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Mars-phobos: A Mars mission architecture with Mars-Moon synergy

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Abstract

A cost effective and sustainable human mission to Mars should take maximum advantage of the Mars system resources, as well as previous efforts at the Moon in terms of habitats, heavy lift boosters and vehicles. However, to make such an effort sustainable over many Presidential administrations, an early human foothold should be established on Phobos, Mars innermost moon, and the Mars surface mission should be staged from there. Due to controversial aspects of nuclear propulsion, an early Mars mission should not make use of nuclear propulsion. It is initially proposed in this architecture that high power Solar Electric propulsion based around the MET (Microwave Electro-Thermal) thruster with water propellant used as an upper stage for a heavy lift chemical booster, will allow a 30 Metric Ton basic payload package to be sent to Phobos to establish a base there. Moreover, a Mars surface base can be constructed tele-robotically and utilize ISRU on Mars for production of RP1 and LOX to achieve Mars ascent and Mars Orbit Rendezvous with a return stage or with Phobos. Two full tests of ISRU and Mars ascent are assumed for man-rating of the system and to preposition water and RP1 Crew rotation occurs synoptically.

Keywords

Mars; Phobos; Moon base; MET thruster; Solar electric propulsion; ISRU.

INTRODUCTION

"Better is the enemy of good enough."
Old Russian Proverb.

The landing and establishing of a human settlement on Mars by the United States will begin a new epoch of human history; however, a human landing and return from Mars is of a far greater difficulty than the Apollo landings and return from the Moon. A human Mars mission may require considerable commitments of resources over several Presidential administrations. So it is important that it is achieved cost effectively, use non-controversial technology, low-risk hardware elements, and have solid milestones or waypoints so that political support does not waver.

It is now well understood that a Mars-Moon exploration program will benefit considerably from utilization of Mars resources and synergism with a program with a return to the Earth's Moon, as well as utilization of the moon of Mars, Phobos, as a staging area. Mars resources: atmosphere, water, and moon system can reduce cost and risk for a human Mars mission. Phobos use, Mars inner-most moon, as a staging area gives considerable advantages to Mars compared to the Moon as a final destination and can partially offset the problems of Mars distance and higher gravity needs. Considerable advantage can also share components[1] with elements of Mars architecture that was once tested on the Moon as part of a LES (Lunar Exploration System). Study of the incremental approach of the Apollo landings, featuring orbits of the Moon to gain confidence and build public excitement, is also useful. It is also understood that nuclear power, while essential for Lunar and Mars bases will cause political complications for a Mars program if applied to propulsion. These complications may cause nuclear propelled Mars Mission plans to be derailed or recast by a change in administrations, even if the incoming administration actually favors a Mars mission. Because a Mars mission effort will likely bridge several administrations, it seems best to create a mission architecture without nuclear propulsion but using advances in Solar Electric power generation and plasma propulsion, in addition to ISRU (In Situ Resource Utilization) to create a Mars mission architecture that is politically sustainable yet capable and remains cost effective. In the rest of this brief article, a Mars mission architecture will be discussed, that uses Mars-Moon synergy and Solar Electric propulsion to create a low cost and sustainable Mars mission effort.

The importance of Phobos and other factors to a human Mars mission

Mars is not a planet but a system, consisting of a planet with two moons in almost equatorial orbits (see Figure 1). The moons are not large, both being potato shaped with Phobos being 13.3 km on its longest axis and Deimos being 7.6 km. The orbits are quite circular at approximately 3 and 7 Mars radii for Phobos and Deimos respectively. The common complaint about Mars is that it lacks a strong magnetic field that is a plus at Phobos. Mars also lacks Van Allen belts. This makes the radiation environment at Phobos fairly benign if the location faces directly toward the surface of Mars. Both moons are in synchronous rotation and thus are tidally locked, keeping the same face towards Mars.

Phobos, being the largest and closest to the Martian surface (see Figure 2) is of the most interest for supporting human exploration of Mars. Phobos is a ready-made space station. It orbits Mars approximately 3 times a day and thus rises in the West and moves across the sky to set in the East. Its image from the surface of Phobos will be roughly the size of the tip of a human index finger held at arm's length. Surface gravity on Phobos is very weak so a human spacecraft will basically dock with Phobos rather than landing on it. The mean density of Phobos is approximately twice that of water so Phobos regolith can be moved easily and used for radiation shielding.

Phobos importance to an American Mars mission is more than just a convenient staging area, a landing on Phobos also is an important goal in itself. A landing on Phobos represents a first human beachhead in the Mars system and an important milestone in human expansion into the Cosmos. Like the Apollo 8 Lunar orbit mission that captured the imagination of the world and convinced humanity that the Apollo program would succeed, so will the first steps be achieved by astronauts on the surface of Phobos. "United States Conquers Fear (Phobos) at Mars" will read the headlines! Phobos-station will then become the "base camp" to support human exploration and settlement of the whole Mars system. It will be a secure "home away from home" for following the human Mars expeditions. Phobos-station also serves, together with a supporting Mars communications satellite constellation, the short-time-lag leg of a tele-robotics effort to create a surface Mars base, in preparation for the human Mars surface landing itself. With a well-equipped Phobos-station established, no human base on Mars surface can consider itself isolated or precarious. In case of trouble on Mars, medical, logistical, or otherwise, the Phobos base can dispatch supplies and personnel in a few hours. Particularly in the case of global dust storms on Mars, Phobos-station, with its close radio contact can be maintained between Earth and the Mars surface base, via the Phobos-station, which will ride unperturbed above the Martian atmospheric clouds and radio-static.

Therefore, for orbital, logistical, and psychological reasons, the Phobos base must be the strategic cornerstone of a human expedition to Mars. Human arrival at Mars begins with the establishment of a base on Phobos. This base will use well-proven habitats used for the American base on the Moon. Next in importance to Phobos, will be the large booster family needed to get everything and everyone to Phobos.

The importance of the Magnum or Saturn V class booster

The recent decision to create a heavy lift booster from shuttle components, termed here generically, the Magnum (see Figure 3), has created a shift in thinking concerning both Lunar and Mars human expeditions and bases. In particular, the capabilities of this large booster have moved thinking back to many concepts and designs that originate in the Apollo era[2,3]. In that era, the Apollo elements of Saturn V, CSM (Command Service Module) and LEM (Lunar Excursion Module) were viewed as proven starting points for an evolving family of vehicles to support continued exploration of the Moon and later, Mars.

The creation of a booster that is able to duplicate the Saturn V capabilities of putting 120 tons (metric tons, 1000kg) into LEO and 47 tons onto an escape trajectory or to the Moon, has revived the LESA (Lunar Exploration System-Apollo) concepts (See Figure 4).

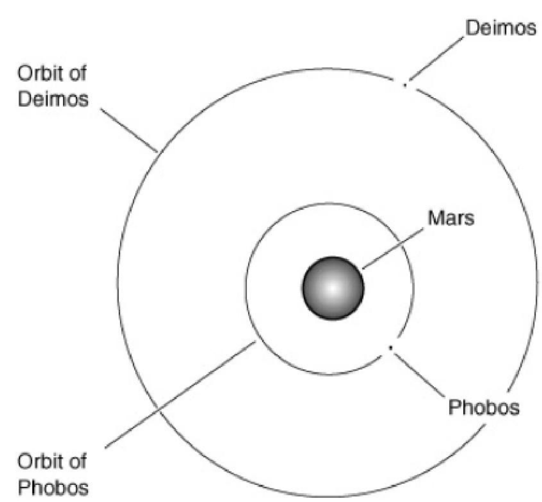


Figure 1 : The relative sizes of mars and the orbits of its two moons.

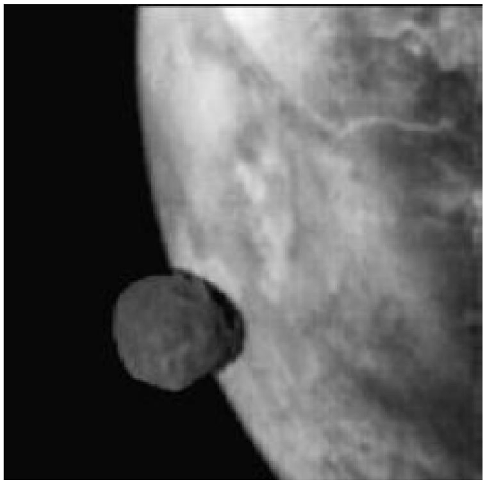


Figure 2 : Phobos in its highly convenient orbit around mars.

Figure 3 : The Magnum shuttle derived heavy lift booster.

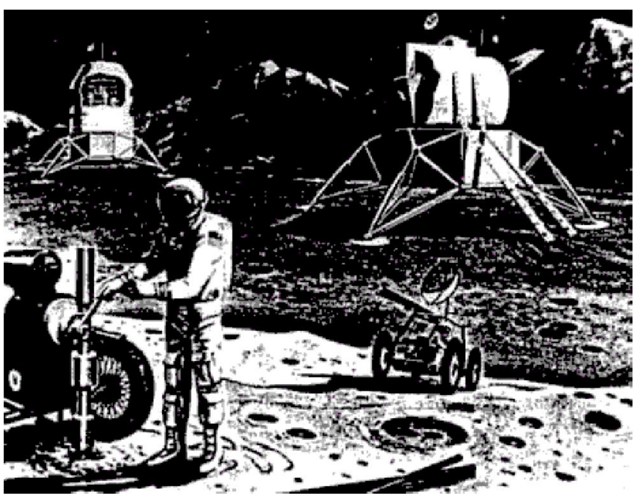


Figure 4 : The very successful Apollo landings gave rise to concepts using the Saturn V and evolved Apollo elements as part of a lunar base and exploration scenario.

The Post Apollo Lunar operation plan was termed LESA (Lunar Exploration System- Apollo) and in it early stages that used the Apollo CSM, is with the extended LEM capable carrying more payload to the Lunar surface and a LEM derived Lunar habitat termed the LASS (Figure 5). The LEM was 15 tons and the CSM (Command Service Module) was 30.3 tons. The CM (Command Module) was 5,809 kg and the Service Module was 24,523 kg. The LASS uses a LEM derived lunar habitat of approximately 21 tons and could support two men for 90 days on the Lunar surface.

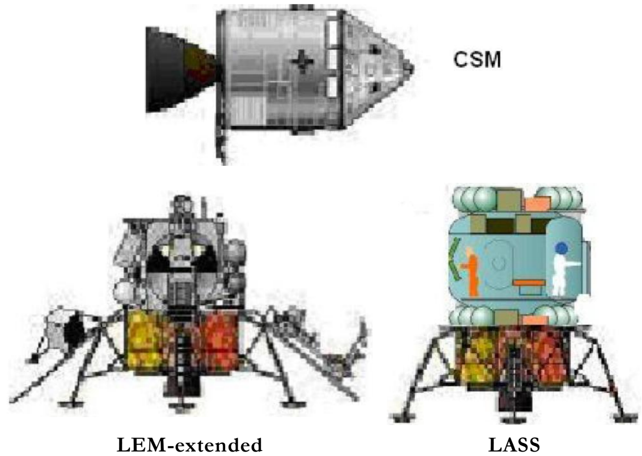


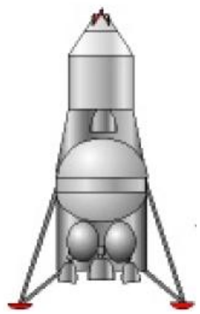
Figure 5 : The LASS was part of a LESA architecture that extended Apollo systems incrementally.

The LASS is proposed to be carried to the Lunar surface by an unmanned Saturn V with a service module derived booster to achieve lunar orbit insertion. See Figure 6.

Figure 6 : The LASS within the Saturn V nose faring with a service module for Lunar orbit insertion.

It should be noted that the requirement that the LASS and similar vehicles fit within the nose faring of the large diameter Saturn V is a design driver, resulting in a "tuna" can or unitary aspect ratio of height to diameter, with its geometry. Mass of a payload scales roughly as its radius squared and linearly in its length, therefore to package maximum mass within a large faring requires the payload to fit the faring diameter and to adjust the mass by adjusting its length, which is less sensitive. The result is that the most efficient package for a large booster payload is a short cylinder or tuna can. This means that mission architectures using a few launches of large boosters without on-orbit assembly will use the tuna-can geometry.

Early Apollo designs also include the concept of a direct landing, using the Apollo CM (Command Module) with a landing and ascent[3] See Figure 7.



North American CSM December 1961

Figure 7 : An early design, direct landing Apollo CM.

New LES (Lunar Exploration System), centered around the Magnum, will probably draw heavily upon Apollo era LESA - Saturn V driven architectures. In particular the CEV (Crew Exploration Vehicle) draws upon the Apollo CM for its design and this philosophy will likely flow down into other elements. This will be especially true for an LES that is designed to optimally support a HMM (Human Mars Mission) since old LESA designs appear to have inspired many of the proposed HMM surface elements.

HMM (Human Mars mission) elements

Recent proposed architectures for HHMs were inspired by the "Mars Direct" architecture proposed by Robert Zubrin[4] that involved the Mars DRM (Design Reference Mission) architecture[5-7] elements for the Mars surface that resembles LESA and early Apollo direct landing vehicles. This is particularly true for the lander habitat shown in Figure 8, that resembles the LASS and the MAV (Mars Ascent Vehicle), which resembles the CM direct lander of Apollo, See Figure 9.

The tuna can –unitary aspect ratio cylinder design for the habitats is driven by the requirement that the habitats efficiently uses large boosters with a large diameter farings in mission architectures that rely on a few large booster launches and no on-orbit assembly similar to the Apollo going to the Moon.

Propulsion for Moon, Mars descent and ascent

If one is to adopt a useful strategy that Lunar and Martian exploration should be synergistic and architectural elements for Mars that should be tested on the Moon, then the fuel systems for descent and ascent from both planetary surfaces should be essentially the same. LOX methane and LOX kerosene are two systems of similar I_{sp} but much possess different storage and synthesis requirements, that are under consideration for both the Moon and Mars operations.

The thermal environment on the Moon makes LOX kerosene the preferable Lunar fuel system because LOX-

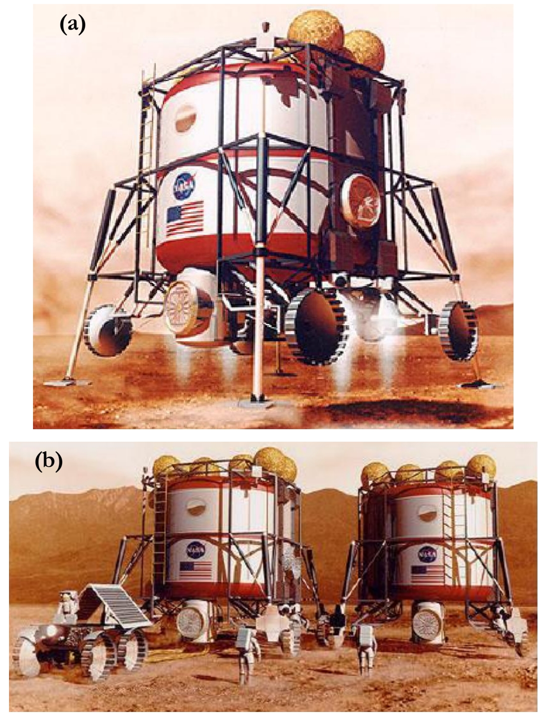


Figure 8(a,b) : Mars lander-habitats.

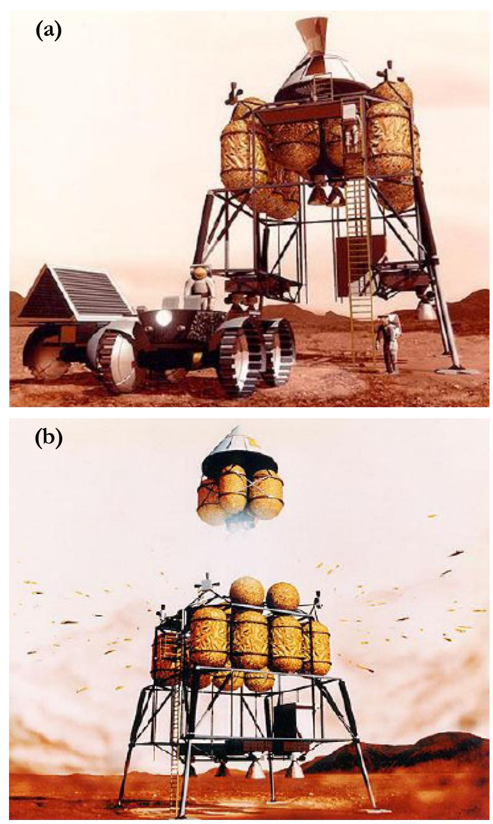


Figure 9(a,b) : MAV loading and liftoff. Note Apollo CM like CEV.

Methane requires twice the refrigeration power for storage on the Lunar surface. Moreover, LOX-methane is presently favored for Mars because of Methane's ease of synthesis from the Martian atmosphere[4-6]. However, Methane, while it gives slightly higher I_{sp} than kerosene, 320seconds versus 300 seconds, requires more hydrogen to carry to Mars[8], a non-trivial consideration. Synthesis of kerosene from the Martian atmosphere has been demonstrated but requires additional refining afterward[8]. Therefore, it is possible that the down-select of methane, propane, or kerosene may be revisited in view of the ease of lunar operations with kerosene.

TMI (Trans Mars injection) propulsion

The Apollo era LOX hydrogen systems of the Magnum will be adequate for lifting payloads to the Moon of the order of 30 tons. However, for the proposed 60 ton landers from the Mars DRM, because of their increased weight and increased delta V required for Mars, a higher I_{sp} propulsion system than chemical fuels will be required. Two proposed systems, either nuclear thermal at 900seconds[4], or Solar Electric at 1500 seconds[9], will be required for a TMI (Trans Mars Injection), which is 3km/sec above escape. A third option is to use the MET thruster using water as fuel at 900 seconds[8,10]. It will be seen that the 60 ton mass estimate for the Mars habitats appears driven by propulsion rather than crew size requirements and so this can be changed.

RESULTS AND DISCUSSION

Drawing from the DRM provides the concept for a 60 ton lander for six people on a thousand day mission. The idea of using similar habitats for both space and Mars surface habitation, we can come up with a simple Moon-Mars architecture. We wish to use the MET thruster SEP system instead of the NTR (Nuclear Thermal Rocket). The problem with the MET SEP system is that it has much less power than the NTR system so that, even though the two systems have comparable I_{sp} (900 seconds), the MET produces much lower thrust. This means the delta V for escape from Earth's or Mars' gravity is approximately double due to the necessity to "spiral-out" rather than undergoing a fast burn to get on an escape hyperbola.

This means we must cut masses and thus crew size, however, we also make use of the MET system's lower mass, and use the LOX hydrogen upper stage of the Magnum, used for Lunar Injection, to boost the Mars payload to an escape trajectory and thus avoid the spiral-out trajectory losses.

Chemical and electric propulsion

We need 6km/sec delta V for a mission to Mars from LEO. It takes 3km/sec to achieve escape velocity and an additional 3km/sec for TMI to Mars. We will assume we have a Magnum derived with 120 tons in LEO.

The advantage of using a combination low I_{sp} chemical and high I_{sp} electric propulsion system for Mars is seen from the following simple calculations:

With LOX hydrogen alone at 500 sec I_{sp} (5km/sec exhaust velocity) we have the equation for payload into TMI in LEO:

$$\mathbf{M_{payload} = M_{intial}\ exp\left(-\frac{\Delta V}{V_{exhaust}}\right)} \quad (1)$$

$$\mathbf{M_{payload} = 120tonnes\ exp(-6km/sec/5km/sec) = 36tonne} \quad (2)$$

For the case of pure electric propulsion the delta V for escape is double by the spiral out process and we have for I_{sp} of 900seconds (exhaust velocity of 9km/sec):

$$\mathbf{M_{payload} = 120tonnes\ exp(-9km/sec/9km/sec) = 44tonnes} \quad (3)$$

only a modest improvement over a chemical system and much longer in time during the months long spiral out burn.

However, if we combine the systems using chemical for escape and the MET for TMI, we have:

$$\mathbf{M_{payload} = M_{intial}\ exp\left(-\frac{\Delta V_{escape}}{V_{exhaust-chem}}\right) exp\left(-\frac{\Delta V_{TMI}}{V_{exhaust-MET}}\right)} \quad (4)$$

$$\mathbf{M_{payload} = 120tonnes\ exp(-3km/sec/5km/sec)\ exp(-3km/sec/9km/sec)} \quad (5)$$

$$\mathbf{M_{payload} = 120tonnes\ (0.54)(0.72) = 46tonnes} \quad (6)$$

Thus we can achieve both high payload to Mars from high I_{sp} electrical and rapid TMI of chemical by combining both systems. The attractiveness of NTR, which has no spiral-out losses, can be seen from a similar calculation where we assume I_{sp} =900 seconds:

$$\mathbf{M_{payload} = M_{intial}\ exp\left(-\frac{\Delta V}{V_{exhaust}}\right)} \quad (7)$$

$$\mathbf{M_{payload} = 120tonnes\ exp(-6km/sec/9km/sec) = 62tonnes} \quad (8)$$

This shows the attractiveness of the NTR despite its high costs and also shows the origin of the 60 ton mass number as the basic size the DRM habitats.

Mars Phobos architecture summary

Here, we briefly describe a system for placing 30 ton packages on Phobos to establish Phobos-station in Mars orbit and the further phases leading to a Mars surface settlement. It must be remembered that the orbital velocity in low Mars orbit is 3.5km/sec whereas the orbital velocity at Phobos is only 2 km/sec. Escape velocity from Phobos orbit is 2.8 km/sec, versus 5 km/sec from the Martian surface. Thus, Phobos-station is good to approach and leave Mars from, but not optimal in terms of access to and from the surface, where low Mars orbit is a better trajectory path waypoint.

First stop and task at Mars will be through Phobos, where a large human base of six persons, is established by digging into the surface regolith. Since this mission will not attempt any surface landing on Mars itself, but instead will do essentially space operations, much more of its payload can be devoted to supplies and living space. Once the Phobos-station is established, it will support, either directly or indirectly, the emplacement of fuel manufacturing stations and habitats on Mars surface. Once supplies are on the surface, Phobos station sets up the Mars base tele-robotically, and monitors its operation. Backup supplies are then stockpiled at Phobos to cover contingencies for any Mars surface base.

The arrival of specially trained and equipped Mars surface landing teams, to occupy the base built tele-robotically from Phobos, will either have a trajectory directly into Mars atmosphere or have a low Mars orbit rendezvous with a landing capsule.

Phobos' orbit is fairly high altitude, and a low Mars orbit rendezvous with an Earth return orbit stage, may therefore be advantageous over an ascent to Phobos. In later phases, a Mars settlement may be better supported by a low orbit Mars space station. Therefore, Phobos-station will serve mostly as a back-up base camp and rescue supply center, than a way station during the final surface landings.

With Phobos' station established, Mars landing mission abort can be achieved to Phobos, with a return to Earth using Mars prepositioned fuel capsules in Mars orbit or at Phobos, and then returning the crew home to Earth. The Mars-Phobos system makes use of Lunar architecture capabilities using LOX hydrogen technology but also the MET high I_{sp} (900seconds) system for the TMI and TEI (Trans Earth Injection) portion of the trajectories. The high thrust chemical thrusters, either LOX kerosene at Mars or LOX Hydrogen at Earth are used for rapid boosts out of Mars' or the Earth's gravity wells and then the MET is turned on to the escape trajectory to supply additional delta V sufficient for interplanetary travel.

First, we reduce the crew size to 3 rather than 6 and adopt a 30 tons habitats and MFP/MAVs (Mars Fuel Plant)/(Mars Ascent Vehicle). We further assume the existence of a Magnum vehicle which puts 120 tons into LEO whose LOX hydrogen third stage to place 50 tons on either a lunar or escape trajectory from the Earth. The twenty ton margin is then available for Lunar operations to land the habitat on the Lunar surface or for TMI propulsion.

The habitats are tested on the Moon and two MFP/MAVs are sent to Mars to test them, first on Phobos and then on the surface. The MFP/MAVs make LOX kerosene fuel and water and put two CEV-mass capsules into Mars orbit to demonstrate end-to-end the MFP/MAV system in the Martian environment. Mars dust may prove itself ingenious in disrupting so called "foolproof" technology tested at Earth. In any case, the Mars for a descent and ascent vehicles, and fueling with ISRU, must be "man-rated" at Mars. The capsules, rather than carrying people from the Martian surface to low Mars orbit, will carry LOX kerosene fuel and water for the return trip from Mars and also for stockpiles held at Phobos. In this way, man-rating of the Mars surface to Mars orbit propulsion will be thoroughly tested, and used to position contingency supplies of fuel in Mars orbit.

The 30 ton MFP/MAV are boosted to Mars by first being part of the 50 ton payload operating on an escape trajectory to Mars by the Magnum third stage. Once on an escape trajectory, the Mars MET-TMI package unfolds 500 kw solar panels and burn 10 tons of water in a cluster of 10 -50 kW METs. These burn for eighteen days to put the spacecraft on a Hohman transfer orbit to Mars. Once at Mars the vehicle burns its MET engines to inject into Mars orbit and aero-brakes into low Mars orbit. From low Mars orbit, the vehicle can drop a 30 ton habitat to the Mars surface or rendezvous with an orbiting Mars fuel and water capsules, orbited earlier to test the Mars surface systems, to obtain fuel for the Earth Return burn. A Mars surface habitat also serves as the crew habitat during the TMI orbit and remains in orbit around Mars when they descend to the surface. For crew descent to the surface after the interplanetary stage is fully fueled in Mars orbit, the crew descends in standard CEV to the surface via retro rocket and parachute. When the stay on the surface is performed, the crew boards the MAV and lifts off the Martian surface and has a rendezvous with the orbiting interplanetary stage habitat. It then burns LOX kerosene to escape from the Mars orbit, where it turns on the MET again to burn water to achieve TEI delta V. This summarizes the system performance.

The thirty ton mass range for packages to and from Mars using mixed LOX hydrogen and MET thruster, meshes well with LOX hydrogen upper stage Magnum capability to place 30 ton LESA-LASS type packages on the Lunar surface. Thus the new Moon-Mars architecture can be viewed as a continuation with new propulsion technology that evolves from the Apollo legacy.

Once a Mars surface base is established, every attempt should be made to establish a colony around it, with the base rapidly reaching self-sufficiency in food, water, and building materials. The basic supply run payload to Mars will then become mainly people. The Phobos-station, so useful in the early days of Mars exploration, will then be supplanted to some extend by a low Mars orbit space station as an Earth-Mars transit hub. Phobos-Station, given its high orbital position, will transition to supporting an asteroid belt human mission to Ceres and other major bodies in the asteroid belt.

Nuclear thermal or Nuclear electric propulsion will supplant the SEP-MET in time, however, water, being very abundant at Mars, and giving good I_{sp}, may become the primary propellant for interplanetary travel using a nuclear electric-MET system.

The establishment of a human presence at Mars, when achieved optimally, and with an eye to the necessity of political support being maintained over several successive Presidential administrations, is best operated using Phobos initially as a base-camp and staging area in the Mars system. Extensive use of Mars ISRU systems to support the Martian surface to low Mars orbit transportation and Solar-electric propulsion.

CONCLUSIONS

Addition of an early Phobos-station to the Mars mission planning "tool-box" as an architecture brings many advantages, and should become part of the Design Reference Mars Mission. As for transportation, the thirty ton mass range for packages to and from Mars using mixed LOX hydrogen and MET thruster, meshes well with LOX hydrogen upper stage Magnum capability to place 30 ton LESA-LASS type packages on the Lunar surface. Thus the new Moon-Mars architecture can be viewed as a continuation extended with new propulsion technology that evolved from the Apollo legacy. The use of LOX-kerosene ISRU-based propulsion on the Martian surface for ascent propulsion, may offer many advantages over LOX methane, the most important of which being that kerosene needs less hydrogen for synthesis. Lunar designed habitats may also be useful for the Mars Phobos-station, and with modification, the Martian surface. Thus, with a reduction of basic crew size, and use of a solar-electric MET interplanetary stage, lunar habitats can be sent to Phobos, and a Mars mission begins, with much less resources than a direct attempt to land and sustain humans on Mars.

The use of Phobos as a base camp and initial beachhead in the Mars system confers many advantages to a Mars mission strategy, not the least of which is to provide an 'early significant accomplishment' of a Mars program and the establishment of an easily sustainable foothold in the Mars system. Phobos is easy to get to, and easy to return from, being relatively high in Mars' gravity potential well. It is the ideal base-camp and staging area for establishing a Martian surface base in preparation for human occupation. The Phobos-station, combined with a Saturn V class booster, ISRU at Mars and Solar-MET propulsion, makes the entire Mars surface landing something that can be performed cheaply and safely over an extended period. This also appears to allow a program that could enjoy political support over successive administrations.

Such a Mars program has considerable synergism with a Lunar base program, using the same large Saturn V class booster, and Lunar habitats, and in its early phases, the establishment of a base on Phobos. The use of Solar-Electric MET propulsion avoids the controversies of nuclear power in any orbit near or approaching Earth. The use of the Martian ISRU for the main tasks of supporting the colony and lifting astronauts and fuel packages off Mars to low Mars orbit for a Mars orbit rendezvous with an Mars-Earth interplanetary stage makes this problem far more solvable than going direct from Earth launch to the Mars surface.

Therefore, taking into account the inherent difficulties of a HMM and the long timescale required for its accomplishment, we must choose an architecture that has non-controversial elements, is incremental with solid milestones, and takes maximum advantage of natural resources and waypoints. Accordingly, we can view a Mars surface landing by humans as part of an incremental generational effort to expand the human habitation across the Solar system, marked, like the Mercury-Gemini-Apollo moon program, by many brilliant milestones. These are: the establishment of permanent space station, the ISS (exists), the establishment of a Moon base, the establishment of a Phobos station, the tele-robotic construction of a Mars base, and finally its human occupation. Moreover, such a program, using a Saturn V class vehicle, Solar Electric propulsion (in its early stages), and using all the resources and advantages afforded by the Earth-Moon and Mars-Moon system, can be sustained politically, and in the end, viewed as the accomplishment of the whole American nation and not just one faction or party.

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