

Assessing Propulsion and Transportation Issues with Mars' Moons

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Abstract

This chapter is focused on transportation issues with Mars' moons: Phobos and Deimos. The moons are small non-spherical bodies that may offer unique specimens for science, a gateway to understanding the asteroid belt, and resource platforms for space industries. The mission delta-V and both chemical propulsion and nuclear electric propulsion orbital transfer vehicles are analyzed. Using nuclear electric propulsion allows very large reductions on the resupply propellant mass over chemical propulsion options. Large delta-V plane changes are also more efficient using electric propulsion. The benefits of electric propulsion are unique, and the vehicle power system can support high power radar science experiments.

Keywords: in situ resource utilization, ISRU, moon base, rocket propulsion, systems analysis, specific impulse, chemical propulsion, nuclear propulsion, electric propulsion

1. Introduction

Mars is the 4th planet from the Sun. Its environment includes a 95% carbon dioxide atmosphere with a very low pressure (5 to 7 millibar), and essentially no magnetosphere, though there are remnants of the magnetic fields in small area of the planet. Exploration programs for Mars have included robotic and human surface visits and human bases. Mars has 2 moons: Phobos and Deimos. The moons are small and akin to asteroids. They can be a great source of materials for exploration and exploitation.

The martian moons are tantalizing objects for scientific investigation. The moons also present a unique set of challenges. Their surface gravity is very low: 8.7×10^{-4} for Phobos and 6.2×10^{-4} Earth gravities (g) for Deimos, as shown in Table 1 [1, 2, 3]. The gravity levels are computed based on an average diameter, as the moons are non-spherical. Based on their shape and features, both moons may be captured asteroids. Science measurements of the moon's structure may lead to a better understanding of the diversity of asteroids in our solar system. Based on spectral analyses, both moons may contain carbonaceous chondrites, other metals, and water. Such materials can be the resources to propel fledgling in-situ resource utilization (ISRU) industries.

Phobos has a giant crater, Stickney, which is 9 km in, a large fraction of the moon's diameter. Deep grooves cover the tiny moon [3]. The crater dynamics have fascinated geologists and planetary impact modelers alike. Photos of the moons are shown in Appendix A.

Any scientific investigations will likely include radar studies to determine the moons' internal structures and surface sampling. Small robotic landers will likely be precursors to human landings. As the moon does not have a uniform shape, the gravity level on different surface locations will vary.

The martian moon overall characteristics and surface gravity is presented in Table 1. The gravity level is computed using the smallest dimension of each moon. Previous missions have sought to rendezvous, orbit, or fly by the moons. As with some comets (67P [4, 5]), the orbital mechanics may necessitate a propulsive station keeping above the moons. The moons' low gravity levels have led research on anchoring technologies for landing vehicles [6-11].

While the moons potentially have water resources, the complexity of extracting the water may be daunting. The low moon gravity will necessitate the use of unique capturing technologies. The low gravity will allow regolith to be liberated and potentially create a dangerous or at least a complicated dust environment. Large boulders may be a more controllable source for regolith processing. The gravity levels of outer planet moon (Naiad) of Neptune are similar to those of Phobos and Deimos. Outer planet moon analyses [12] have suggested using an artificial gravity space base for high value ISRU materials processing. Such a factory might reside near the moon or be anchored to its surface. The regolith might be fed into the factory and the artificial gravity system with the appropriate thermal energy would assist in separating the water resources from the dust and rock. Investigating several mining methods for extremely low gravity moons will be essential for any successful ISRU architecture.

2. Mission design and options

Phobos and Deimos exploration methods has been studied for many decades: landers, flybys, etc. [6-11]. While landers have been assessed in the past, this chapter will focus on the orbital transfer delta-V requirements and orbital transfer vehicle designs that would allow the 2 moons' exploration and exploitation.

Three general missions were assessed: flights from the moon's orbit to Mars orbit (LMO), flights between the two moons, and flights from the moon's orbit to a very high Mars orbit (100,000 km altitude). A fourth mission delta-V, for transfer to the areosynchronous Mars orbit, was also computed.

Additional delta-V calculations for missions to high inclination orbits were also investigated. The high inclinations may be attractive for polar monitoring or specialized payloads for surface observations, atmospheric studies, and interplanetary communications or power satellites.

Both high-thrust missions and low-thrust missions were assessed. The high-thrust delta-V values were computed with a standard Hohmann transfer equations [13]. The values for the low-thrust delta-V were calculated using the Edelbaum equation (Ref. 14). The nominal semi major axes for Phobos and Deimos are 9,378 and 22,459 km [2].

Figures 1 and 2 depict the round-trip delta-V for Phobos and Deimos missions, respectively. Both high thrust and low thrust delta-V values are presented. Due to the typical gravity losses with high thrust propulsion systems, a 20% delta-V increase is added; no added losses were imposed on the low thrust systems. In Figure 1, the highest value is the Phobos to 100,000 km delta-V 2.99 km/s. The Phobos to low Mars orbit (LMO) delta-V was 2.74 km/s.

The LMO altitude is 100 km. At Deimos, the highest round-trip delta-V is for the Deimos to LMO transfer: 4.3 km/s. The transfer to 100,000 km requires only 1.42 km/s.

Figure 3 shows the high thrust plane change delta-V values to reach high inclinations while performing the plane changes at the orbital altitudes of Phobos and Deimos. In Figure 4, the high thrust and low thrust delta-V for the inclination change being performed the high altitude of 100,000 km is presented. The two-way delta-V for the Phobos or Deimos orbital transfer to 100,000 km would have to be added to the values in Figure 4. These 2 cases are presented, in that if the very high inclination changes are performed at high altitude, the total mission's delta-V is reduced over the low-altitude inclination changes.

3. Propulsion options

High thrust chemical propulsion, using oxygen/hydrogen rocket engines is a natural choice [12]. If indeed water were available on the martian moons, it would make sense to capitalize on that water resource.

Electric propulsion systems with either ion or Hall thrusters or pulsed inductive thrusters are potential options. Xenon or other inert gases are the typical choice for such thrusters. Using hydrogen as an electric propulsion propellant has also been proposed [12]. However, the hydrogen propellant option is a far term prospect [12].

Mass scaling equations were developed for the O₂/H₂ and the nuclear electric propulsion systems [12].

3.1 Advanced propulsion options

Several advanced propulsion options for lunar base construction and industrialization were investigated. They include nuclear electric propulsion options, lunar base design options, propellant industrialization, and outer planet mining with associated outer planet moon bases. Chemical propulsion and nuclear electric propulsion (NEP) for Earth-Moon orbital transfer vehicles (OTVs) were assessed. Design parameters, vehicle mass scaling equations, and summaries of these analyses are presented

3.1.1 Chemical propulsion OTV sizing

In sizing the chemical propulsion OTVs, a vehicle mass scaling equation is used [12]:

$$m_{dry,stage} = m_{dry,coefficient} * m_p + a_{fixed}$$

where.

$m_{dry,stage}$ = the stage dry mass, including residual propellant (kg).

$m_{dry,coefficient}$ = the B mass coefficient (kg of tank mass/kg of usable propellant mass).

M_p = usable propellant mass (kg).

a, fixed = chemical OTV fixed mass (kg)

The chemical propulsion OTVs had a B coefficient of 0.4. The fixed mass was 500 kg. The fixed mass includes guidance systems, adapters and reaction control system masses. The martian moon OTVs were single-stage vehicles.

3.1.2 NEP OTV sizing

The NEP OTV mass and trip time were estimated based on the power system and the propulsion system design [11]. The following dry mass scaling equation was used [11]:

$$m, dry, stage, NEP = \alpha * P + 0.05 m, p + m, fixed$$

where-

m, dry, stage, NEP = NEP dry mass (kg)

alpha = NEP reactor specific mass (kg/kWe)

P = NEP power level (kWe)

0.05 = tankage mass coefficient (kg / kg m, p)

m, p = NEP usable propellant mass (kg)

m, fixed = NEP fixed mass (kg)

The OTV sizing was conducted for a wide range of power levels: 0.5 MWe to 30 MWe. Three nuclear reactor specific masses were used: 10, 20, and 40 kg/kWe (kilograms per kilowatt, electric). The OTV propulsion fixed mass, apart from and in addition to the reactor mass, was 20 MT, and the propellant tankage mass was 5% of the mass of the required propellant.

The Isp and efficiency of the electric propulsion systems were 5,000 seconds with overall thruster-propulsion efficiencies of 50% for each design. These design points are typical of advanced designs of either magnetoplasmadynamic (MPD) or pulse inductive thrusters (PIT). While hydrogen is suggested for both propulsion system thrusters, the possibilities of the higher Isp option using inert gases (xenon, krypton, etc.) are also viable. The low thrust OTV delta-V value varied based on the destination of the martian moon missions.

4. Mission effectiveness

4.1 Phobos and Deimos payload missions

Figures 5 and 6 depict the Phobos and Deimos O₂/H₂ propulsion system initial masses. For the 50 MT payload case for Phobos, the OTV initial mass is 141 MT. Nearly the same OTV mass

is needed to perform the Phobos to LMO and Phobos to 100,000 km. For Deimos, the highest OTV mass is 256 MT.

The payload mass cases presented range from 1, 10, 20 and 50 MT. If the payload mass is less than 10 MT, the O₂/H₂ OTV mass is very small. If small 1 MT payloads must be sent quickly from one orbit to another, the O₂/H₂ OTV is an excellent choice; the propellant mass of the chemical propulsion system is very low compared to the NEP propellant mass. Alternatively, if five 10 MT payloads can be manifested together, the NEP OTV has a significant propellant mass advantage over the O₂/H₂ OTV.

Figures 7, 8, and 9 present the round trip mission trip times for the NEP vehicles for 1, 10 and 50 MT respectively. The NEP trip times are many days long: for a 5 MWe NEP OTV with a 50 MT payload, the trip time for Phobos to LMO is 55 days, whereas the chemical propulsion trip times are less than 1 day. However, the benefits of reduced NEP propellant resupply mass are quite significant.

With NEP OTVs, the 10 MWe power levels provide the shortest trip time, however, if the payload can be delivered more slowly, the 1 MWe power level allows a very large propellant mass savings over the higher 10 MWe power level. The NEP propellant mass savings for large payloads are a critical part of any sustainable architecture. The propellant mass savings are noted in the succeeding sections.

Fast transfers of critical items under 1 MT are best accomplished with O₂/H₂ OTV propulsion. There may be a critical need for the delivery of medical supplies; also, the delivery of space parts or a repair crew may be needed. The O₂/H₂ OTV would be best suited for these small 1 MT payloads.

Figures 10 through 13 compared the propellant masses for the O₂/H₂ system with several NEP systems. For the NEP cases, power levels of 0.5 to 10 MWe are shown. Figures 10 and 11 present the Phobos and Deimos cases for 10 MT payloads and the 50 MT payload cases are shown in Figure 12 and 13. In Figure 10, for a 10 MT payload, the Phobos to LMO NEP cases will allow large propellant savings over the O₂/H₂ OTV for NEP OTV power levels of less than 5 MWe. In the Deimos case, shown in Figure 11, the NEP OTV provides significant propellant mass savings over O₂/H₂ with power levels up to 10 MWe. The Figure 12 data for Phobos to LMO with a 50 MT payload shows very large NEP propellant mass reductions over O₂/H₂ for the 10 MWe power level; for a 5 MWe power level, the propellant mass reduction was from 57 to 10 MT. Similarly, in Figure 13, the Deimos to LMO cases show very significant propellant mass benefits, reducing the propellant needed by a factor of 6 to 10 or more over O₂/H₂. In nearly all cases, the NEP systems allow large propellant mass reductions. For large mission architectures over a long-term Mars project, the mass reductions can be as high as a factor of 5 to 10 over O₂/H₂ systems.

4.2 Mars lander options

Past studies of Mars landers have included an innovative single stage to orbit (SSTO) design [15]. The Mars Base Camp mission suggested an aerospacecraft that would carry an astronaut crew to the surface of Mars and return to orbit, all with a single stage. The Mars sortie vehicle would be refueled with oxygen and hydrogen propellants created from in-situ water resources from the Martian moons. A water electrolysis factory would be delivered to one of the moons and the water would be wrested from the moon's regolith.

In Reference 15, the Mars sortie vehicle was designed to use 80 MT of O₂/H₂ propellant. The initial mass would be approximately 108 MT.

Figure 14 presents the initial mass and propellant mass for a Mars sortie vehicle. The dry mass fraction, B, is varied from 0.1 to 0.25. In the Reference 15 analysis, the 80 MT propellant load would require a somewhat optimistic B fraction of less than 0.10. Using a B fraction of 0.2, the required propellant mass is nearly 200 MT. Therefore five, 40 MT ISRU water resupply flights would be required to support any Mars sortie vehicles.

Using electric propulsion for the resupply flights would enhance the overall architecture, by significantly reducing the total propellant mass needed for the sortie vehicle refueling. Five NEP resupply flights from Phobos would require 50 MT, whereas nearly 300 MT (approximately 6 times the mass) of O₂/H₂ propellant are needed to transport that propellant to LMO. Many propellant delivery benefits are also gained at lower NEP power levels.

5. Concluding remarks

Electric propulsion offers the ability to transfer large payloads between the martian moons and in Mars orbit space over O₂/H₂ propulsion. The benefits of electric propulsion are not only in the reduction of propellant masses, but the capability of the high-power reactor system to perform unique science investigations, using radars and other high energy science instruments.

The NEP systems have a flexible design and can allow many payloads to be manifested together, reducing the overall propulsion architecture. High inclination Mars orbits can be more easily accessed with NEP OTVs with small amount of propellant (compared to the propellant for O₂/H₂ OTVs).

Mining the moons will require specialized factories and processes. The extremely low gravity on the Martian moons will be a challenge in controlling dust, anchoring the spacecraft factory and controlling processes. An artificial gravity factory will likely be needed to maintain the water and propellant processing quality.

	Body	μ (km ³ /s ²)	R (km)	G	m (kg)	a (m/s ²)	g level	
	Mars	4.28E+04	3,396.20	6.67E-17	6.42E+23	3.71E+00	3.79E-01	
	Phobos	7.07E-04	9.1	6.67E-17	1.06E+16	8.54E-03	8.72E-04	
	Deimos	1.60E-04	5.1	6.67E-17	2.40E+15	6.16E-03	6.29E-04	

Table 1. Gravity levels of Mars and its moons

	Payload flights - Phobos and Deimos		
	Access low Mars orbit (LMO)		
	Access all orbital inclinations		
	Access areosynchronous Mars orbit (AMO)		
	Deliver and recover high altitude payloads		
	Resupply factories		
	Carry ISRU propellants		
	Carry ISRU products, other than propellants		

Table 2. Mars moon's orbit payload options and delivery destination –

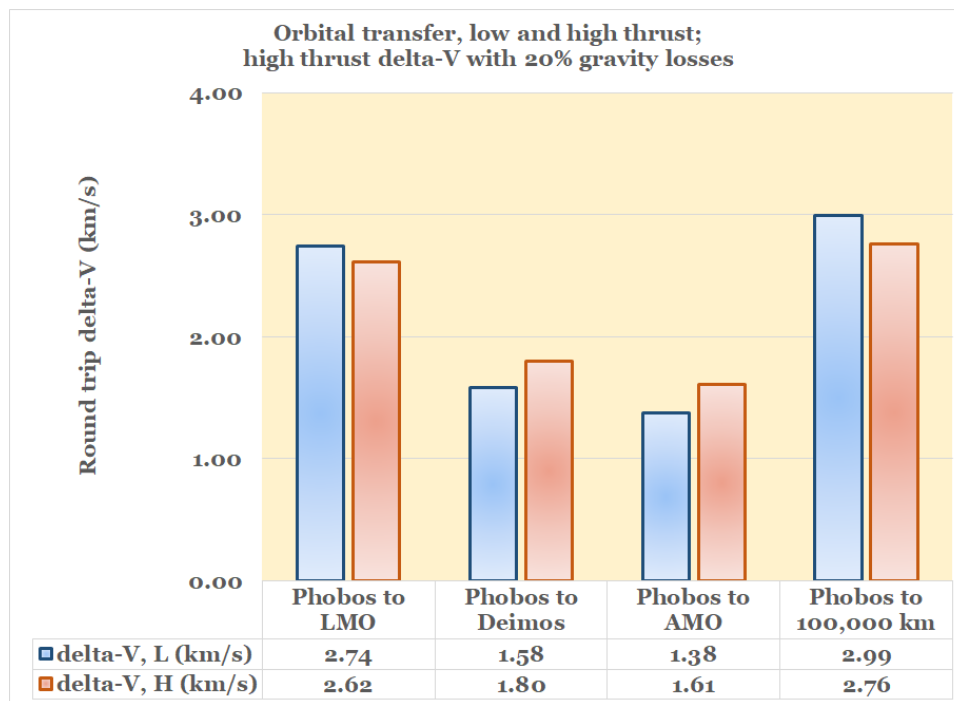


Figure 1. Mission options and delta-V – Phobos, using low thrust (blue) and high thrust (orange)

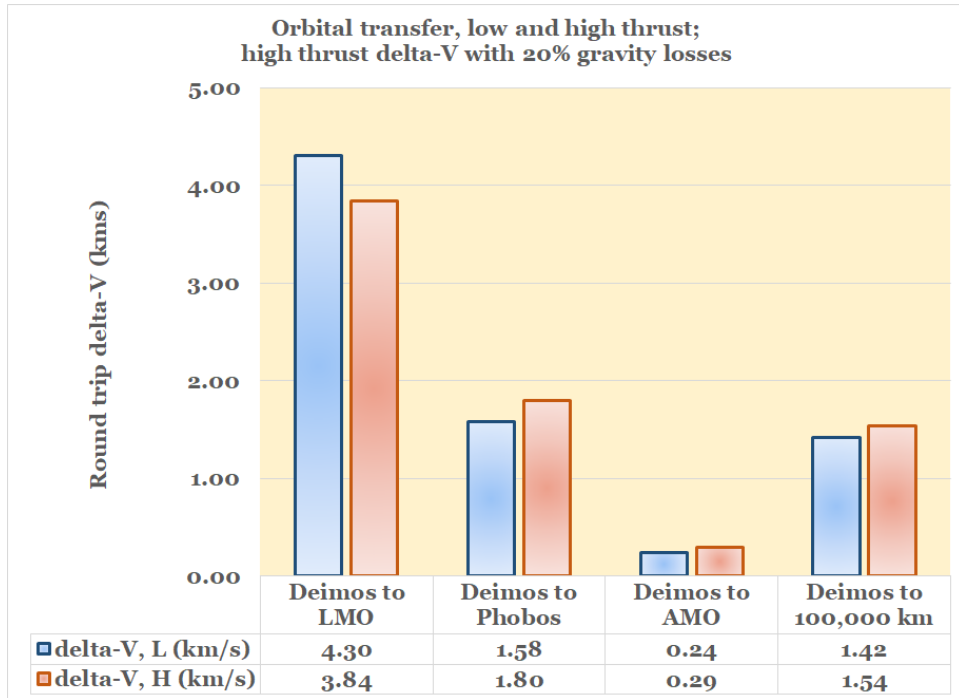


Figure 2. Mission options and delta-V – Deimos, using low thrust (blue) and high thrust (orange)

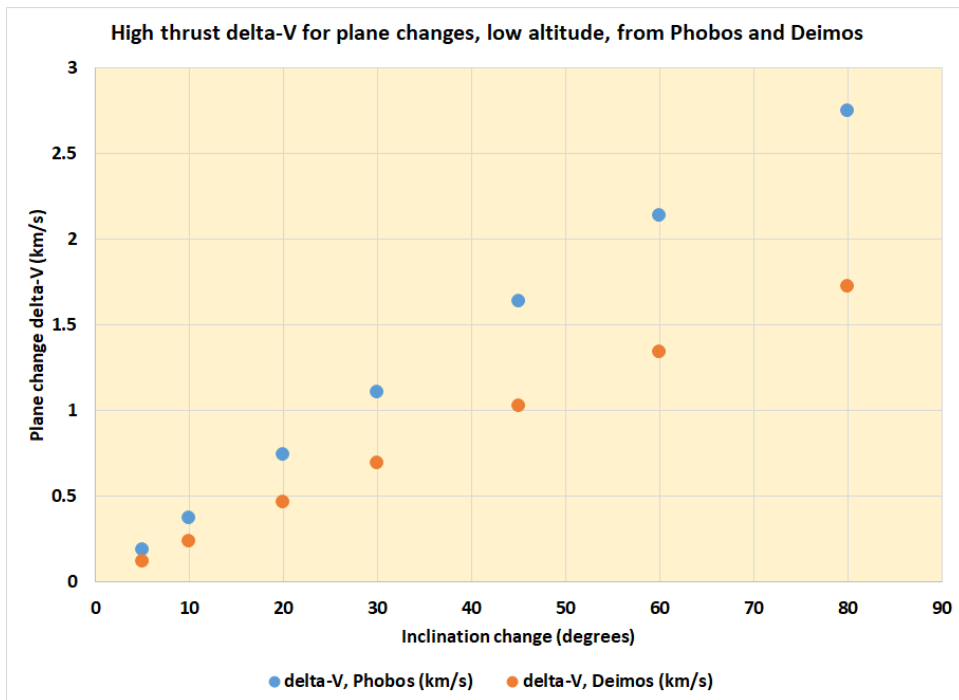


Figure 3. Orbital transfer at low altitude – Phobos and Deimos altitude

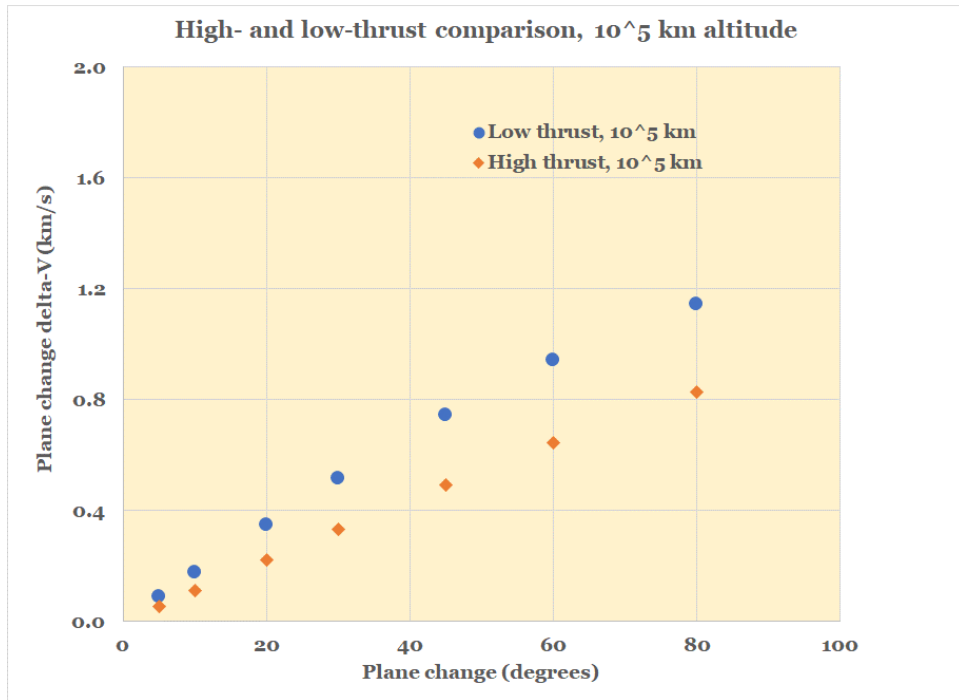


Figure 4. Orbital transfer – high altitude plane change, 100,000 km

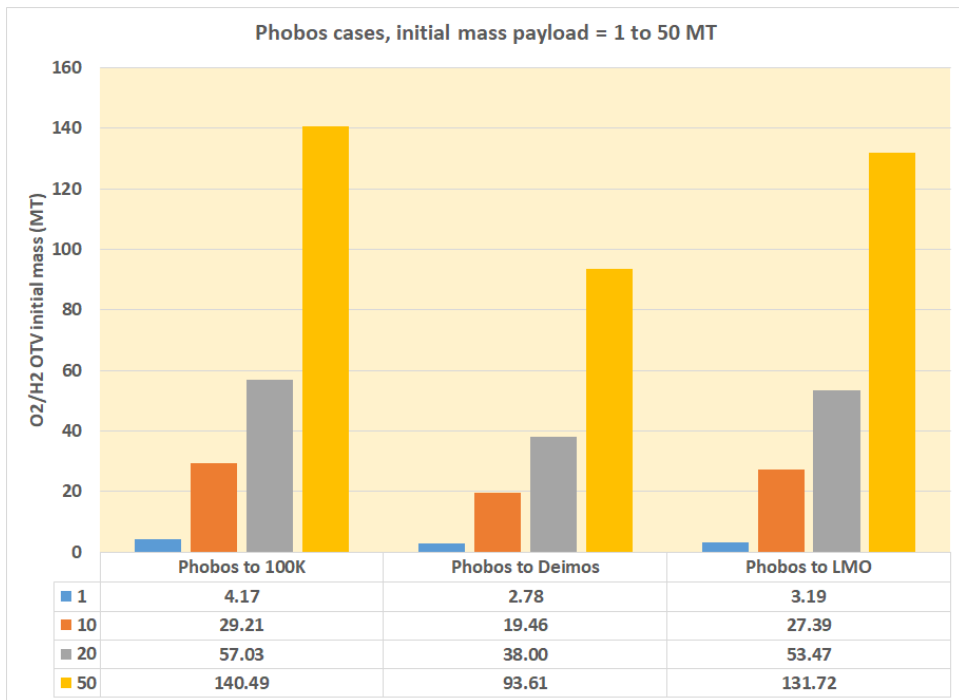


Figure 5. Phobos OTV initial masses – O₂/H₂ propulsion

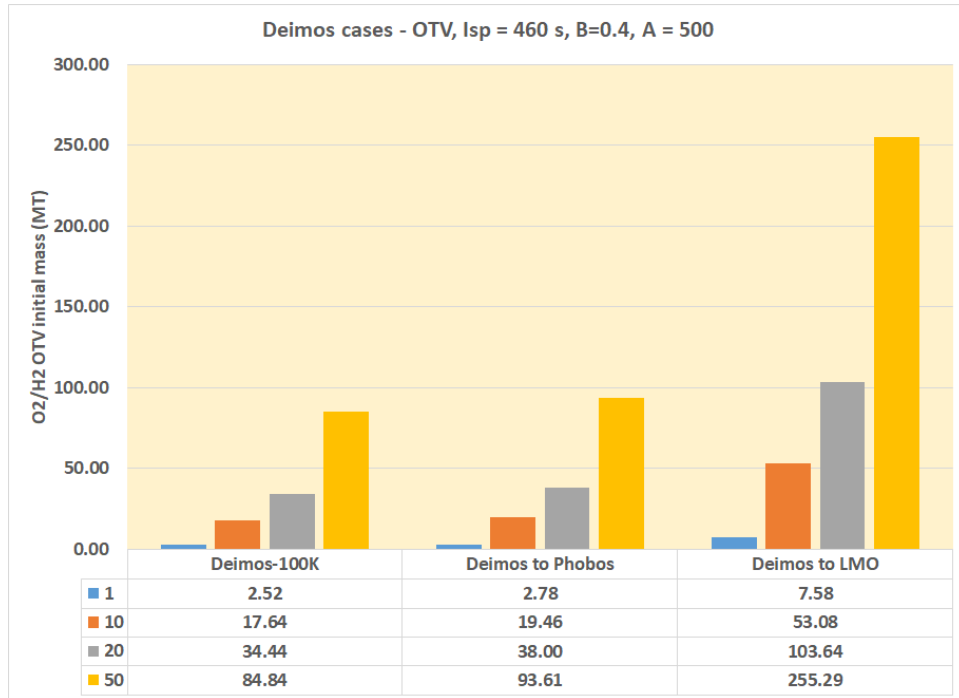


Figure 6. Deimos OTV initial masses – O₂/H₂ propulsion

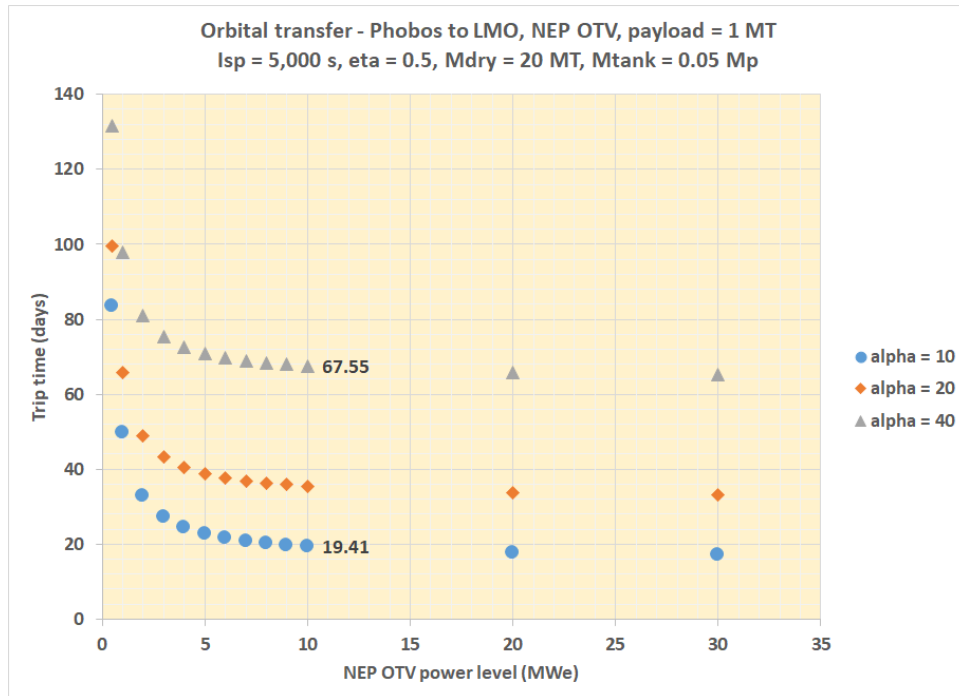


Figure 7. NEP OTV trip time, 1 MT payload: Phobos to LMO

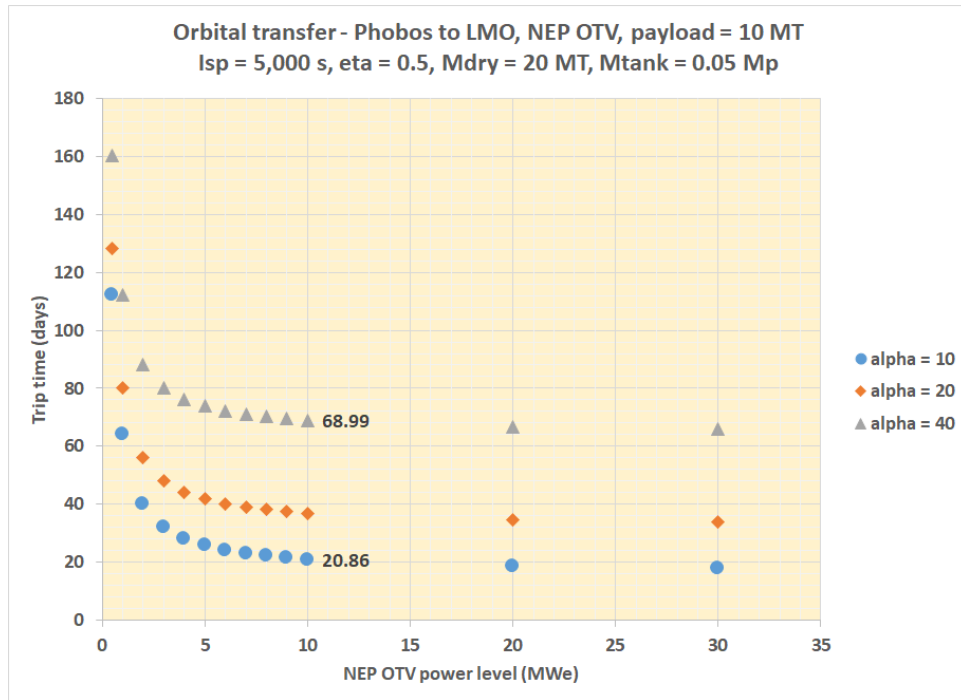


Figure 8. NEP OTV trip time, 10 MT payload: Phobos to LMO

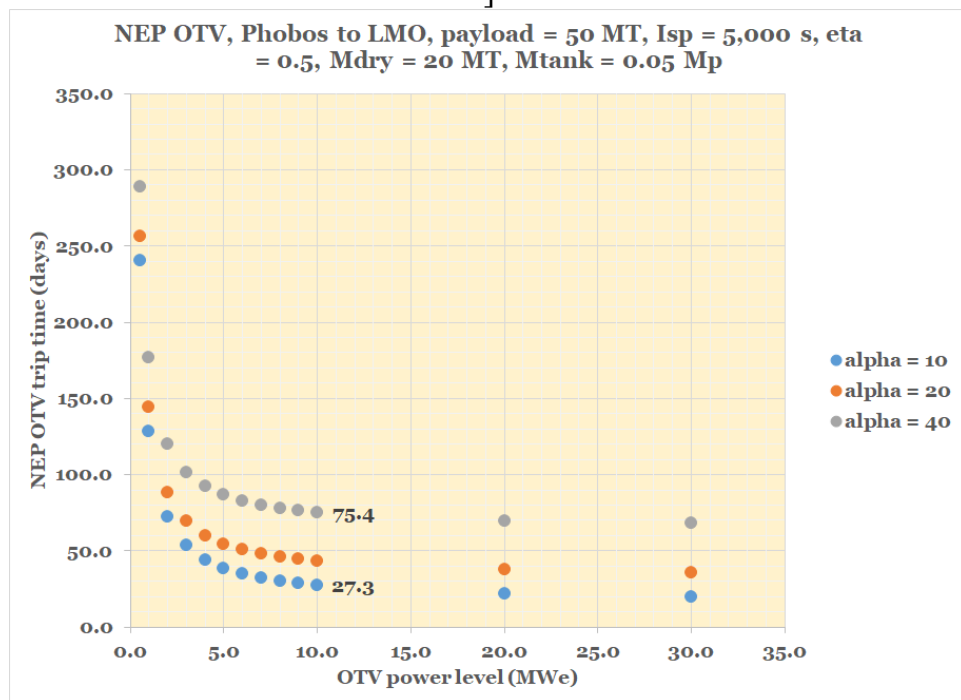


Figure 9. NEP OTV trip time, 50 MT payload: Phobos to LMO

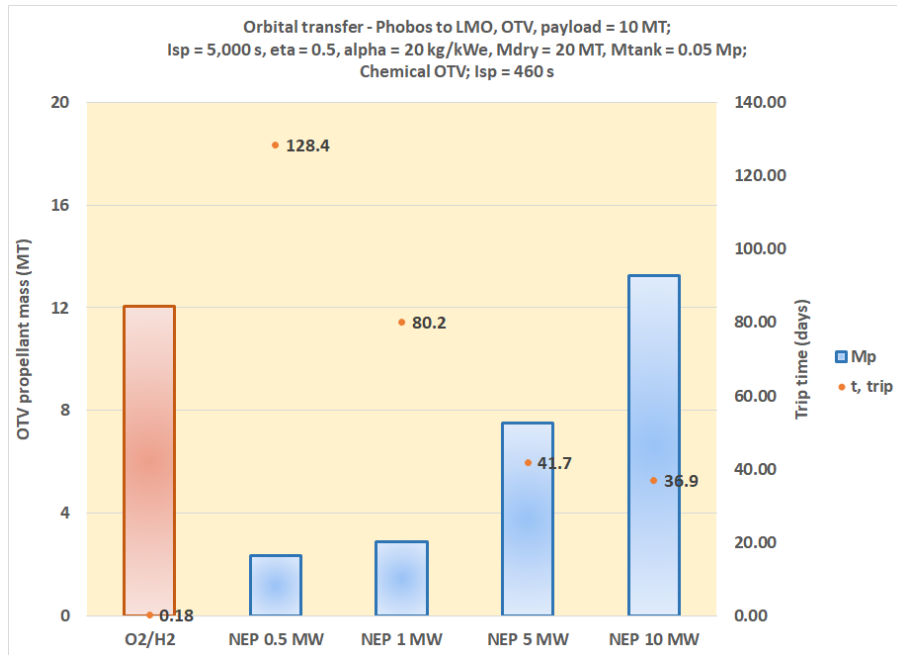


Figure 10. Resupply propellant mass and round-trip time for O₂/H₂ and Xe Ion NEP OTVs – Phobos to LMO, 10 MT payload mass

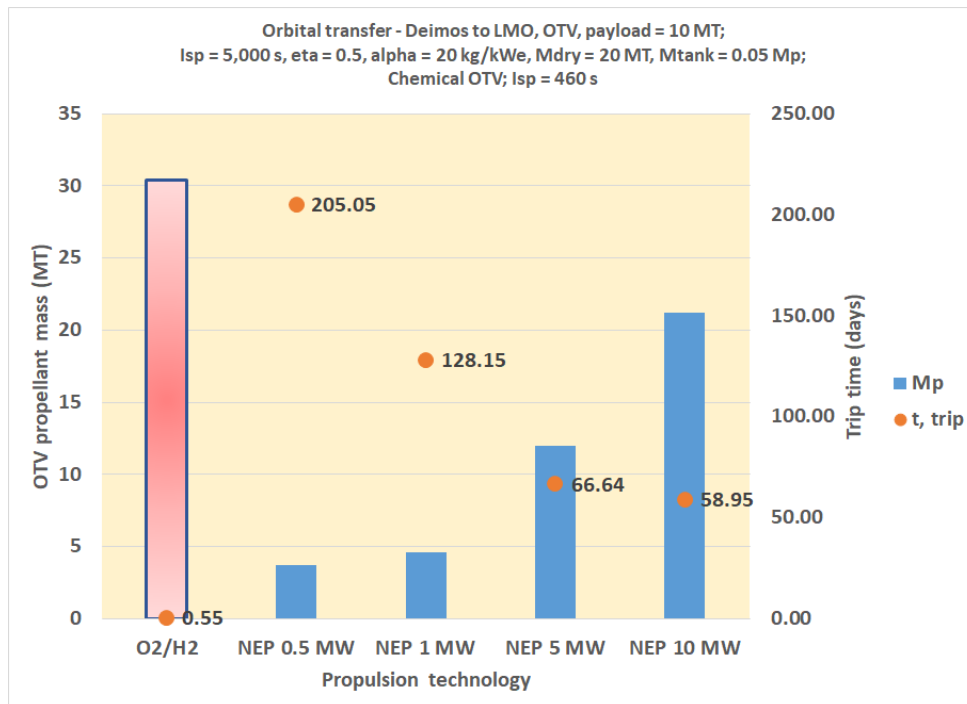


Figure 11. Resupply propellant mass and round-trip time for O₂/H₂ and Xe Ion NEP OTVs – Deimos to LMO, 10 MT payload mass

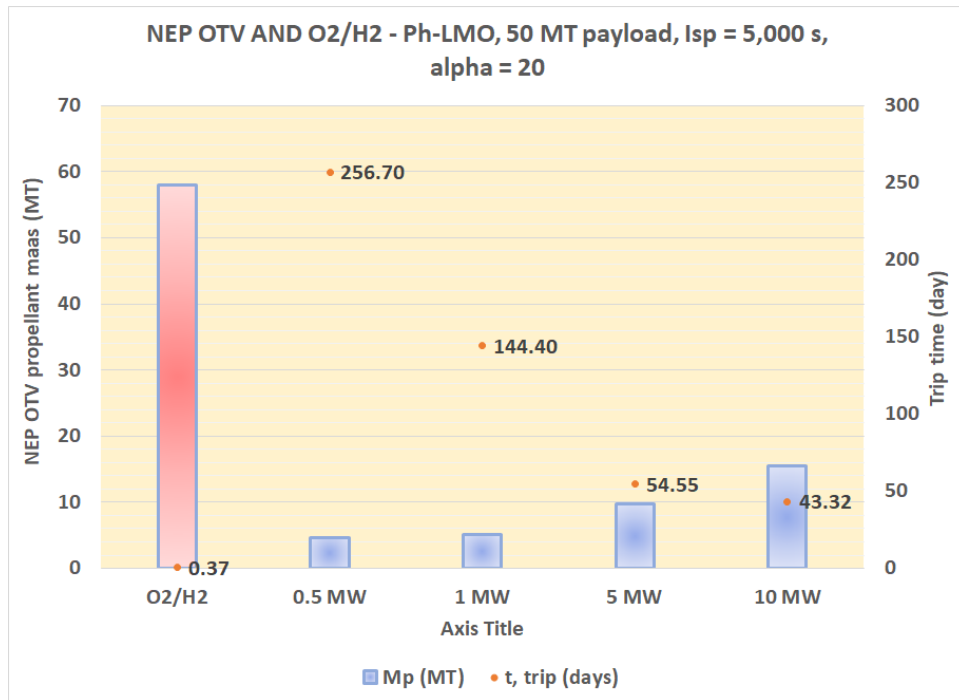


Figure 12. Resupply propellant mass and round-trip time for O₂/H₂ and Xe Ion NEP OTVs – Phobos to LMO, 50 MT payload mass

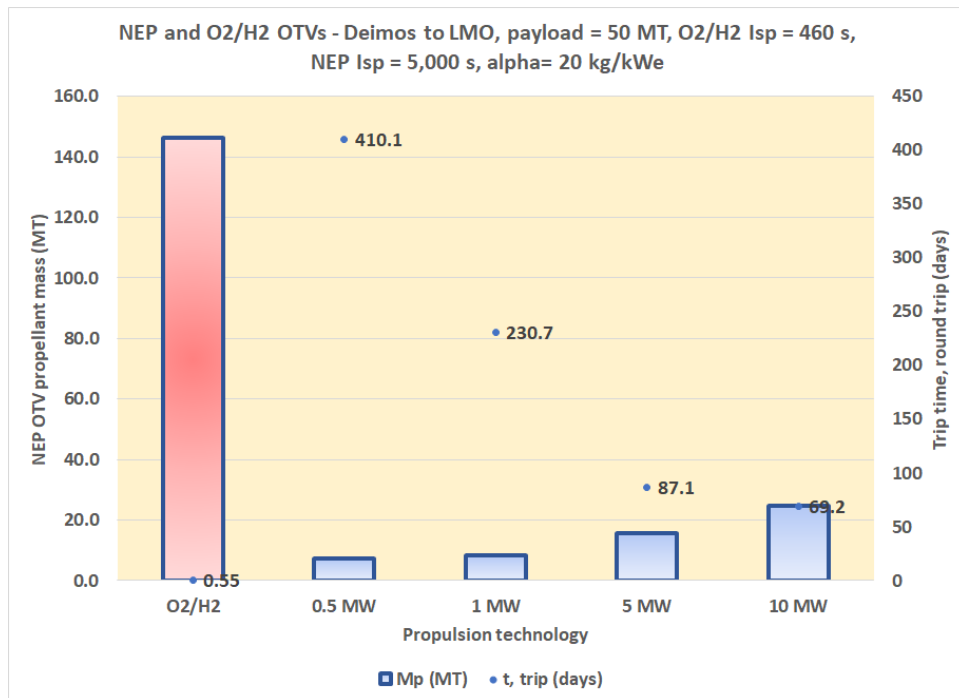


Figure 13. Resupply propellant mass and round-trip time for O₂/H₂ and Xe Ion NEP OTVs – Deimos to LMO, 50 MT payload mass

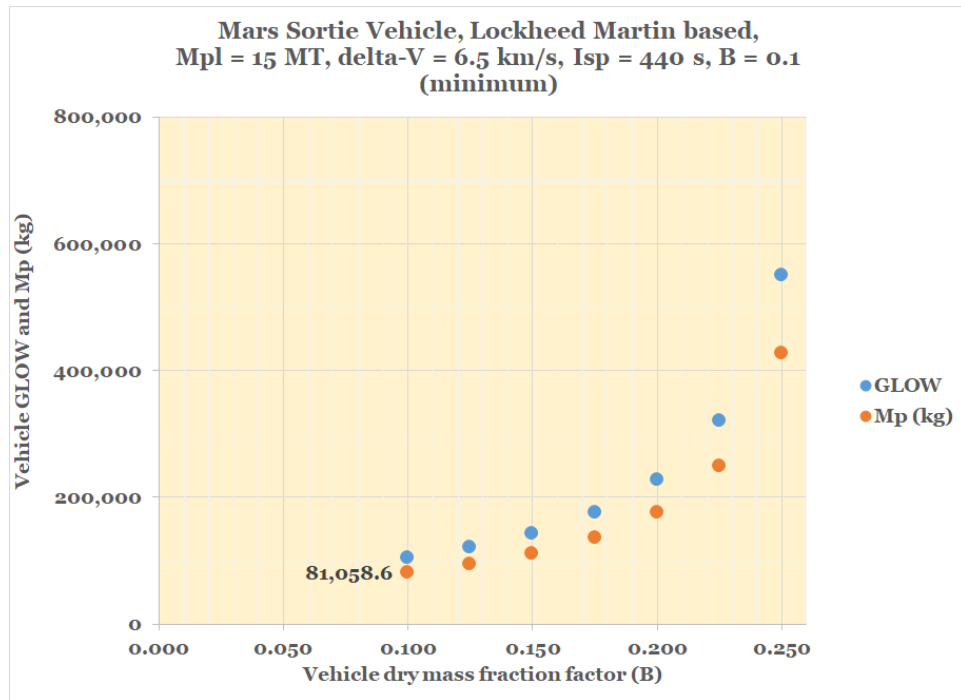


Figure 14. Mars sortie vehicle initial mass and propellant masses: SSTO capability

Nomenclature

a	Acceleration of gravity
delta-V	Velocity change
g	Gravity level (compared to Earth)
GLOW	Gross liftoff weight
H ₂	Hydrogen
ISRU	In-situ resource utilization
LMO	Low Mars orbit
m, p	Propellant mass
m, pl	Payload mass

O₂/H₂ Oxygen / hydrogen
SSTO Single stage to orbit

References

[1] The Planet Mars: A History of Observation & Discovery, W. Sheehan, University of Arizona Press, 1996

[2] Mars fact sheet, National Space Science Data Center,
nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html

[3] Veverka, Joseph; Noland, Michael; Sagan, Carl; Pollack, James; Quam, Lynn; Tucker, Robert; Eross, Botand; Duxbury, Thomas; Green, William (1974). "A Mariner 9 Atlas of the Moons of Mars," *Icarus* 23 (2): pp. 206–289.

[5] Bernard Godard(1), Frank Budnik(2), Pablo Muñoz(3), Trevor Morley(1), and Vishnu Janarthanan, "ORBIT DETERMINATION OF ROSETTA AROUND COMET 67P/CHURYUMOV-GERASIMENKO," 2015.
https://issfd.org/2015/files/downloads/papers/124_Godard.pdf

[5] Godard B, Budnik F, Muñoz P, et al. Orbit determination of Rosetta around Comet 67P/Churyumov-Gerasimenko. In: Proceedings of 25th International Symposium on Space Flight Dynamics. Munich, 2015

[6] "First International Conference on the Exploration of Phobos and Deimos," LPI contribution number 1377, held at NASA Ames Research Center, November 5-7, 2007.

[7] Bosanac, N., et al., "Manned Sample Return Mission to Phobos: a Technology Demonstration for Human Exploration of Mars," 2014 IEEE Aerospace Conference, June 2014.

[8] "A Study of System Requirements for Phobos / Deimos Missions. Volume II, Phase I Results – Satellite Rendezvous and Landing Missions," NASA Contract NAS1-10873, Martin Marietta Corp., June 1972.

[9] Abercromby, A., et al., "Human Exploration of Phobos," 2015 IEEE Aerospace Conference, 7-14 March 2015.

[10] Pascal, Lee, et al., "First International Conference on the Exploration of Phobos and Deimos: The Science, Robotic Reconnaissance, and Human Exploration of the Two Moons of Mars," Moffett Field, California, November 5-7, 2007. Lunar and Planetary Institute, LPI Contribution No. 1377

[11] Utashima, Masayoshi, "Design and Analysis of Phobos-Rendezvous Orbit," Systems Engineering Department, National Space Development Agency of Japan, *Journal of the Japan Society for Aeronautical and Space Sciences*, Vol. 44 No. 506, March 1996, Published by The Japan Society for Aeronautical and Space Sciences, National Space Development Agency of Japan, NASDA English Translation, December 1997,

[12] Palaszewski, B., “Atmospheric Mining of the Outer Solar System: Resource Processing Moon Base Propulsion, and Vehicle Design Issues,” AIAA 2019-4031, August 2019.

[13] Roger R. Bate, Donald D. Mueller, Jerry E. White, “Fundamentals of Astrodynamics,” Dover Books on Aeronautical Engineering, Jan 1971.

[14] Edelbaum, T. N., “Propulsion Requirements for Controllable Satellites,” ARS Journal, Vol. 31, Aug. 1961, pp. 1079–1089.

[15] Timothy Cichan, Sean O’Dell, Danielle Richey, Stephen A. Bailey, Adam Burch, “MARS BASE CAMP UPDATES AND NEW CONCEPTS,” Lockheed Martin Corporation. IAC-17,A5,2,7,x40817, 68th International Astronautical Congress (IAC), Adelaide, Australia, 25-29 September 2017.

Appendix A: Phobos and Deimos

Phobos

https://nssdc.gsfc.nasa.gov/imgcat/html/object_page/vo1_357a64.html



Phobos



Appendix A: Phobos and Deimos (continued)

Deimos

<https://photojournal.jpl.nasa.gov/catalog/PIA11826>

