Chapter

Martian Moons and Space Transportation Using Chemical and Electric Propulsion Options

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Abstract

Using chemical and nuclear electric propulsion for the exploration of the Martian moons will be investigated. Both oxygen/hydrogen chemical propulsion and nuclear electric propulsion with 500 kilowatt electric (kWe) to 10 megawatt electric (MWe) reactors will be assessed. The initial masses, propellant masses, and trip times for a variety of space vehicle payload masses will be compared. For high energy orbital transfer, the nuclear electric propulsion vehicles required a small fraction of the propellant mass over oxygen/hydrogen orbital transfer vehicles (OTVs). The moons, Phobos and Deimos, may hold resources for refueling future space vehicles. In-situ resource utilization (ISRU) can be a powerful method of reducing Earth dependence on space vehicle propellants, liquid water, and breathing gases. Historical studies have identified the potential of water in carbonaceous chondrites on the moons. The moon-derived propellants OTVs that move payloads between the moons and to other important operational Mars orbits. Also, the propellants have been suggested to support reusable Mars landers. To extract the water, the mined mass, its volume and the mining time were estimated. The water mass fraction may be as low as $2x10^{-4}$. Very large masses were needed to be extracted for up to 100 MT of water.

Keywords: Phobos, Deimos, Mars, electric propulsion, chemical propulsion, in-situ resource utilization, orbital transfer

1. Introduction

The Martian moons may be an important part of future Mars local planetary exploration and exploitation [1–11]. The moons have orbits that are relatively close to Mars, making them potential spacecraft berthing stations. Both oxygen/hydrogen (O2/H2) chemical propulsion and nuclear electric propulsion (NEP) orbital transfer vehicles were assessed. Their initial mass, propellant mass, and trip times were computed for several orbital transfer missions and orbital locations.

The moons may be sites of future in-situ resource utilization (ISRU), where metals and water may be wrested. The mining options for Phobos were assessed, showing the potential availability of water. A range of water mass fractions was investigated, and the potential masses of water were computed. The required mining time was also assessed.

2. Mission design and options

2.1 Orbital transfer delta-V

Phobos and Deimos exploration and exploitation methods have 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.

The orbital missions are controlled by the delta-V or change of velocity needed for the orbit transfers. Both high-thrust missions and low-thrust missions were assessed. The high-thrust delta-V values were computed with a standard Hohmann transfer Equations [12]. The values for the low-thrust delta-V were calculated using the Edelbaum equation [13]. The nominal semi major axes for Phobos and Deimos are 9,378 and 22,459 km [2].

In all cases, the delta-V values are for round trip missions. There are 5 trips that were assessed: Phobos to Deimos, Phobos to areosynchronous Mars orbit (AMO), Phobos to 100,000 km altitude, Deimos to AMO, and Deimos to 100,000 km altitude.

Figure 1 and **Table 1** provide the round trip delta-V for Phobos and Deimos missions. 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

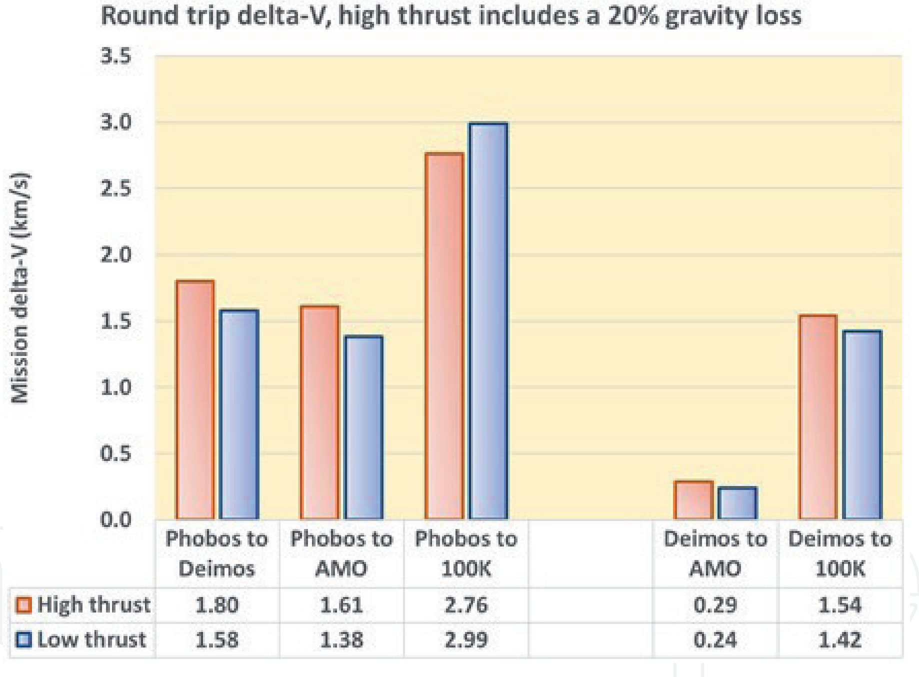


Figure 1.
OTV delta-V, Phobos and Deimos orbital transfer missions.

Mission option	High thrust	Low thrust
Phobos to Deimos	1.80	1.58
Phobos to areocentric Mars orbit (AMO)	1.61	1.38
Phobos to 100,000 km altitude	2.76	2.99
Deimos to areocentric Mars orbit (AMO)	0.29	0.24
Deimos to 100,000 km	1.54	1.42

Table 1.
Orbital transfer mission options (for the high thrust options, the delta-V is increased by 20%).

was added; no added losses were imposed on the low thrust systems. In **Figure 1**, the Phobos to 100,000 km low thrust delta-V was 2.99 km/s. The Phobos to Deimos low thrust delta-V was 1.58 km/s. At Deimos, the highest round trip delta-V is for the Deimos to AMO transfer was 0.24 km/s. The round trip low-thrust transfer to 100,000 km required only 1.42 km/s.

3. Propulsion options

High thrust chemical propulsion, using oxygen/hydrogen rocket engines is a natural choice [14]. If indeed water were available on the Martian moons, it would make sense to capitalize on that water resource, and finally producing rocket-purity oxygen and hydrogen.

Electric propulsion systems with either ion or Hall thrusters are potential options. Xenon or other inert gases are the typical choice for such thrusters. Using hydrogen as an electric propulsion propellant with a pulsed inductive thruster (PIT) has also been proposed.

3.1 Advanced propulsion options

Several advanced propulsion options for Martian moon transportation, exploration, and industrialization were investigated. Chemical propulsion and nuclear electric propulsion (NEP) with a range of power levels for Martian orbital transfer vehicles (OTVs) were assessed. Design parameters, vehicle mass scaling equations, and summaries of these analyses are presented; Mass scaling equations were developed for the O2/H2 chemical propulsion and the nuclear electric propulsion systems [14].

3.1.1 Chemical propulsion OTV sizing

In sizing the chemical propulsion OTVs, a vehicle mass scaling equation is used [14]:

$$m(dry, stage) = m(dry, coefficient)\ x\ m(p) + a(fixed) \quad (1)$$

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 [14]. The following dry mass scaling equation was used [12]:

$$m(dry.stage, NEP) = alpha\ x\ P + 0.05\ x\ m(p) + m(fixed) \quad (2)$$

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) [15]. 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 specific impulse (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

A range of payload masses were included in the comparative orbital transfer cases: 1, 10 and 50 metric tons (MT). In general, the initial masses of the NEP OTVs are higher than the O2/H2 OTVs initial masses. However, the propellant masses of the NEP vehicles are generally significantly lower that most O2/H2 vehicle propellant masses. Thus, the propellant resupply masses for the NEP OTVs offer a substantial resupply mass benefit over chemical propulsion OTVs.

4.2 OTV mass comparisons

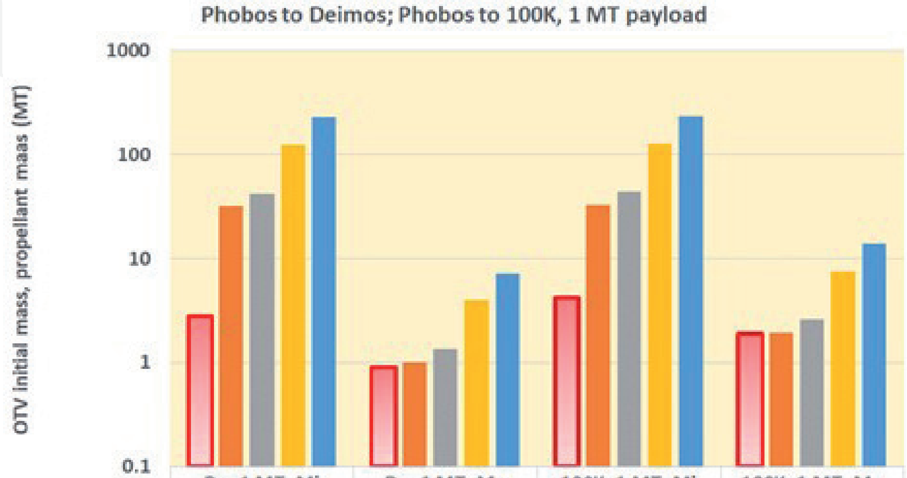
An initial comparison of the chemical and NEP option for the 1 MT payload cases is presented in **Figure 2**. Both the Phobos to Deimos and the Phobos to 100,000 km cases are shown. Overall, the initial masses of the NEP cases, for Phobos to Deimos and the Phobos to 100,000 km, are very similar; therefore, the larger Phobos to 100,000 km OTV NEP cases can perform both the Deimos and 100,000 km missions. The only NEP OTV designs that have a comparable propellant mass to the chemical propulsion OTV is the OTV with the 0.5 MWe power level.

The associated 1 MT payload OTV trip times for the chemical and NEP cases is presented in **Figure 3**. The Phobos to Deimos round trip time is for the 0.5 MWe case is 56.6 days. The 100,000 km round trip time is 108.9 days. The higher power levels provided a shorter trip time; however, the required propellant mass is higher than any chemical OTV propellant mass.

A summary of the initial masses of the chemical and NEP OTVs for the Phobos to Deimos and Phobos to 100,000 km is shown in **Figures 4** and **5**, respectively. The payload masses for both OTV mass estimates were 10 and 50 MT. The payload mass is carried on the full round trip mission In the Phobos to Deimos cases with a 10 MT payload mass, the benefit of the NEP system over the chemical OTV is best with NEP power levels of 0.5 to 1 MWe. For the 50 MT payload, the NEP OTV provides a very significant propellant mass benefit for power levels up to 10 MWe. For the

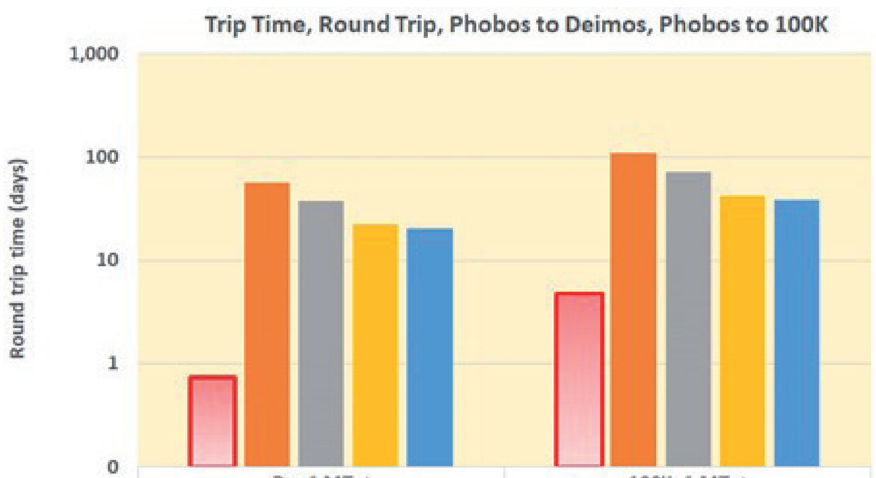
50 MT cases, the chemical OTV required about 31 MT of propellant, while the NEP OTV at a 10 MWe power level required only 9 MT.

The Phobos to 100,000 km orbital transfers are compared in **Figure 5**. Both the initial masses and propellant masses are shown. Comparisons are shown for 10 and 50 MT payload cases. The payload mass is carried on the full round trip mission. In general, the NEP OTV propellant mass savings over the chemical OTVs are very similar to the Phobos to Deimos cases. For the 50 MT cases, the chemical OTV required about 64 MT of propellant, while the NEP OTV at a 10 MWe power level required only 17 MT.



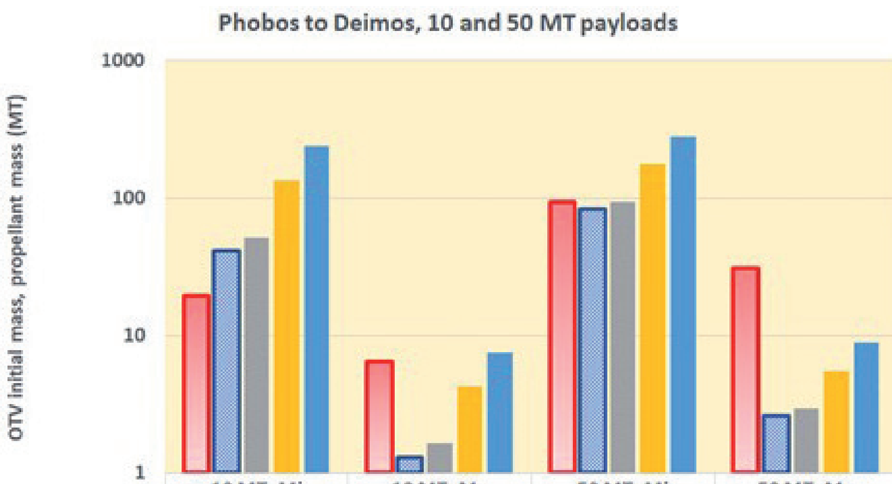
	De, 1 MT, Mi	De, 1 MT, Mp	100K, 1 MT, Mi	100K, 1 MT, Mp
O2/H2	2.8	0.91	4.18	1.91
NEP, 0.5 MWe	32.1	1.02	33.1	1.96
NEP, 1 MWe	42.4	1.35	43.7	2.60
NEP, 5 MWe	125.2	4.00	129	7.63
NEP, 10 MWe	228.6	7.30	235.6	13.94

Figure 2.
Initial mass and propellant resupply mass, Phobos to Deimos and Phobos to 100,000 km, round trip, 1 MT payload.



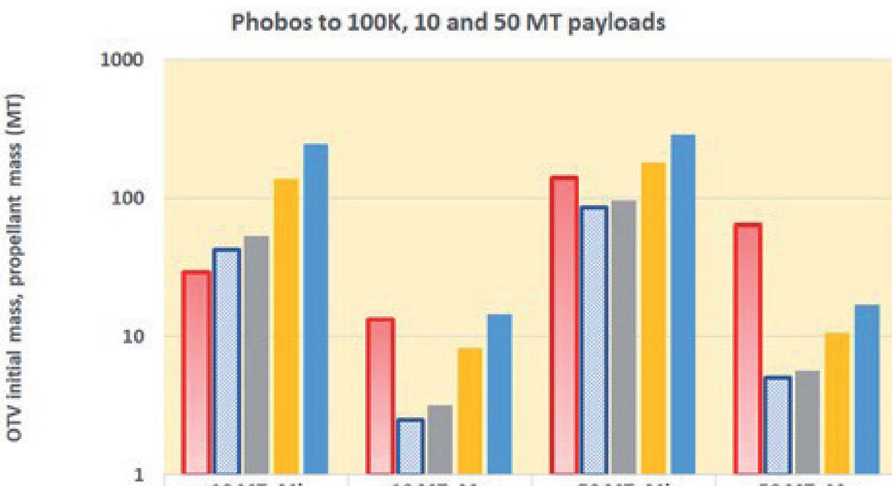
	De, 1 MT, t	100K, 1 MT, t
O2/H2	0.74	4.71
NEP, 0.5 MWe	56.60	108.90
NEP, 1 MWe	37.40	72.00
NEP, 5 MWe	22.10	42.50
NEP, 10 MWe	20.20	38.80

Figure 3.
Round trip time, Phobos to Deimos and Phobos to 100,000 km, round trip, 1 MT payload.



	10 MT, Mi	10 MT, Mp	50 MT, Mi	50 MT, Mp
O2/H2	19.5	6.4	93.6	30.8
NEP, 0.5 MWe	41.4	1.31	82.8	2.6
NEP, 1 MWe	51.7	1.64	93.1	3.0
NEP, 5 MWe	134.5	4.26	175.9	5.6
NEP, 10 MWe	237.9	7.55	279.3	8.9

Figure 4.
Initial mass and propellant resupply mass, Phobos to Deimos, round trip, 10 and 50 MT payload.



	10 MT, Mi	10 MT, Mp	50 MT, Mi	50 MT, Mp
O2/H2	29.2	13.37	140.5	64.28
NEP, 0.5 MWe	42.7	2.52	85.3	5.05
NEP, 1 MWe	53.3	3.15	96.0	5.68
NEP, 5 MWe	138.6	8.20	181.3	10.72
NEP, 10 MWe	245.3	14.50	287.8	17.03

Figure 5.
Initial mass and propellant resupply mass, Phobos to 100,000 km, round trip, 10 and 50 MT payloads.

The trip time for the Phobos to Deimos with a 50 MT payload is shown in **Figure 6** for three reactor specific masses: 10, 20 and 40 kg/kWe. The NEP power levels of 0.5 to 10 MWe are of interest; once the power level reaches 10 MWe, the OTV has gained the greatest trip time benefits over the lowest power levels of 0.5 MWe. This example was provided to show the influence of reactor power level and specific mass on the OTV trip time.

For space science missions, the 1 MT payload cases can be important for several reasons. A small payload may be left in orbit or on the surface of one of the moons. The NEP OTV can then conduct radar experiments in concurrence with the orbiting or landed payload. Based of ground based meteorite analyses and spectroscopic measurements, Phobos and Deimos may have a surface of carbonaceous chondrites.

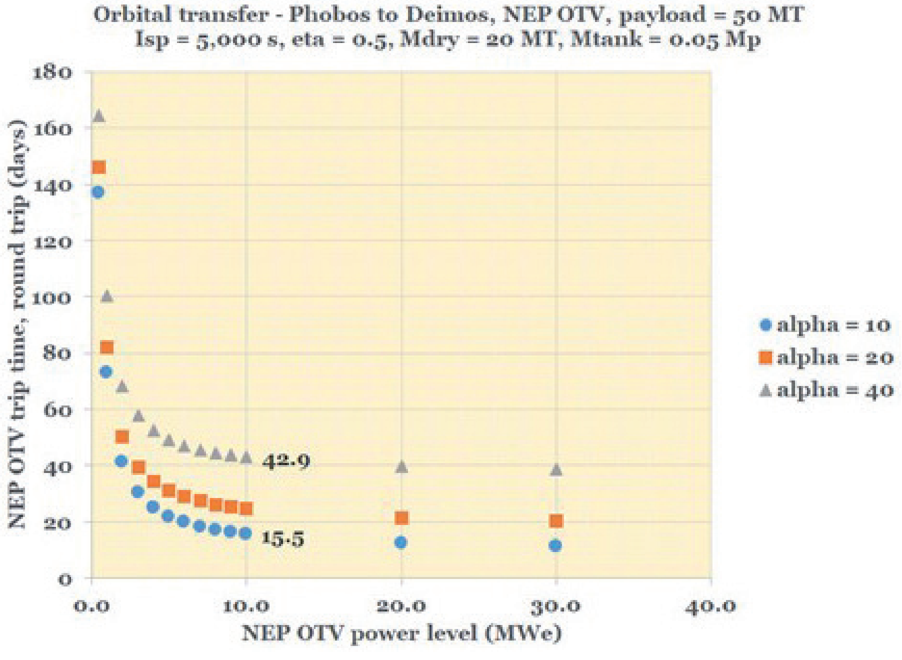


Figure 6.
NEP round trip time versus power level, Phobos to Deimos, round trip, 50 MT payload.

From this information, and from orbital gravity measurements, it is inferred that the moons may have a high porosity. The radar measurements can illuminate or knowledge about the moons' interior geological structures and the potential locations of frozen water reserves.

Detailed comparisons of the chemical and NEP OTV resupply propellant masses and specific trip times for the 10 MT payload cases are presented in **Figures 7–11**. The set of cases for the 50 MT payloads are presented in **Figures 12–16**. In general, the NEP trip times are many days, whereas the chemical OTV trip times are much shorter. The Phobos to 100,000 km orbit transfer required the largest mission delta-V and the largest OTVs; therefore, this OTV design can encompass all the suggested OTV missions.

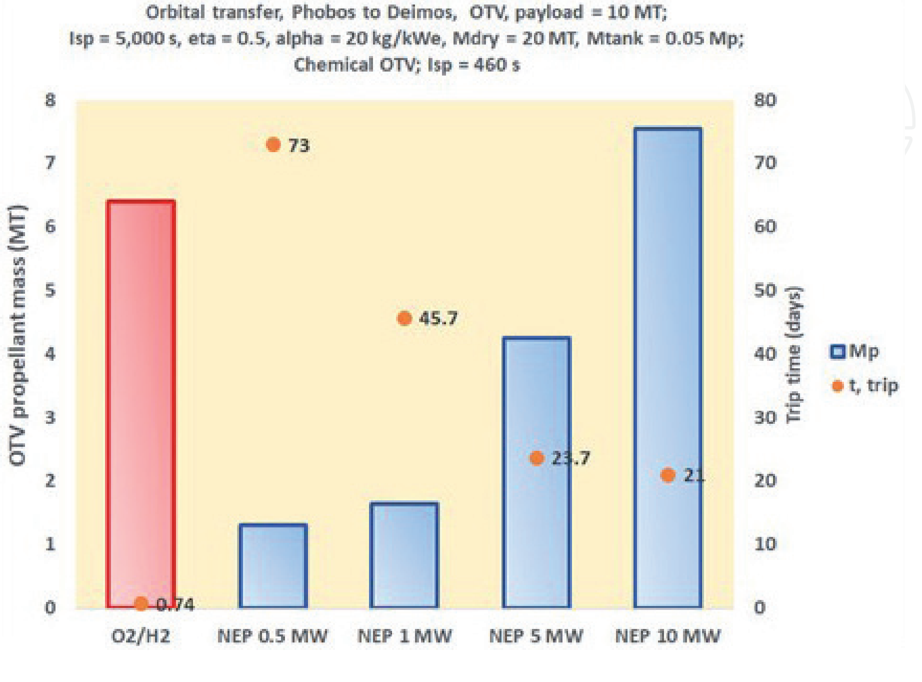


Figure 7.
Propellant resupply mass, Phobos to Deimos, round trip, 10 MT payload.

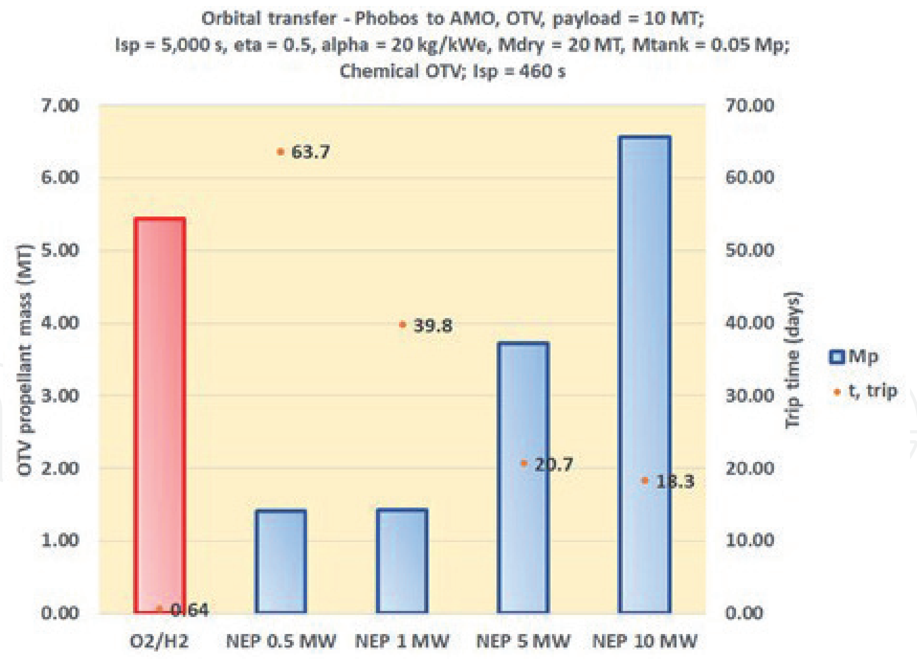


Figure 8.
Propellant resupply mass, Phobos to AMO, round trip, 10 MT payload.

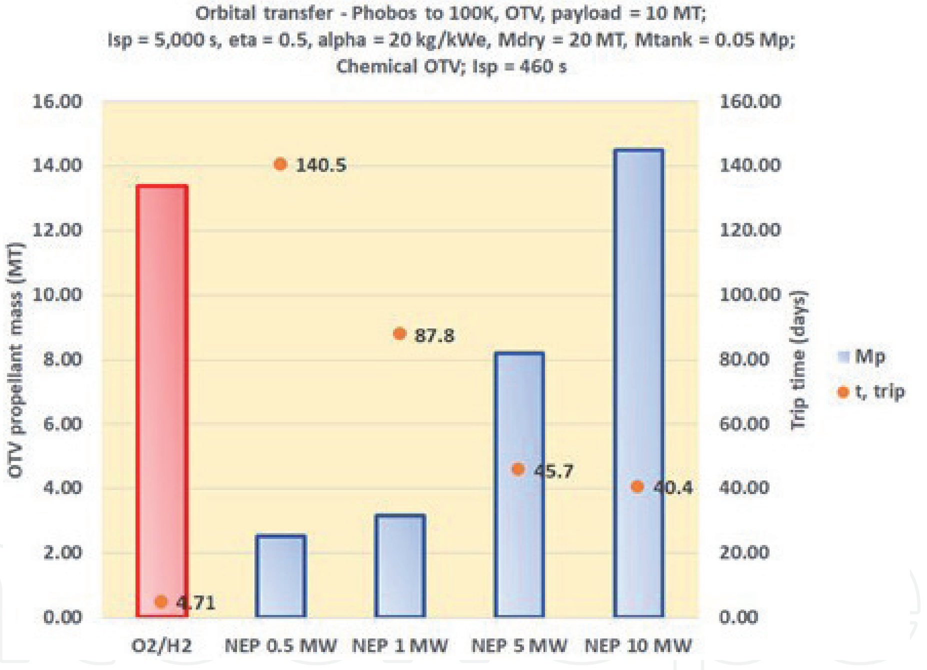


Figure 9.
Propellant resupply mass, Phobos to 100,000 km, round trip, 10 MT payload.

4.3 Martian moons and ISRU - water mining

Phobos has been studied in detail over many decades. Models of the moon have suggested that the surface may have a large fraction of carbonaceous chondrites. These chondrites may have a sizable water content. Preliminary estimates of the water mass fraction range from $1\text{x}10^{-5}$ to $1\text{x}10^{-1}$. The estimates were based on models and laboratory measurements of meteoritic chondrites.

If water in indeed available, it can be used to create resupply propellants for the Martian OTVs. In addition to the refueling of the NEP and chemical OTVs, Mars lander analyses (Mars Base Camp) [16] have shown a need for approximately 100 MT of water to create the required 78 MT of O2/H2 propellant. This 100 MT water mass was used as a guide for the ISRU analyses.

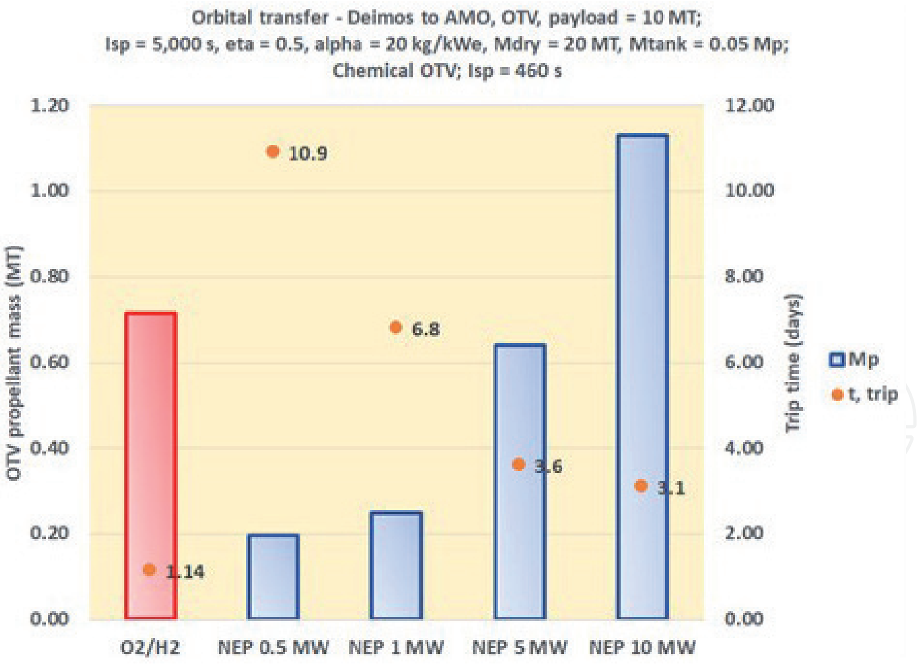


Figure 10.
Propellant resupply mass, Deimos to AMO, round trip, 10 MT payload.

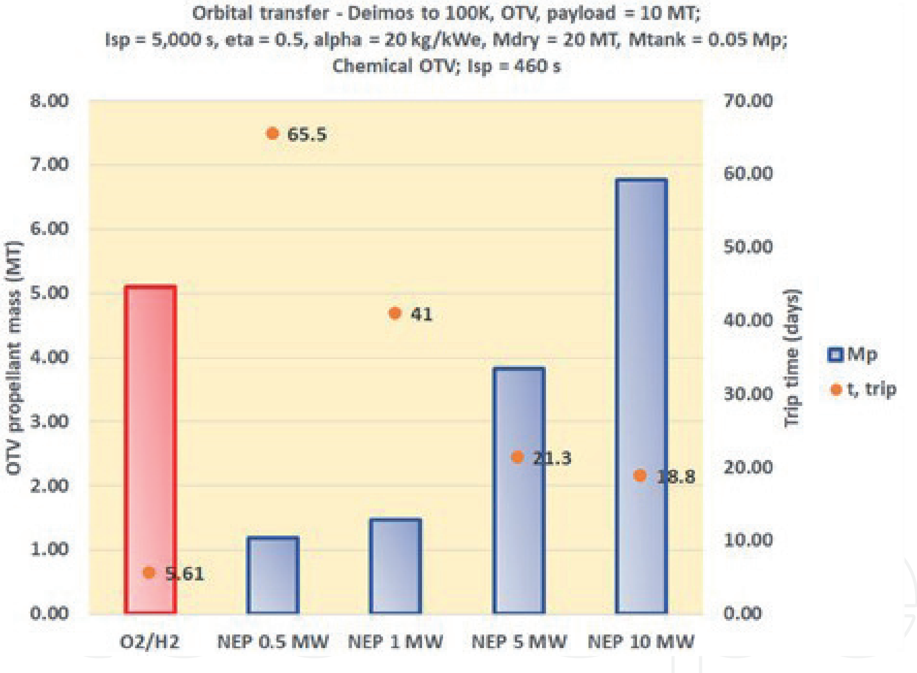


Figure 11.
Propellant resupply mass, Deimos to 100,000 km, round trip, 10 MT payload.

While water is an important commodity that may be wrested from the Martian moons, the mass of water for the chemical OTV propellant resupply can be very high. In future cases using pulsed inductive thrusters, hydrogen propellant can be used in NEP OTVs, and therefore benefit from such water reserves. With the high NEP Isp values, the propellant mass is much lower than that for chemical OTVs, significantly reducing the mining requirements.

4.3.1 Issues of water unavailability

There has been much speculation regarding the water content of the Martian moons. Research programs have suggested that the moons agglomerated from the matter that formed Mars. The water content was estimated to be $2x10^{-4}$ (or 0.02

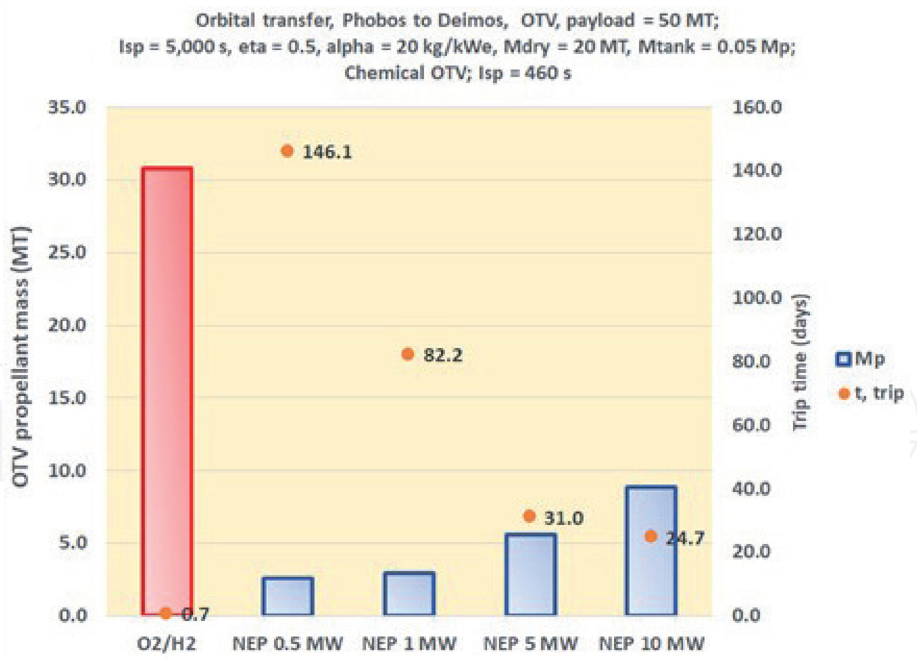


Figure 12.
Propellant resupply mass, Phobos to Deimos, round trip, 50 MT payload.

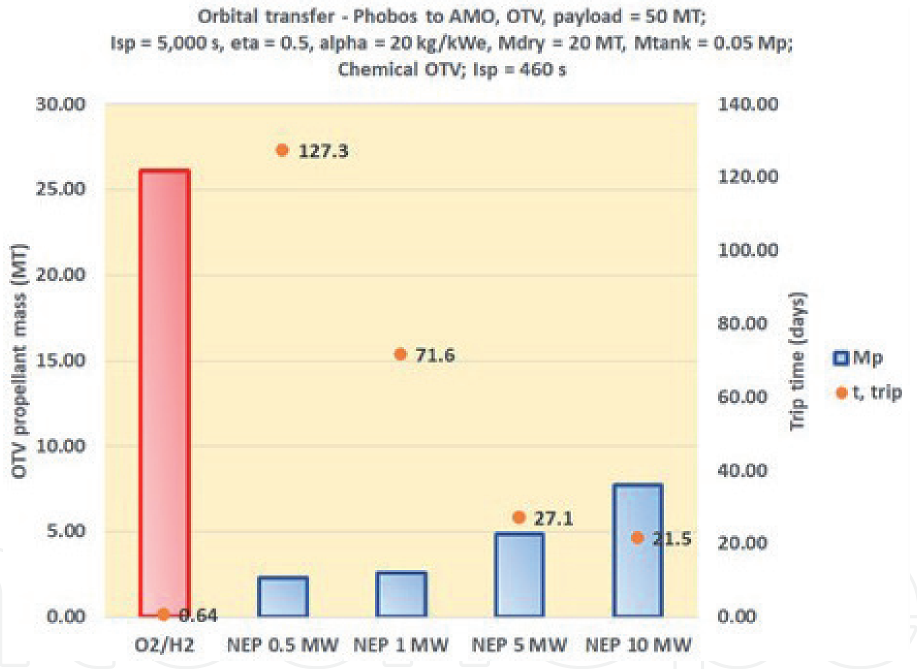


Figure 13.
Propellant resupply mass, Phobos to AMO, round trip, 50 MT payload.

weight%) [17]. Recent lunar water research has suggested widespread water on the Moon as being 1 to 4×10^{-4} weight% [17]. Given the wide range of possible water mass fractions, analyses were conducted using a mass fraction of 1×10^{-5} to 1×10^{-1}. **Figure 17** shows the water mass that may be available on Phobos. For simplicity, the radius of Phobos was assumed to be 9 km. The area mined is 10 x 10 meters and 1 meter deep. With the lowest mass fraction of 1×10^{-5}, the total water available would be approximately 18,000 MT; implying that approximately one hundred and eighty (180), 100 MT water loads can be extracted. For the mass fraction of 10^{-5}, the area to be mined is 180th the moon's surface area: approximately 5.66 km^2.

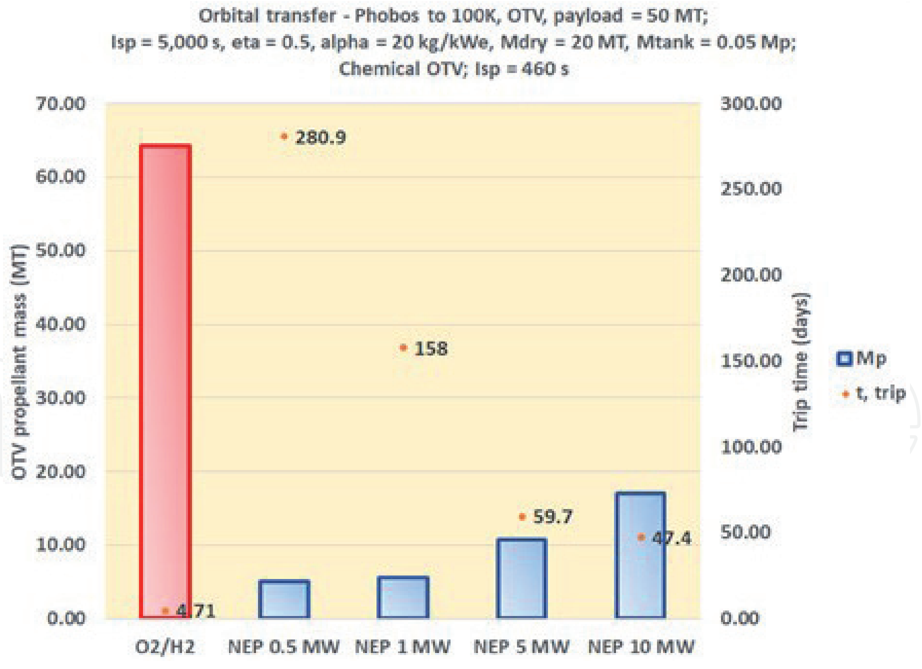


Figure 14.
Propellant resupply mass, Phobos to 100,000 km, round trip, 50 MT payload.

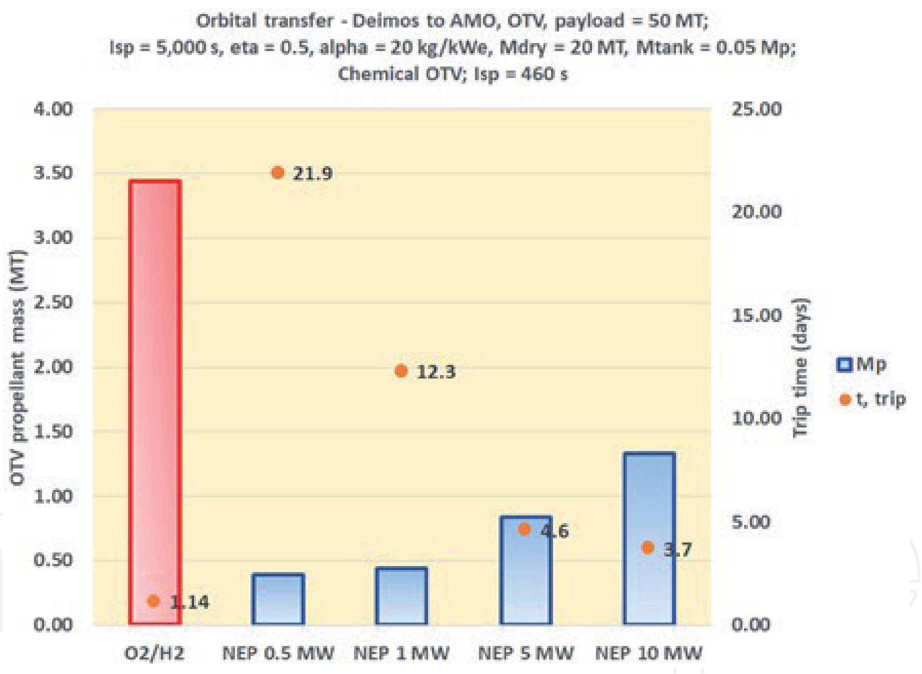


Figure 15.
Propellant resupply mass, Deimos to AMO, round trip, 50 MT payload.

The mined water mass is a very small fraction of the total regolith to be processed. The volume of the mined mass or radius of a proposed spherical mining container was computed and shown in **Figure 18**. For the mass fraction of 1×10^{-2}, the capture tank radius would be 11 meters; for the 1×10^{-5} mass fraction, the radius would be 110 meters. Separation of the water from the total mined mass will be quite a challenge; the water and the regolith must be separated in the very low gravity field on the moons. The water and the final production propellant purity must be maintained to make the ISRU-based propulsion systems a success.

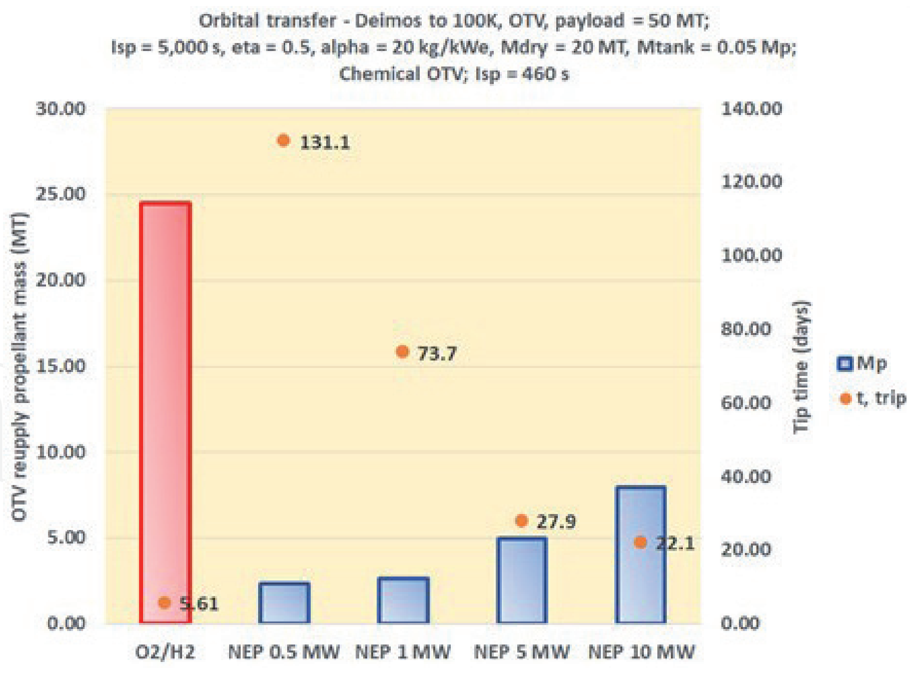


Figure 16.
Propellant resupply mass, Deimos to 100,000 km, round trip, 50 MT payload.

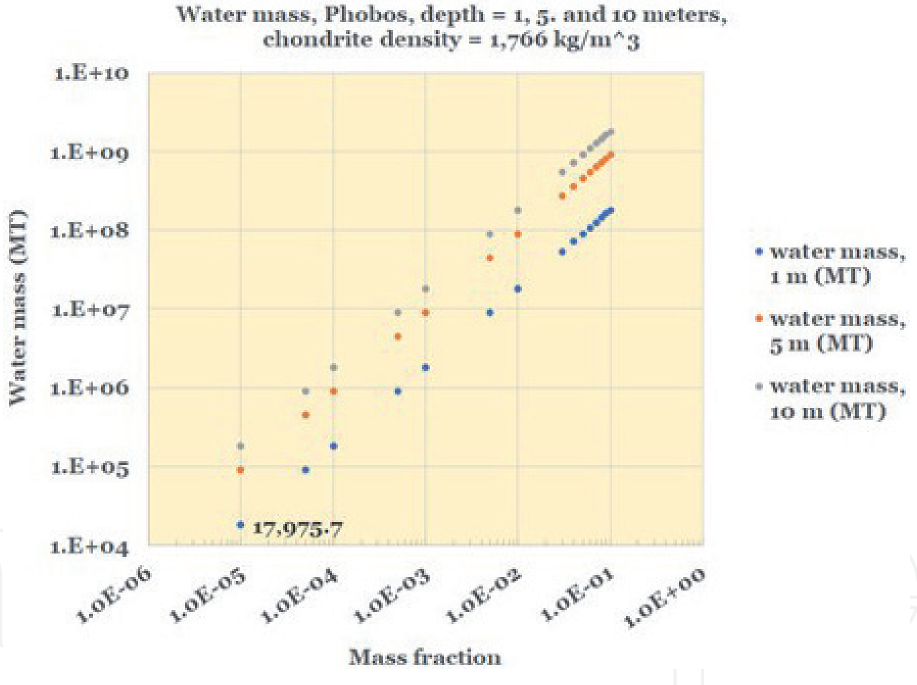


Figure 17.
Water mass predictions, Phobos, water mass fraction: $1x10^{-5}$ to $1x10^{-1}$.

The Phobos water mining time is shown in **Figure 19**; the figure shows the time needed to extract a wide range of water masses. If the mass fraction is $1x10^{-2}$, the mining time is approximately 57 days to extract 100 MT. For the $1x10^{-5}$ mass fraction, the mining time is 57,000 days. Thus, only the higher the mass fractions will be useful for large scale water production.

Once the water mass fraction is established, more effective planning and designing of the mining machines will be possible. One possibility is that the water may exist as ice deep inside Phobos [18]. Reference 17 notes that the ice location may be 10 to 100 meters below the surface. Extracting the water would therefore require a very sophisticated mining system, far more complicated than any surface mining

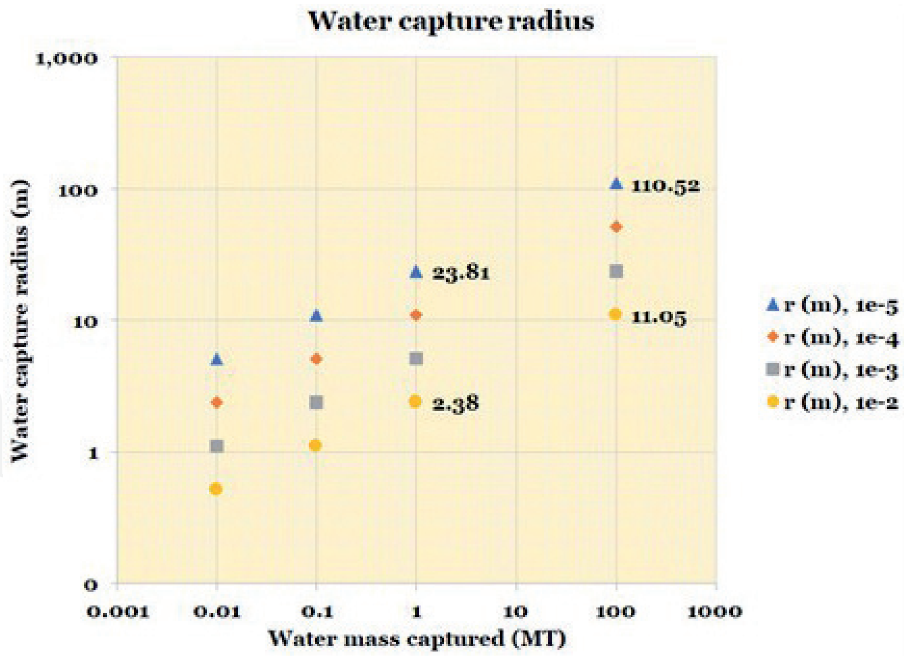


Figure 18.
Water mining storage vessel radius, Phobos, water mass fraction: 1x10^{-5} to 1x10^{-2}.

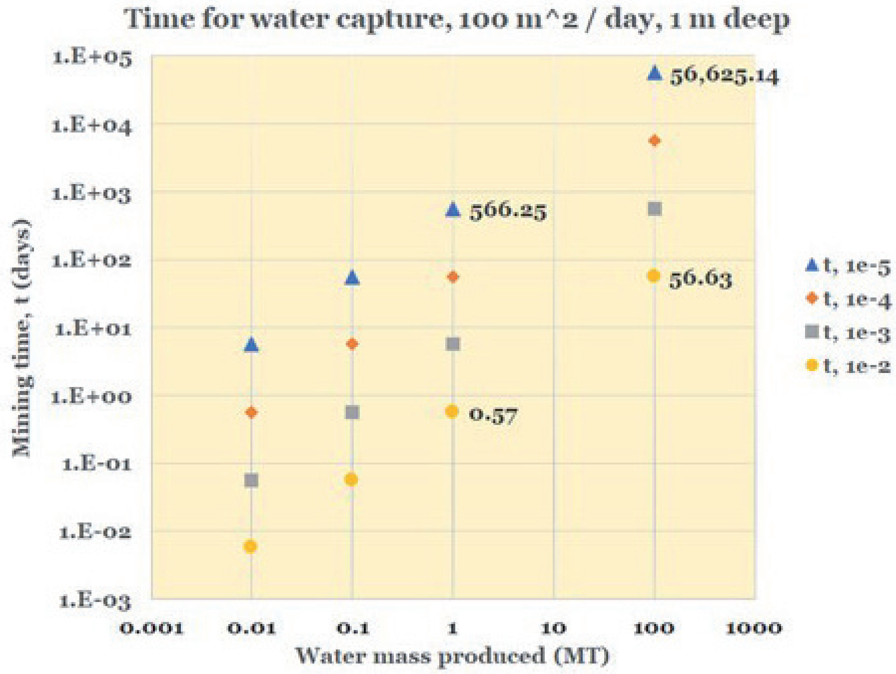


Figure 19.
Water mining time, Phobos, water mass fraction: 1x10^{-5} to 1x10^{-2}.

system. If the moons' surfaces do not possess any water, then the metal and other raw materials would be the best Phobos ISRU products.

5. Conclusions

For exploration and exploitation of the Martian moons, both chemical propulsion and electric propulsion orbital transfer vehicles (OTVs) were assessed. For large payloads of 10 to 50 MT, the nuclear electric propulsion (NEP) OTVs require a small fraction of the chemical propulsion OTV propellant mass. If 10 MT payload masses can be manifested together, the 50 MT NEP OTV would be a more propellant efficient OTV option over a using five 10 MT NEP OTVs. The Phobos to 100,000 orbit transfer required the largest mission delta-V and the largest OTVs; therefore, this OTV design can encompass all the suggested OTV missions.

For small 1 MT payloads, chemical propulsion OTVs were more efficient than NEP OTVs. However, the NEP OTV can enable several special missions. Radar science missions and observations can be conducted; a small 1 MT payload might be left in orbit about a Martian moon and the NEP OTV can use a high power radar to transmit signals through the moon. The smaller payload would gather the reflected radar signal and allow more accurate determination of the moons internal structure.

Mining water on the Martian moons may be used for resupplying propellants to chemical and NEP OTVs. Mining systems on the surface may be able to provide the needed water to make hydrogen and oxygen. However, the water mass fraction on the surfaces Phobos and Deimos may be small; the estimates have a wide range from $1x10^{-5}$ to $1x10^{-1}$. Deep caches of water ice may also exist, but these deep caches may be difficult to mine. In the best estimates, 100's of MT of water may be wrested from Mars' moons, assisting in make Mars exploration truly Earth independent.

Nomenclature

a	Acceleration of gravity
AMO	Areosynchronous Mars orbit
delta-V	Velocity change
g	Gravity level (compared to Earth)
H2	Hydrogen
Isp	Specific impulse
ISRU	In-situ resource utilization
m(p)	Propellant mass
m(pl)	Payload mass
NEP	Nuclear electric propulsion
O2/H2	Oxygen/hydrogen

A. Appendix

Phobos maps:

https://astrogeology.usgs.gov/search/map/Phobos/Viking/Phobos_Viking_Mosaic_40ppd_DLRcontrol

https://astrogeology.usgs.gov/search/map/Phobos/MarsExpress/SRC/Phobos_ME_SRC_Mosaic_Global_16ppd

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