DESTINATION DEIMOS

A convergence of unique attributes and historical forces arguably make Deimos the most valuable piece of real estate in the solar system. But human exploration missions to the outer Martian moon will require imagination, innovation and a daring new approach.

By James S. Logan & Daniel R. Adamo

Without precursors to 'Warp Drive,' 'Shields Up' and 'Beam Me Up' technologies, boldly going where no one has gone before will present formidable challenges. Round trip crewed missions into orbit about Mars are beyond the reach of current capabilities – but just barely. Sufficient attention to new and as yet untested concepts of operations, robust mission architectures, vehicle designs and redundancies mixed with some old-fashioned "Right Stuff" could bring Mars-orbiting missions into the realm of practical human spaceflight.

Deja Vu

Sailing ships routinely plied the Mediterranean Sea for several thousand years before the Golden Age of Exploration began in the 15th century. However, once transoceanic voyages were attempted it didn't take crew, captains or their respective patrons long to realize long-duration voyages across vast expanses of open ocean were a whole new ball game. Ferdinand Magellan left Spain in August of 1519 with five ships and a crew of 265 men. Three years later only one stricken ship and 18 men, half-dead from starvation and disease, limped into Seville harbor after circumnavigating the globe. The great navigator lost fully 80 percent of his crew to Scurvy, a known but heretofore rare disease, crossing the Pacific. Even so, he and his voyage changed the course of history.

Fast forward to the 21st Century. After being mired in low earth orbit (LEO) since 1972, long-duration crewed voyages across interplanetary distances are being seriously contemplated. If successful, history will undoubtedly change course once more. But the warning analogy is clear: in extending human space travel from LEO to interplanetary destinations, we face difficulties no less formidable than did Magellan.

Magellan's voyage was undertaken with primitive 16th century technology. Likewise, the first forays into interplanetary space will be accomplished with rather primitive legacy technologies, many of which date from the 1960s. Propulsion and re-entry techniques for human spaceflight haven't fundamentally changed since the dawn of the space age.

Cumulative Space Experience

Since the first cosmonaut rocketed into space in 1961, over 500 people on more than 270 missions have accumulated over 100 person-years of spaceflight experience. But the vast majority of that experience has been in LEO. The average time on the lunar surface for the twelve Apollo moon walkers was only 2.08 days; the average lunar extravehicular activity (EVA) time only 13.5 hours. Mankind's total experience on another celestial body is less than 7% of a single man-year. Not only are we not experienced interplanetary travelers – yet – but despite hundreds of billions of dollars spent, no human being has been farther from the Earth's surface than San Francisco is from Los Angeles in over forty years.

Return to the Moon Fizzles

Project Constellation, NASA's return to the moon program, was canceled in 2010 for reasons much more complicated than 'been there, done that.' Although scientific justifications for going back to the moon persist, programmatic limitations conspired to reduce the effort to little more than an expensive redo of the same sortie-style missions that were accomplished 45 years ago. The lack of enthusiasm in the general public, Congress and even the halls of NASA itself (where the authors were at the time) was due, in part, to the uneasy feeling it just wasn't bold enough. There was little to excite those passionately desiring human footprints on Mars or those advocating human missions to near Earth asteroids. If science was the ultimate justification for going back to the moon, detractors argued that could be accomplished just as efficiently and vastly cheaper by robots directed from Earth.

Mars remains the beacon for human exploration. Generations of science fiction writers and multiple successful space probes and rovers have established Mars in the core of our collective consciousness. More than any other place, Mars beckons humanity. Although an eventual human landing on Mars is inevitable, most experts agree it is currently a 'bridge too far.' However, there is an alternate path to Mars, one that not only has intrinsic value itself, but also one that would enable the first wave of human visitors to the Mars system to conduct extensive 'humans-in-the-loop' real time tele-robotic exploration of the Martian surface from a natural staging area, the red planet's outer moon Deimos.

Why Deimos?

Deimos has many virtues that make it the logical gateway to the Mars system. It is a full 15 km by 12.2 km by 10.4 km in size; much bigger than near-Earth asteroids NASA is considering visiting in the near term. Unlike the vast majority of near earth asteroids, a launch window to Deimos opens up consistently every 2.14 years. Many experts believe Deimos actually *is* an asteroid, perhaps a carbonaceous chondrite, captured eons ago by Mars' gravitational field.

Only 20,000 km away from the Martian surface, Deimos is less than 5% the distance from the Earth to the Moon. The round trip light time, very important for line-of-sight tele-robotics, is only a little over a tenth of a second, almost 18 times less than from Earth to the Moon and back.

Surprisingly, Deimos is easier to get to energetically from LEO than the lunar surface. Escape velocity from the surface of Deimos is a paltry 12.5 mph (20km/h). Unlike our Moon, no dedicated lander is required. You don't 'land' on a small celestial body with no gravity well; you 'berth' to it. Phobos, the inner, larger Martian moon, resides much deeper in the red planet's gravity well and therefore requires 6.5% more round trip propellant, a seemingly small but significant penalty when considering multiple trips and the distances involved.

Like our moon, the same side of Deimos faces Mars at all times. Because its orbit is just above Mars synchronous orbit (MSO), Deimos would appear to move very slowly east to west as seen from the surface of Mars. From the perspective of Deimos, Mars would appear to slowly rotate eastward at only 2.7 degrees an hour. A Mars surface feature would undergo two sunrises and two sunsets, remaining continuously visible, before rotating out of view. If several surface assets were positioned at regularly spaced longitudes, Deimos-based human tele-operators could circulate westward from one to the next and explore 24/7 [see http://www.youtube.com/watch?v=X10GAqA4Ky4]. Over a period of 5 days 11.2 hours, the entire planet is seen except for extreme polar regions. This "short-range" human telepresence would meet all Mars surface exploration objectives currently documented in NASA Mars Design Reference Architecture [DRA] 5.0, Section 3: Goals and Objectives. Phobos is so close to Mars it unfortunately has a much narrower view of the planet. Because Phobos rises and sets four times a day, acquiring and operating surface assets from the inner moon would be much more challenging than from Deimos.

Those opposed to tele-exploration of Mars from its moons often lament this concept places humans 99.99% the distance between Earth and Mars and stops. Our answer is the majority of funding and consumables expenditures, complexities and risks accrue in traversing the last one hundredth of one percent. Likewise, the base camp at Mount Everest is 99.96% the distance between Houston, Texas and the summit. Yet it is obvious the majority of challenges are in the final fraction of a percent. Successful ascents to the summit of Mt. Everest occur only *after* significant resources and supporting infrastructures are deployed at various base camps, the majority of these resources never reach the summit.

Depending on the resources discovered, Deimos could be utilized as a staging area for the entire Mars system, including the surface. Deimos may hold valuable resources within its interior, and transportable Main Belt asteroid resources may lie just outside the orbit of Mars. In situ resource utilization (ISRU) at Deimos could be a game-changer for Mars exploration. If water ice deposits are found beneath the surface, a Deimos "gas station" could facilitate Earth return transits and even human missions to the Martian surface far sooner than anticipated.

Mission Architecture Is Key

A mission *architecture* encompasses not only hardware but also the operational aspects, the *way* a mission is flown, to optimize efficiency, flexibility, safety and success. The architecture also serves as a technology driver by identifying crucial aspects or elements in need of advancement or further definition through research and development. The chief feature of elegant mission architecture is *synergy*, the process of bringing together various elements so the whole is more than the sum total of the parts. A truly innovative mission architecture makes feasible what otherwise wouldn't be possible. Human missions to the Mars system remain beyond the cusp of the *standard approach*, a *combination* of chemical propellant, minimal radiation shielding, frequent EVAs and no ISRU (other than sunlight). Not only is the *standard approach* insufficient for human interplanetary spaceflight, it is dangerous.

We propose, therefore, a bold and daring yet *essential* departure from the standard approach: A program-level architecture for human tele-exploration of Mars from Deimos resulting in mankind's first viable toehold in interplanetary space as a precursor to permanent human presence on Mars itself.

Any innovative mission architecture derives from challenges. The two biggest for human interplanetary spaceflight are Flight Dynamics, always constrained by the cold hard physics of the rocket equation, and Bioastronautics, the psycho-physiological realities of human adaptation, or lack thereof, to the deep space environment.

Once in orbit about a planetary body such as Earth or Mars, *distance* to an interplanetary destination generally depends on change in velocity (so-called delta-V) and transit time. The higher the delta-V and the more massive the spacecraft, the greater the amount of propellant required. Cargo can tolerate long transit times to minimize delta-V but humans cannot.

A draconian example of the rocket equation's tyranny is Apollo 17. The Apollo moonships were *self-contained* exploration systems. Everything needed to get to the lunar surface and back (crew, supplies, lander, structures, entry vehicle and propellant) was included in a single launch package that stood as high as a sixteen-story building weighing 2,961,860 kg on the launch pad. Just twelve minutes after liftoff 86% of the launch mass had been shed as either spent propellant or jettisoned stages. At mission end less than *two-tenths of one-percent* of the original liftoff mass (the Command Module with the crew) returned to Earth.

For trips to the Mars system and back *including* required stay times, *self-contained* exploration systems are simply not possible.

Precursor Robotic Pre-Emplacement Missions

To reduce the total mass of any human Deimos Transit Vehicle (DTV) to feasible levels, consumables, return propellant and other resources required for extended stay times and Earth return must be pre-emplaced at Deimos. This aspect of our mission architecture should not be surprising. Since its inception in 1927, trans-Atlantic air transport has essentially been a one-way proposition. Even today, round trips across transoceanic distances are possible *only* because pre-emplaced return consumables are available for transport resupply at the destination. Interplanetary transport will share the same dependency.

Establishing a human foothold at Deimos will require a series of increasingly sophisticated unmanned precursor missions with robotic probes capable of everything from detailed mapping and remote sensing of the moon to multiple sample analyses of surface and subsurface strata; excavation and preparation of a radiation-protected subsurface habitat (see below) and storage facilities for pre-emplaced crew consumables and Earth return propellant for visiting crew. Support infrastructure (e.g. power, communications, cooling (heat rejection), refrigeration, environmental control and life support, etc.) must be transported, deployed and proven operational prior to human visitation. With round trip light times from Earth ranging from 7 to 41 minutes, preparation of Deimos Base will present worthy challenges to robotics, automation and artificial intelligence experts.

The sheer amount of consumables required to support a crew of three for a 933-day Deimos mission plus the standard 5% safety margin is formidable. Utilizing standard NASA "Open Loop Life Support" numbers extrapolated for interplanetary flight, a total of 96,658 kg, almost 97 metric tons of water, oxygen, food, crew supplies, gasses lost to space and systems maintenance equipment is required. However, a DTV would only take 25% of the total amount on the outbound leg. The remaining 75%, (for Deimos loiter and Earth return phases) would be pre-emplaced prior to any human visitation.

The Open Loop approach is essential, especially for the first several crewed missions. Complex recycling technology with limited 'person-years' of continuous operation could break down, essentially dooming the crew. It therefore requires adequate spare parts mass be pre-emplaced before crew use. Open Loop may be simple but it works. At Deimos, especially if ISRU resources are available, the risks of implementing closed-loop technologies earlier may be acceptable.

Enhanced Radiation Protection

Space radiation is the chief biomedical 'show-stopper' for human interplanetary spaceflight. Space is a seething cauldron of relentless undulating ionizing radiation with energies sufficient to destroy molecular bonds, strip electrons off atoms creating free radicals and generally wreak havoc on biological systems. Damage results in genome instability, increased mutation rates leading to cancer and accelerated changes usually associated with aging including deterioration of the central nervous system.

Although the Earth's magnetic field deflects lower energy particles toward the poles, for high-energy space radiation it's the *mass shielding* effect of Earth's atmosphere that protects the biosphere from harm. All creatures on Earth benefit from a natural, passive and constant 1030 grams per square centimeter (g/cm^2) radiation shield. We have devised a simple radiation protection scale pegged to the shielding equivalent provided by Earth's atmosphere. A shielding equivalent of 1030 g/cm^2 provides 100% of Earth radiation protection – or RP100. At 18,000 feet above sea level half of the atmosphere is above and half is below - the equivalent of RP50. By contrast, the most protected areas of the International Space Station provide RP2 and the spacesuit provides less than RP0.1.

NASA career space radiation exposure limits are based on the REID concept, Risk of Exposure Induced Death. REID is a statistical metric pegged to a single radiation effect: death_from cancer directly attributable to the exposure. NASA's astronaut career dose limits accept a lifetime increase of cancer mortality of 3%.

The average daily dose rate, measured *inside* the Mars Science Laboratory (MSL) spacecraft, on its 253-day, 560-million kilometer journey to Mars was a whopping 1.8 millisieverts (mSv) per day, 180 times the average daily radiation dose at sea level. This is equivalent to getting a whole-body CT scan once every 5-6 days.

A typical round trip to Deimos consists of an outbound leg of 203 days, a Deimos stay time of 497 days until the next Earth return window opens followed by a 233 day Earth return. Assuming the average radiation dose rate at Deimos is half the interplanetary dose rate (a reasonable assumption considering the Mars surface dose is roughly one-third the interplanetary dose – Mars does have an ultra-thin atmosphere and it is much more massive than Deimos), a rough estimate of the total mission radiation dose *without additional shielding* can be calculated – approximately 1.232 Sievert (Sv) - a number that exceeds the current LEO *career* radiation dose limits for all astronauts except males aged 55 years or older. It also equates to more radiation than one would receive in 342 lifetimes on Earth.

Long-duration exposures to microgravity result in deleterious effects in multiple organ systems and subsystems including loss and alteration of skeletal and cardiac muscle, irreversible trabecular bone demineralization, decreased immune function and permanent changes in vision. Evidence suggests the combination of radiation and microgravity is worse than either alone. Remembering Magellan's experience, attempting interplanetary flight without adequately addressing these issues risks inadvertently ushering in a dangerous, prolonged and ultimately preventable 'Scurvy Phase' of space exploration.

Although pharmaceuticals and even genetic modification may play a role in the long term, for the foreseeable future *mass shielding,* however disdainful*,* appears to be the only viable option for enhanced crew radiation protection. As a general rule some shielding is better than none and more shielding is better than less.

By invoking a single operational requirement, providing RP100 at Deimos (the equivalent protection of Earth's atmosphere at sea level), accomplished by pre-emplacing the Deimos habitat *inside* the moon rather than on the surface, total mission radiation dose is reduced by almost 40% (compared to surface exposures *without* enhanced radiation protection) and total number of exposed days by 53%. Provided the equivalent of about seven meters of Deimos regolith separates the crew from interplanetary space, this requirement will be met. This same level of protection can be provided on the Moon and Mars by burying habitats 4.12 and 2.65 meters below the surface respectively (http://spaceenterpriseinstitute.org/2014/07/space-radiation-the-elephant-in-the-room-trumpets/).

During interplanetary transit radiation protection is more problematic. Severe weight and volume constraints make mass shielding seem impractical for long-duration missions. NASA adheres to the ALARA principle (as low as reasonably achievable) regarding radiation exposure. As our understanding of basic mechanisms of radiobiology expands and supporting technology improves, the level of radiation protection considered 'reasonably achievable' continues to evolve.

RP5 (51.5 g/cm^2 shielding equivalent) is a particularly attractive compromise level of protection for the entire crew compartment in transit. Not only will it protect the crew from acute radiation sickness for all but the most intense solar storms, it is an inflection point beyond which additional shielding doesn't decrease the dose equivalent significantly until much higher levels of shielding are attained. In other words, RP5 provides the *most* reduction in radiation dose for the *least* mass. Considering other attributes of our proposed mission architecture (see below), RP5 (2.5 times the protection provided by any spacecraft to date, over 10 times the protection of the Apollo lunar lander and 50-100 times the protection of the spacesuit) can now be considered within the realm of *reasonably achievable*.

Part II

Synergy of Radiation Protection, Multi-use Propellant and Advanced Propulsion

Due to its high hydrogen content, water is an excellent radiation shielding material. Because significant quantities are required to provide RP5, depending on the surface area of the crew compartment, increased efficiencies can be realized if shielding materials can be multi-use.

The largest mass component of any foreseeable interplanetary vehicle, or any rocket for that matter, is propellant. Water is a storable liquid over a wide range of easily maintained temperatures and can be used as a viable propellant with Nuclear Thermal Propulsion (NTP), a technology that has been eagerly anticipated for decades and has a 40-year developmental pedigree including static test firings of evolving prototypes of increasing power, duration and complexity. Basically NTP consists of a rocket engine that is a solid core of controlled fissionable material. As the nuclear core heats up, liquid water is used to cool the core. At 2600^{o}C water flashes into steam but also begins to dissociate into hydrogen and oxygen atoms that exit the engine nozzle at high speed generating thrust.

The space shuttle main engines, using liquid hydrogen and oxygen, are the most efficient *chemical* propulsion system currently attainable with a specific impulse (I_{SP}), a measure of rocket engine efficiency, of approximately 465 s. If NTP core temperatures could be maintained well in excess of 3000^o C, a formidable but ultimately solvable materials challenge, the vast majority of water molecules dissociate directly into hydrogen and oxygen atoms instead of steam resulting in I_{SP} approaching 900 s, essentially providing twice the '*kick'* of chemical propellant.

Once a mission architecture encompassing the synergistic elements described is embraced, a reference interplanetary transport spacecraft begins to take shape. Liquid water can be transported and stored over long intervals in space with ease, especially compared to the exotic technical and power burdens necessary to produce and maintain cryogenic propellant or the toxicity hazards associated with hypergols. Water will arguably be the most common volatile found on asteroids or minor moons and therefore easily integrated into any usable ISRU scenario.

Because it is utilized for crew sustenance and hygiene, radiation protection and propellant, liquid water will account for almost 54% of the gross mass of our envisioned spacecraft prior to interplanetary departure. We therefore propose the first human interplanetary transport spacecraft be christened *Aquarius* in deference to the Zodiacal Water-Bearer of that name.

Age of *Aquarius*

Three nuclear thermal engines with a cumulative mass of 41,700kg (not counting propellant and water tank structural mass) achieving an I_{SP} of 900 s and generating a total thrust of 333,617 Newtons (Nt) and exhaust speed of 8.826 km/sec will propel *Aquarius* and her crew of three on round trip missions to Deimos utilizing short-way (Type 1) transits lasting 200-240 days in accord with conjunction mission profiles. [NOTE: First generation "Pewee" NTP engines (core size of 20x52 inches) developed by the U.S. NERVA project the late 1960s and early 1970s generated 20,000 pounds of thrust with an *I*sp of 825 s. Engines envisioned for *Aquarius* require only a 25% increase in output per engine, Approximately 500 days will be spent at Deimos dedicated to tele-robotic Mars exploration and *Aquarius* resupply from pre-emplaced or ISRU resources before an Earth return transit of 200 to 240 days duration can begin. The three engines, utilizing "bi-modal" reactor operations, will power all electrical loads aboard Aquarius during cruise periods.

Open loop environmental control and life support systems (ECLSS) maximize simplicity and reliability avoiding operational risks of complex reclamation and recycling technologies. Almost 99 kg of consumables per day are dumped/vented overboard resulting in a vehicle approximately 20,000 kg lighter at Mars capture, decreasing the amount of propellant required for Deimos rendezvous.

A cylindrical Hab, 4.6 m in diameter by 12.2 m in length, will provide 67.58 m^3 per crewmember, 3.38 times the NASA standard for "Optimal" per capita habitable volume for missions longer than 6 months. RP5 (51.5 g/cm^2) for the entire Hab will be accomplished by a special shielding "jacket" with two components: (1) Hab structure and strategic consumables placement will provide 14.5 g/cm^2; and (2) a sleeve surrounding the structure consisting of 87,053 kg of multi-use water propellant will provide the remaining 37 g/cm^2. At Deimos, RP100 during crew loiter periods between transits is assumed. Because the water radiation shield can be consumed as propellant as Mars is approached, radiation protection will dip below 51.5 g/cm^2 for less than ten hours prior to Deimos arrival.

A Docking/Airlock/Centrifuge (DAC) module, 4 meters in radius and 2 meters in length with a mass of 26,461 kg (including a 1700 kg 3-meter short-arm centrifuge designed to give the crew intermittent exposure to a gravity gradient of 1.0g at the heart and 2.5g at the feet), will be located at the forward end of the Hab. Although pressurized, crew access will be limited to less than 2 hours/day because its volume is shielded from radiation only by DAC structure.

Synergy of Spacecraft Design, Assembly and Reusability

Even with pre-emplacement of resources required for Deimos stay and Earth return, the mass of *Aquarius* just prior to interplanetary departure is 357 t, approximately 90% current ISS mass. Attempting the same mission with chemical propellant (I_{SP} =450s) would increase departure mass to 832 t, 210% current ISS mass.

Rather than the notional sci-fi version of a pencil-shaped interplanetary spacecraft with the crew quarters in the forward 'nose' of the vehicle and the engines in the rear, *Aquarius* is designed to provide maximal radiation protection by surrounding the crew with spacecraft infrastructure, tankage, plumbing, consumables, propellant as well as dedicated propellant shielding. Ideally, she could assume a more spherical shape with engines protruding from aft compartments.

Aquarius build-up and assembly takes place over a multi-month period in a special 2-day 7,700 km by 113,300 km Earth elliptical parking orbit (EEPO) to reduce human and electronic exposure to particle radiation trapped in the geomagnetic field and to take advantage of upper stage cryogen propellant in each of seven assembly boosters to propel *Aquarius* part way out of Earth's gravity well during buildup. Each assembly booster is designed to place 130 t into LEO. From there an upper stage will deliver a 50,000 kg payload using cryogenic propellant as *Aquarius* is assembled and supplied in EEPO.

The final delivery to *Aquarius* would consist of the crew, their gear and personal items ferried by a much smaller launch vehicle. After appropriate checkout of *Aquarius* systems, a small retrograde burn of 0.242 km/s at EEPO apogee will lower the perigee height from 7725 km to a mere 400 km. At perigee the combination of a prograde 1.116 km/s Trans Mars Injection (TMI) burn and the Oberth "slingshot" effect will propel *Aquarius* out of Earth's gravity well and into an interplanetary trajectory intercepting Mars 203 days later.

At closest approach to Mars a retrograde Mars Orbital Insertion (MOI) burn of 1.586 km/sec places *Aquarius* on an intercept trajectory to Deimos. A final prograde burn of 0.751 km/s enables *Aquarius* to catch up to Deimos to implement final approach and rendezvous. The total delta-V expended during the 204-day transit from EEPO to Deimos is 3.695 km/s.

Upon Deimos arrival, transfer of crew and cargo to the RP100 subsurface Habitat is via a pressurized docking interface. During a 497-day stay time dedicated to extensive tele-robotic exploration of the surface of Mars and perhaps both moons as well, the same interface would facilitate transfer of pre-emplaced water and other consumables from Deimos infrastructure to *Aquarius* prior to Earth return transit.

On Mission Day 700 a fully resupplied *Aquarius* performs a departure retrograde burn of 0.652 km/s initiating a Mars fly-by six and a half hours later. At closest approach, on the daylight side of the red planet, a prograde 1.553 km/s Trans Earth Injection (TEI) burn puts *Aquarius* on an intercept path to Earth 237 days later.

During this cruise phase of the mission profile, *Aquarius'* water radiation shield is in full RP5.1 (52.7 g/cm^2) protection mode. It is at precisely *this* point in the mission profile, as Earth looms ever larger at the end of the return transit, the *synergy* of multi-use propellant, enhanced radiation shielding and advanced propulsion demonstrates its *greatest* advantage. In standard mission architectures, the crew would now be forced to transfer to a dedicated smaller vehicle and perform an Apollo-style direct entry. Slamming into the Earth's atmosphere at speeds in excess of 11.9 km/s after 933 days of almost continuous exposure to microgravity would put the crew at significant risk.

But since *Aquarius* can burn part of her radiation shield at mission end, i.e. use the water in her radiation shield as propellant, an entirely new scenario resulting in reusability, avoidance of direct entry and complete resupply with only 52% of her initial assembly mass now becomes routine on a repetitive basis.

At closest Earth approach on Mission Day 933, rather than ending her first and only mission by becoming just another piece of space junk, *Aquarius* ignites her nuclear engines once again for a retrograde 0.935 km/s Trans Lunar Injection (TLI) burn, utilizing a portion of her radiation shield as propellant, setting her on a path to a special parking orbit. Almost 70 hours later she performs a retrograde 0.378 km/s Lunar Orbit Insertion (LOI) burn. About 7.5 hours after that *Aquarius* executes a final prograde burn of 0.309 km/s to gently enter the most stable orbit known in cis-lunar space, a selenocentric distant retrograde orbit (SDRO), one that takes the least amount of energy to maintain over extended periods of time.

Far from being fully depleted, her radiation protection level decreases from RP5.1 to 4.2, 3.8 and 3.5 at TLI, LOI and SDRO insertion respectively, the last still providing an impressive 35.7 g/cm^2 shielding equivalent.

In SDRO *Aquarius* will rendezvous with previously established resident infrastructure providing full RP5 protection and equipment for a 30-day intensive exercise crew rehabilitation program before the crew returns to Earth in a separate vehicle. *Aquarius* will be resupplied, undergo required maintenance and no doubt receive much needed TLC from her tenders for 574 days until the next Earth departure season for Mars. With a full consumables load prior to beginning her next mission, *Aquarius* can provide RP7.8 (80.4 g/cm^2) equivalent radiation shielding.

Our mission architecture avoids lugging a 10 t Earth entry vehicle all the way to Deimos and back, then using it 933 days into the flight. It also eliminates the expense and complexity of rebuilding an *Aquarius* replacement from scratch for *each* subsequent mission.

The capacity to burn her radiation shield as propellant in contingency situations provides yet another synergistic advantage: expanded abort capability. Given the amount of water onboard, *Aquarius* could initiate return to her point of origin (Deimos or Earth) up to two weeks after departure.

Approximately 19 months after first entering SDRO, a fully resupplied and crewed *Aquarius* will execute three small burns leading to a Trans Earth Insertion trajectory from which a prograde TMI burn of 0.891 km/s assisted by the Oberth effect will again put her on a path to Deimos for the second time.

The *Aquarius* concept is only one potential solution to practical interplanetary human spaceflight. Innovative synergistic mission architectures can bring into the realm of feasibility missions and destinations otherwise beyond the cusp of current capabilities. In this case the *combination* of precursor missions, resource pre-emplacement, advanced propulsion, enhanced radiation protection, multi-use propellant, intermittent artificial gravity, stable parking and departure orbits and heavy lift Earth launches conspire to create a new class of *reusable* human interplanetary transport spacecraft, one pre-adapted to maximally benefit from the discovery of extractable water on *any* small body in the solar system. By demonstrating practical roundtrips to Deimos, *Aquarius* could transport human explorers to more than 1100 known near-Earth asteroids (NEAs) whose accessibility is occasionally greater.

A more technical description of the *Aquarius* concept can be downloaded at http://spaceenterpriseinstitute.org/2014/07/aquarius-a-reusable-water-based-interplanetary-human-spaceflight-transport/.

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