospacecraft (ASC) fleet mass versus number of flights for ASC payloads of 1 to 100 MT

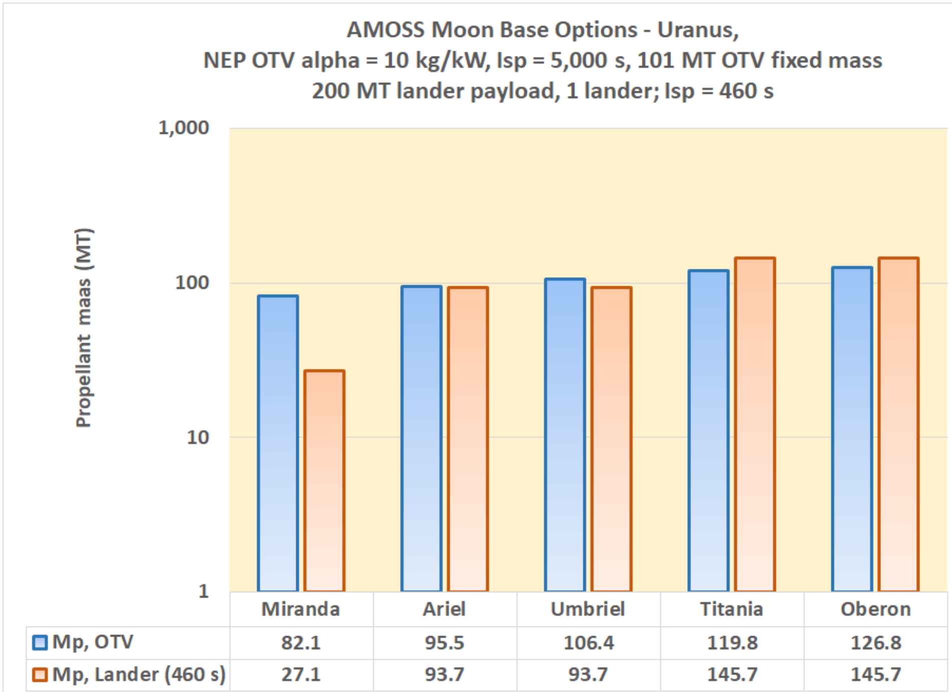


Figure 7. Propellant masses for Uranus AMOSS operations

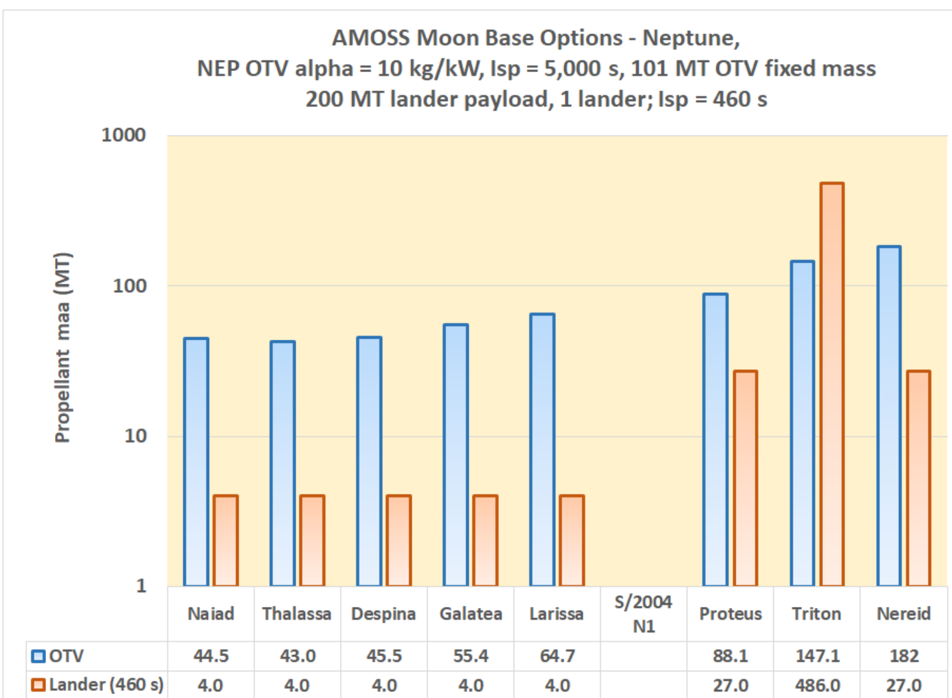


Figure 8. Propellant masses for Neptune AMOSS operations

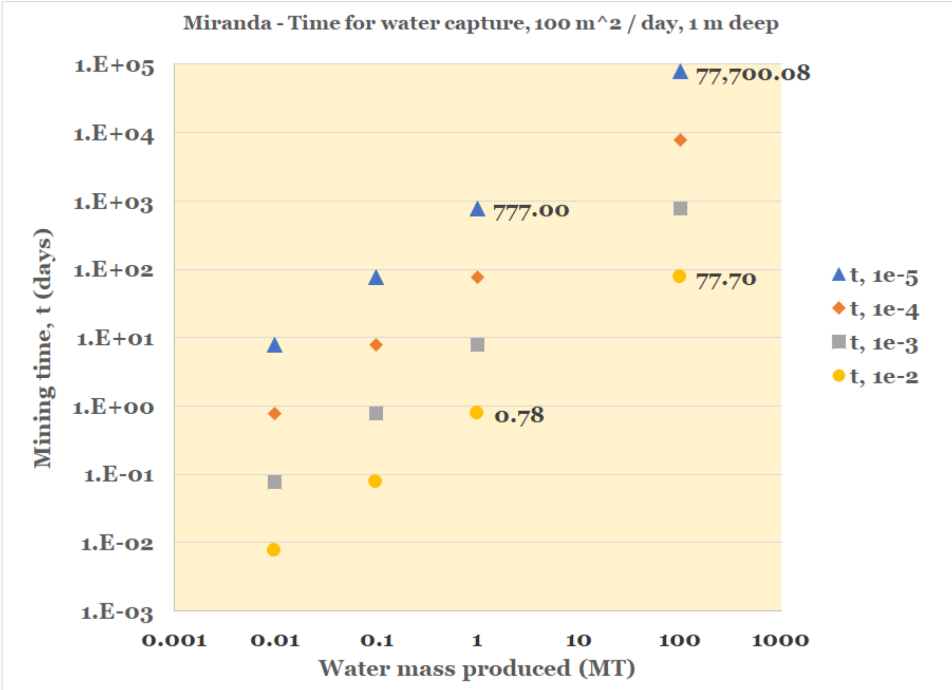


Figure 9A. Miranda water capture time at Uranus

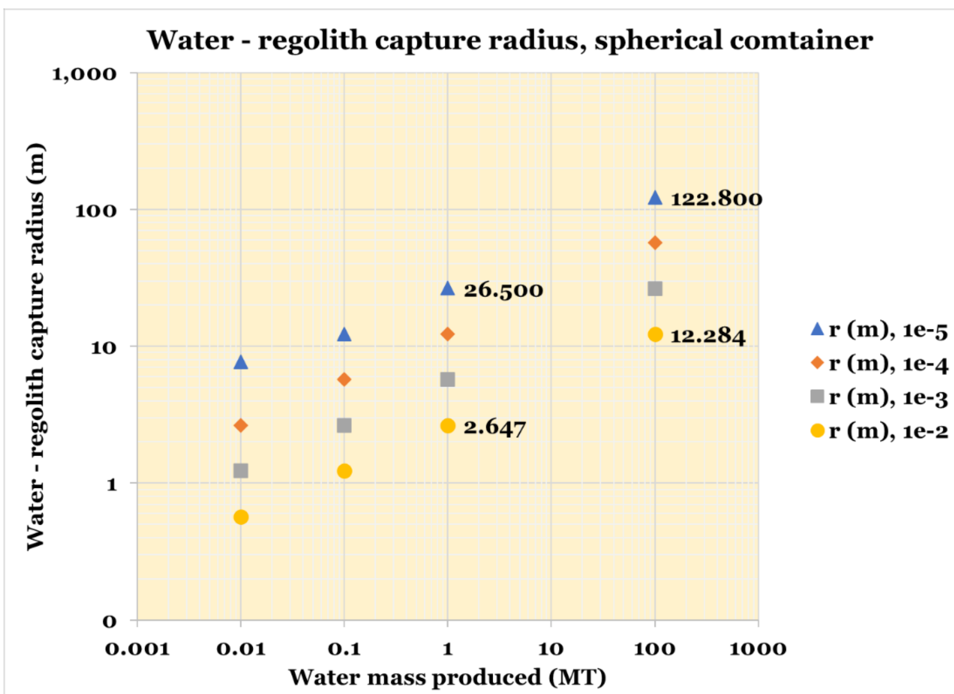


Figure 9B. Miranda water capture bag sizing at Uranus

V. Mining Architecture Implications

While the AMOSS architecture elements will be operating in Uranus' or Neptune's vicinity, additional vehicle masses will be needed to emplace them. Both Earth launch vehicles (LVs) and interplanetary transfer vehicle (ITVs) will be needed. Based on past studies of launch vehicles, a 200 MT payload to low Earth orbit (LEO) was selected (Ref. 14). Similarly, the ITV payload and initial mass were estimated based on past studies (Ref, 16). The ITV initial mass was 2,000 MT and the payload delivered to Uranus or Neptune was 200 MT.

Figure 10 depicts the number of launches needed for supporting the AMOSS architectures. In this example, 22,000 MT would be delivered to Uranus or Neptune. When completing the architecture in 10 years, nearly 120 LV flights will be required. If the architecture were to be completed in 40 years, the number of Earth launch vehicles per year can be reduced to 28. Many options to reduce the number of LV flights are possible. Larger launch vehicles with out to 1,000 MT payloads have been envisioned. Additionally, the AMOSS architecture mass may be reduced with increases in ASC, OTV and lander specific impulses.

Water ice mining on the outer planet moons will require several supporting machines on the moon itself. Analyses of the moons of Uranus have shown there is a large fraction of water ice there. Reference 1 noted the ice shell depths surrounding Uranus' moons were 100's of km. At Miranda, the ice shell was predicted to be 134 km. . While the precise architecture is open to further analyses, the number of machines needed can be estimated. In this analysis, a machine may be a miner, hauler, or hopper to transfer the water ice to a refinery for purification. Figure 11 provides the number of machines that may be needed for mining 100 MT of water. The machine payload was varied from 0.1 to 100 MT. The water fraction in the mined moon regolith material was 75%. If the machine payload were 0.1 MT, the number of machines would be 1,134. For a 10 MT payload, the number of machines is 14. Further analyses will be needed to determine the precise number of machines needed.

Figures 12 and 13 depict the number of machines needed for several cases. In Figure 12, 4 cases are presented: water fractions of 0.99, 0.75, 0.05 and 0.01. Again the total mass of mined water is 100 MT. The machine payload is 10 MT. For the 0.99 and 0.75 water fraction cases, the number of machines is between 11 and 14. With the 0.05 water fraction case, 201 machines are required. Reducing the complexity of the mining architecture will always be important; thus, the mining machine number will need to be low, and the water fraction should be high. Once prospecting has been conducted on the outer planet moon, the best locations for mining with high water fractions will be identified. On the moon of Uranus, the water ice fraction analyses are very promising for reducing many aspects of the mining operational complexity.

In Figure 13, the number of machines for a broad range of water fractions is estimated. For water fractions of 0.8 and above, the number of machines is less than 13. For water mass fractions less than 0.2, the number of machines begins to exceed 50. At Miranda and the other moons of Uranus, the estimated water fractions are high (Ref. 1); again, it is desirable to find areas of high water fractions, and any moon mining locations will be assessed before beginning any extensive operations.

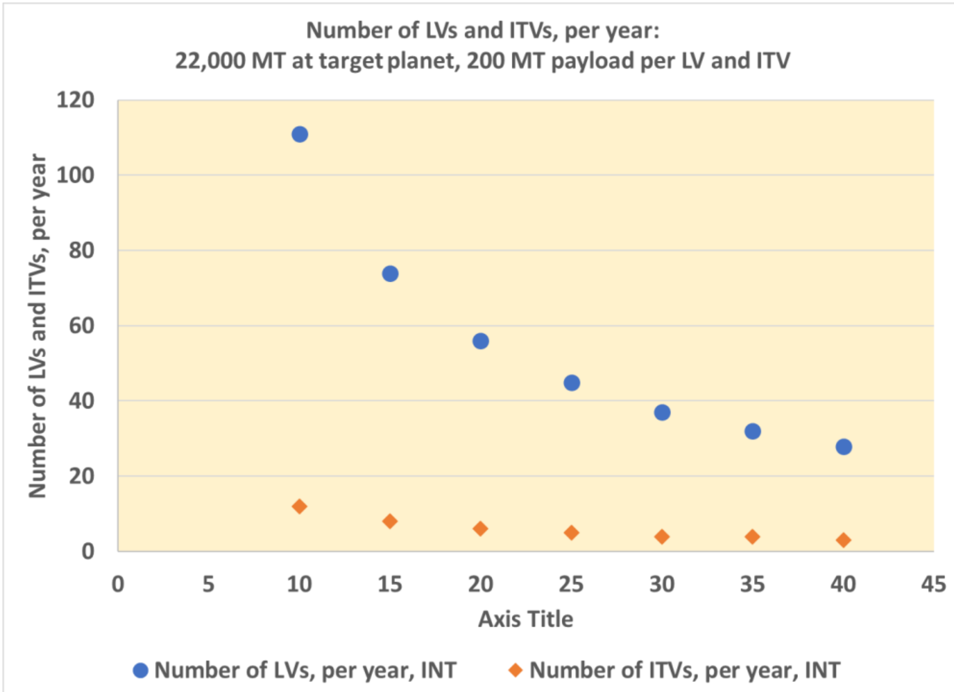


Figure 10. Number of launch vehicles and interplanetary transfer vehicles needed per year for AMOSS deployment

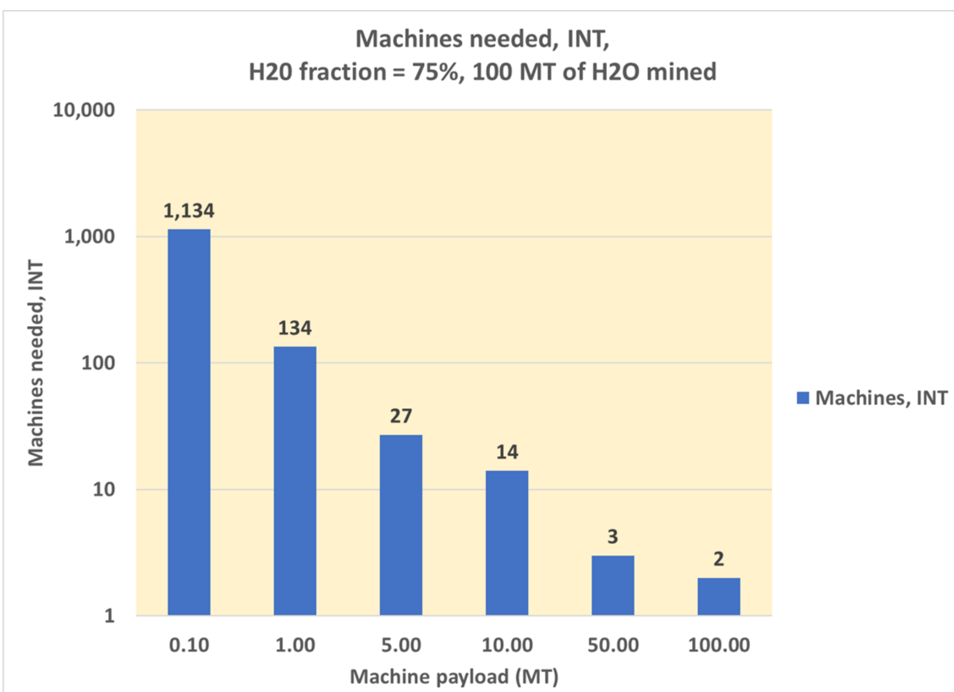


Figure 11. Machines needed versus machine payload mass

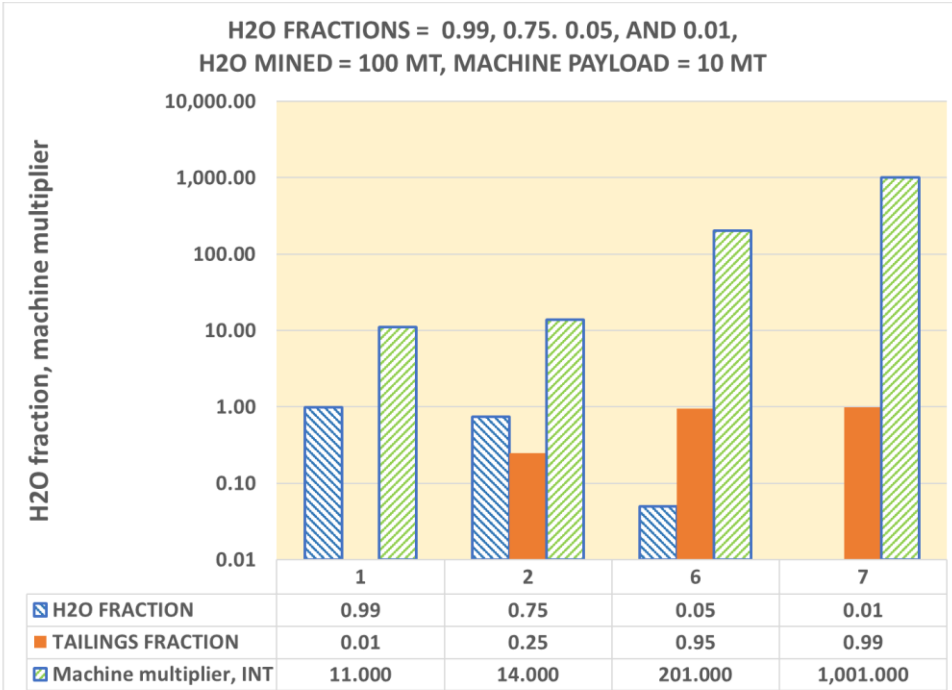


Figure 12. Water fraction, tailing fraction and machine multiplier: for water fractions of 0.99, 0.75, 0.05. and 0.01

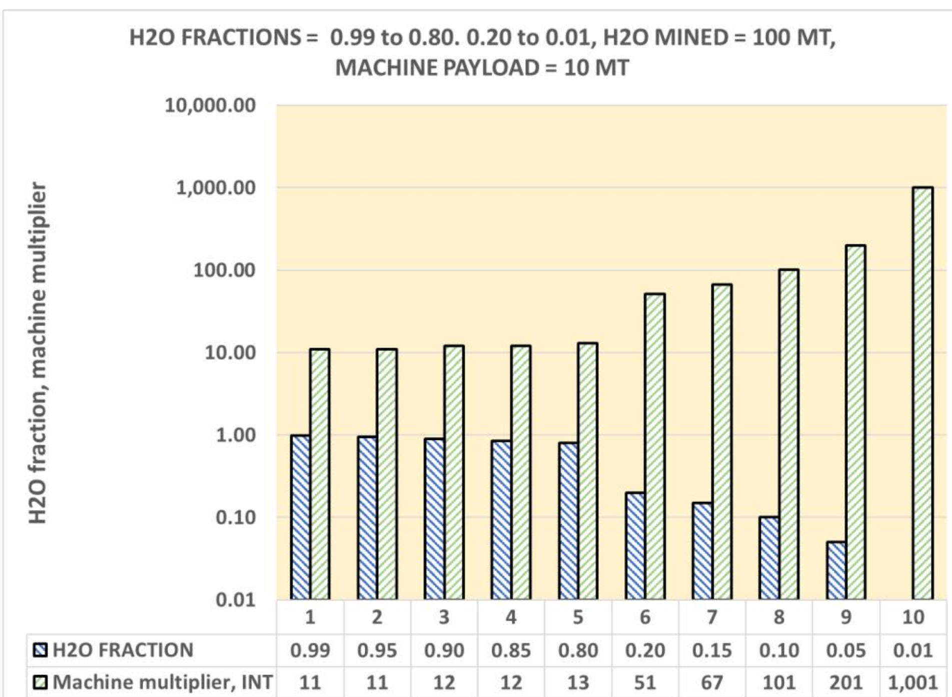


Figure 13. Water fraction and machine multiplier: for multiple water fractions

VI. Concluding Remarks

Atmospheric mining in the outer solar system has many significant benefits. The use of ISRU in the outer solar system will entail wresting nuclear fuels from Uranus and or Neptune. Using outer planet moon bases for mining the propellants for OTVs and landers is an important option. Storing the AMOSS nuclear fuels away from the atmosphere will minimize the potential for unanticipated deorbiting of the orbiting storage facility. Using the moons for storage of the nuclear fuels and base of operations for OTV refueling is an excellent option. Though the gravity of these moons is much lower than that of Earth, that gravity will assist in any processes for mining and fuel processing. The 10 MWe power levels for the OTV seems best for providing a relatively short moon-to-planet trip time. The OTVs and landers will rendezvous near the escape condition of the small moon, shortening the trip time for the OTV (eliminating the need to spiral into low moon orbit). Larger landers (of 200 MT payloads) are more attractive than small landers, as the large landers require fewer flights to resupply the OTVs with fuel. The OTV trip times may be too long for effective use of the more distant outer planet moons. Moons that are closer to the planet may be required. Generally, the smaller moon closer to the planet are more mass efficient, requiring smaller OTV and smaller landers.

Both Uranus and Neptune transportation system mass estimates are presented. Of the five major moons of Uranus, the moons closest to the planet required the lowest transportation system mass. For Uranus, Miranda has the lowest transportation system mass. The lander mass has a strong influence on the overall mass. The result is similar for the 8 major moons of Neptune. The transportation system for Thalassa has the lowest overall mass of the 8 Neptune moon destinations. Thalassa is the moon with the lowest gravity, allowing the lander to be much smaller than any of the 4 cases. Therefore, increasing the lander Isp or using a moon with reduced gravity has a powerful effect on the overall mass. Reducing the NEP OTV reactor mass also has a strong influence on reducing the overall transportation system mass.

The transportation masses for all of the major moons of Uranus and Neptune were investigated. At both Uranus and Neptune, the smaller moons near the planet had the lowest transportation masses. While this is an important result, it is also critically important to address the need for additional gravity for processing of fuels and propellants. Centrifuges (or other equally effective technologies) to separate the water ice and rocky feed stocks from the outer planet moon's surface will likely be needed. The low gravity of the outer planet moons will not be sufficient to process the ISRU related materials and allow efficient production of OTV and lander propellants. All of the outer planet moons have such low gravity levels that some added artificial gravity to assist the ISRU processes will be very important for the overall architecture's success.

The overall architecture masses were estimated for a range of replacement schedules. The delivery schedules included a 6 to 7 year replacement schedule and addressed the major architecture components: the atmospheric mining ASCs, the OTVs, the landers, and the in-space factories. The use of artificial gravity space bases or centrifuges on the moon bases will very likely be required. The masses of the robotic in-space bases with artificial gravity were in the range of 143 to 461 MT. These added space base masses do not significantly increase the overall architecture masses, and they truly make the architecture more viable than one without artificial gravity.

The mining issues will be critical to making the mining architecture successful. Capturing the regolith-water ice mix and separating the water ice from the regolith are major challenges. Purification of the water ice and the resulting oxygen and hydrogen propellants will be a serious consideration.

The number of launch vehicle flights needed to support the AMOSS architectures can be reduced extending the length of the deployment. In a 10 year scenario, nearly 120 launch vehicles per year are required. By extending the deployment time to 40 years, the launches per year are less than 30.

Numerous machines will likely be needed for the mining of water ice. There will likely be machines for miing, hauling, and hoppers to transfer the water ice to a factory for purification and separation into oxygen and hydrogen. For a 100 MT water mining operation, if the water fraction is 75%, using a 10 MT payload machine, approximately 14 machines will be needed. Based on past analyses, the water ice fraction on the moons of Uranus should be very high, making mining more efficient.

Further optimizations and creative usage of propulsion technologies will likely lead to great improvements in the transportation systems and reduce its cost and mass. The exploration of the outer planets and their ultimate use in powering future fusion powered space vehicles will allow unlimited options for solar system exploration, and ultimately, flight to the stars.

Appendix: Lander and OTV delta-V values

Tables A-I and A-II provide the delta-V needed for these round trips from the outer planet moon's surface to escape velocity for the moons of Uranus and Neptune, respectively. The landers depart the moon's surface to meet the OTV, transfer its propellant cargo, and then return to the surface for another flight. The delta-V values were computed with standard orbital mechanics equations. At Miranda, the round trip escape delta-V was 0.5 km/s for the lander mission. The delta-V included the escape velocity from the moon, for each leg of the round trip, and a 20% additional delta-V for gravity losses. For Titania, the moon's escape velocity is approximately 0.95 km/s (including gravity losses, uncertainties, etc.). The round trip delta-V was therefore 1.9 km/s. Each lander delta-V is assigned a sizing category. The category represents that highest delta-V in the range of delta-V values for the landers. For example, in the Uranus sizing category b, the landers for Ariel and Umbriel will be sized for the largest of the 2 delta-V values.

Tables A-III and A-IV list the round trip delta-V values for travel from Uranus to its moons and from Neptune to its moons, respectively. The delta-V values were computed with standard orbital mechanics equations. For Titania, the low-thrust round trip orbital delta-V would be 22.4 km/s, which includes the required plane change of 0.14 degrees. The lander that would rendezvous with an OTV would deliver 1.9 km/s (for the round trip flight). Thus, the rendezvous could occur near the escape conditions for the moon or at the lower orbital altitude. The OTV is sized to deliver 22.4 km/s (equal to a round trip flight to Titania from low Uranus orbit). For Neptune, the moons Thalassa and Triton were investigated. Thalassa required a round trip OTV delta-V of 9.4 km/s. The round trip lander delta-V was 80 m/s. For Triton, the round trip OTV mission required a delta-V of 26.2 km/s, and the round trip lander delta-V was 3.5 km/s.

Table A-I. Uranus Moon Lander delta-V Values

Moon	Round-trip delta-V (km/s)	delta-V Capability (km/s)	Sizing Category
Miranda (UV)	0.44	0.5	a
Ariel (UI)	1.34	1.4	b
Umbriel (UII)	1.24	1.3	b
Titania (UIII)	1.85	1.9	c
Oberon (UIV)	1.74	1.8	c

Table A-II. Neptune Moon Lander delta-V Values

Moon	Round-trip delta-V (km/s)	delta-V Capability (km/s)	Sizing Category
Naiad (NIII)	0.06	0.06	a
Thalassa (NIV)	0.08	0.08	a
Despina (NV)	0.13	0.14	b
Galatea (NVI)	0.17	0.18	b
Larissa (NVII)	0.19	0.19	b
S/2004 N1			
Proteus (NVIII)	0.44	0.50	c
Triton	3.49	3.50	d
Nereid	0.37	0.40	c

Table A-III. Uranus to Moon Orbital Transfer delta-V Values

	Planet to moon orbital transfer, low thrust delta-V		
	delta-V (km/s), 1 way	delta-V (km/s), 2 way	delta-V capability (km/s)
Miranda (UV)	8.216	16.432	16.5
Ariel (UI)	9.320	18.640	18.7
Umbriel (UII)	10.162	20.324	20.4
Titania (UIII)	11.180	22.360	22.4
Oberon (UIV)	11.675	23.350	23.4

Table A-IV. Neptune to Moon Orbital Transfer delta-V Values

	Planet to moon orbital transfer, low thrust delta-V		
	delta-V (km/s), 1 way	delta-V (km/s), 2 way	delta-V capability (km/s)
Naiad (NIII)	4.808	9.616	9.7
Thalassa (NIV)	4.675	9.350	9.4
Despina (NV)	4.950	9.900	9.9
Galatea (NVI)	5.860	11.720	11.8
Larissa (NVII)	6.720	13.440	13.5
S/2004 N1	too small		
Proteus (NVIII)	8.736	17.472	17.5
Triton	13.072	26.144	26.2
Nereid	15.269	30.538	30.6

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