Comments on *Human Exploration of Mars Design Reference Architecture 5.0*

The document at which commentary in this paper is directed was published as NASA/SP-2009-566 in July 2009. It and related documentation may be downloaded from http://www.nasa.gov/exploration/library/esmd_documents.html [accessed 2010 January 8]. Human Mars exploration architecture documented by NASA/SP-2009-566 will be referenced as "DRAv5.0" throughout this paper.

The author's interests and viewpoints as an independent astrodynamics consultant have motivated this commentary as follows.

A) Technology and operational feed-forward assumed by DRAv5.0 documentation are consistent with what the Review of U.S. Human Space Flight Plans Committee (HSFPC) subsequently came to term the Program of Record (PoR). Consequently, ISS and lunar outpost missions from the PoR provide the bulk of feed-forward to DRAv5.0. Best available intelligence on HSFPC-developed options favored by the Obama Administration indicates the PoR will be modified into a more incremental feed-forward approach to human Mars exploration. Mars feed-forward from deep space human exploration destinations other than the Moon, most notably near Earth objects (NEOs), therefore motivates a subset of commentary. The HSFPC's final report may be downloaded from http://www.nasa.gov/pdf/396093main_HSF_Cmte_FinalReport.pdf [accessed 2010 January 11].

B) Over the past year, the author has researched and developed a lunar surface rendezvous (LSR) mission mode based on two heavy-lift launches conducted over an interval spanning one to five months. A subset of commentary is therefore motivated either by LSR's commonality with DRAv5.0 or by LSR's feed-forward applicable to DRAv5.0. An LSR executive summary and white paper may be downloaded from http://www.nasa.gov/pdf/373994main_036%20-%2020090608.17.LSRvirtuesR6.pdf [accessed 2010 January 11].

C) Certain DRAv5.0 concepts have been clarified in consultation with NASA/SP-2009-566 editor Bret G. Drake and are to be documented in this commentary.

The following enumerated list of specific DRAv5.0 comments contains citations and quotations from NASA/SP-2009-566, including page numbers. Add 14 to a NASA/SP-2009-566 page number to obtain the corresponding page in this document's downloaded PDF file. The author may be contacted at adamod@earthlink.net with feedback on these comments.

1) (p. 2) "...*human Mars missions are assumed to have been preceded by a sufficient number of test and demonstration missions on Earth, in the ISS, in Earth orbit, on the Moon, and at Mars (by robotic precursors) to achieve a level of confidence in the architecture such that the risk to the human crews is considered acceptable.*" There is a huge Earth distance gap between human operations on the Moon (~400,000 km) and on Mars (up to ~400,000,000 km). Corresponding communication latencies jump from several seconds to tens of minutes, and transit

times jump from several days to several years. The Moon to Mars distance gap can be incrementally spanned by increasingly more challenging human NEO missions. Although NEO communications latencies and transit times are generally greater than those associated with the Moon, propulsive and destination-specific systems requirements for NEO round-trips can be considerably less than for lunar round-trips. Thus, it may be possible to embark on a series of progressively more challenging human missions to NEOs with less initial expense and at an earlier date than would be associated with a human return to the Moon.

2) (p. 2) "*This, the so-called 'pre-deploy' or 'split mission' option, would allow a lower energy trajectory to be used for these pre-deployed [cargo-only] assets, which allows more useful payload mass to be delivered to Mars for the propellant available.*" Because the PoR brings lunar crew and cargo together in LEO, only 0.05% of the distance to the destination, it's unable to take advantage of this efficiency. Although the author's LSR research has not quantified increased mass deliverable to the Moon on long-transit trajectories, the LSR mission mode offers this potential efficiency if Descent Module (DM) cryogenic propellant mass can be sufficiently preserved. Thus, LSR's DM becomes a Mars feed-forward technology test bed.

3) (p. 3) "*Due to the significant amount of mass required for a human mission to Mars, numerous heavy-lift launches would be required.*" If the heavy-lift launch vehicle can be human-rated, LSR will provide DRAv5.0-relevant operational experience with paired launches by this vehicle in a context with minimal time criticality. Similar multi-launch scenarios by this vehicle could be associated with human missions to NEO destinations. The number of heavy-lift launches supporting a NEO mission would likely be at least two, and more remote destinations including Mars orbit could entail launch campaigns approaching those associated with a single DRAv5.0 cargo Mars transfer vehicle (MTV) as documented on pages 27 and 29 in Tables 4-1 and 4-2, respectively.

4) (p. 3) "*This* [autonomous deployment] *strategy includes the capability for these* [Mars surface] *infrastructure elements to be unloaded, moved significant distances, and operated for significant periods of time without humans present.*" In an LSR mission, the crew exploration vehicle (CEV)/DM lands on the Moon with its human payload adjacent to the pre-emplaced return consumables module (RCM)/DM. In addition to its automated landing, the RCM/DM is required to resupply the CEV with propellant and any other consumables required for the crew's return to Earth from the lunar surface. The resupply would ideally be conducted robotically with minimal human involvement while the crew explores the lunar surface. Although not essential to LSR, RCM/DM surface activities could be evolved to include lunar in-situ resource utilization (ISRU) such as LOX production, storage, and transfer to the CEV. Nearly all RCM/DM-related LSR activities on the Moon have their counterparts with pre-emplaced DRAv5.0 Mars surface elements. Pre-emplaced robotic resources, possibly including ISRU capabilities, could also enable or enhance human NEO missions.

5) (p. 7) "...*search* [for extraterrestrial life] *could be permanently compromised if explorers carry Earth life and inadvertently contaminate the martian environment.*" This *forward contamination* issue is unique to missions requiring humans on the martian surface because any robotic missions with insufficient sterilization have presumably already done their harm beginning with the *Viking 1* landing in 1976. Consequently, there should be compelling reasons to place humans on the martian surface if forward contamination risks to native martian life are to be tolerated. It is arguable such motivation should include survival of our species since humans on the martian surface may inadvertently trigger the extinction of some native species there. Particularly in the early phases of human Mars exploration, when potential subsurface life is still an open question for example, consideration should be given to confining human explorers to Mars orbit. This degree of proximity would reduce communications latency to the extent required for practical teleoperated Mars surface and subsurface exploration. It would also eliminate the need to transport extra propulsive mass and specialized systems to Mars orbit because human descent and ascent from the martian surface is not initially required. Human explorers confined to Mars orbit could be emplaced sooner and at less initial expense than ones transported to the surface. Natural platforms for teleoperated Mars exploration by humans would be the moons Phobos and Deimos. Because these moons share common physical properties with NEOs, human NEO exploration has excellent feed-forward potential to offer this initial Mars exploration strategy. In effect, initial human exploration of Mars from its moons can be regarded as yet another increment in NEO exploration.

6) (p. 9) "*Based on assessments to date, the aerostationary orbit* [equatorial Mars inclination with 1.026-day period] *option is selected as the most desirable dedicated orbit option* [for communications and navigation support of Mars surface operations]*, in particular based on its continuous coverage capability.*" Deimos inclination ranges from 0.9° to 2.7°, and its orbit period of 1.262 days at a mean altitude of 23,459 km is nearly aerosynchronous. Its nadir drifts westward over martian equatorial regions at the rate of 65.6°/day, and it would therefore remain continuously visible to a non-polar fixed location on the martian surface for 2.5 days. If several robotic exploration facilities were emplaced around Mars at roughly equal intervals in longitude, humans confined to Deimos could remain engaged full-time in teleoperated Mars surface/subsurface exploration with these facilities.

7) (p. 10) Human characteristics applicable to Mars exploration science "*include: speed and efficiency to optimize field work; agility and dexterity to go places that are difficult for robotic access and to exceed currently limited degrees-of-freedom robotic manipulation capabilities; and, most importantly, the innate intelligence, ingenuity, and adaptability to evaluate in real time and improvise to overcome surprises while ensuring that the correct sampling strategy is in place to acquire the appropriate sample set. Real-time evaluation and adaptability especially would be a significant new tool that humans on Mars would bring to surface exploration.*"

With the secondary exception of agility and dexterity, all these human attributes can be provided from Mars orbit with undiminished effect. It is also arguable that human agility, particularly when encumbered by pressurized apparel, is superior to robotic mobility on the martian surface. For example, if a location is too hazardous for robotic access, clambering to it in an environment with lethal ambient conditions likely represents a significant and inadvisable risk to human life and limb too. Given the relative ease with which human exploration of Mars may be initiated when humans are confined to Mars orbit, the relatively minor compromises imposed on scientific objectives appear to be a trade worthy of serious future consideration. Many of these compromises could be minimized by capability to interactively transport selected surface and subsurface samples from robotic facilities on the martian surface to humans waiting in orbit.

8) (p. 11) "*Under real-time human control, robotic probes could traverse great distances from the human habitat, covering distances/terrain too risky for human exploration; undertake sensitive, delicate sample handling operations; and return rock and dust samples to the habitat for triage and laboratory analyses.*" This teleoperated operations concept applies equally well to human explorers confined to Mars orbit. The "sensitive, delicate sample handling operations" also appear to contradict robotic dexterity concerns previously quoted from p. 10. On succeeding pages, an effort is made to extrapolate Mars scientific knowledge into the 2025 timeframe, but a similar robotic technology extrapolation is absent. Perhaps this is responsible for apparent contradictions in what can and cannot be accomplished by robotic systems on Mars by the time humans arrive in the vicinity.

9) (p. 20, including bold-face text) "***From the perspective of our scientific goals, it is clear that our progress would be optimized by visiting multiple sites and by maximizing the stay time at those sites.***" This multi-site DRAv5.0 exploration strategy could be initiated years earlier by implementing it with humans confined to Mars orbit in a single mission as opposed to landing humans at 3 martian surface locations over the course of 2 additional mission cycles (reference p. 3, Figure 2-1 for a 2-mission timeline). The single orbital mission could likely be launched many years before an initial human mission to the martian surface due to its freedom from previously cited Mars decent/ascent performance and systems development requirements.

10) (p. 25) "...*further assessments regarding manufacturing, assembly, integration, test, and checkout of the systems that are required for the higher launch rate that is associated with the Mars missions, as compared to the lunar missions, is warranted.*" These assessments should include impact of a Mars launch campaign on lunar infrastructure and its supporting logistics. Ignoring Ares I launches, Table 4-1 (p. 27) and Table 4-2 (p. 29) indicate these campaigns will entail Ares V launches at uninterrupted 30-day intervals over periods from 90 to 180 days. As indicated by Figure 2-1 (p. 3), the crewed MTV launch campaign for Mission N overlaps with cargo campaigns for Mission N+1 and could easily span a year. Previous LSR research has revealed that, even if both Launch Complex 39 (LC39)

pads are compatible with Ares V, two parallel launch vehicle processing flows cannot support a sustained launch rate greater than once per month. Unless LC39 infrastructure and Ares V production rate undergo significant augmentation, lunar logistics must therefore be suspended during DRAv5.0 launch campaigns for intervals spanning up to a year. These lunar logistics outages will commence at ~26-month intervals.

11) (p. 28) "*A separate block upgrade version of the Orion vehicle [CEV] remains docked to the transit habitat [MTV] until shortly before Earth return, when the crew would separate from the transit habitat and perform a direct-entry Earth return.*" Per mission sequence Step #9 in Figure 2-2 on p. 5, this CEV undocks from the MTV and transports the crew to the pre-emplaced surface habitat (SHAB) waiting in Mars orbit. Prior to the crew initiating SHAB deorbit/entry/descent/landing on Mars, this CEV would presumably return to and dock with the MTV under autopilot control. Propellant and other consumables required for this CEV round trip must be budgeted in CEV mass at trans-Mars injection (TMI).

12) (p. 30) "*Earth entry speeds from a nominal Mars return trajectory may be as high as 12 km/s, as compared to 11 km/s for the lunar CEV.*" Preliminary NEO mission designs indicate this entry speed gap can be filled at manageable increments by progressively more remote destinations with appropriate Earth return transit times. Thus, NEO exploration again provides excellent feed-forward prospects to DRAv5.0.

13 (p. 31) "*Note that limiting the* [Earth return] *entry speed to the DRA 5.0 recommended limit of 12 km/s can provide significant reduction in TPS technology requirements as compared to previous studies with entry speeds up to 14 km/s.*" Consultation with NASA/SP-2009-566 editor Bret G. Drake in January 2010 has verified the 12 km/s speed limit is not arbitrary but rather the consequence of eliminating Earth return trajectories from Mars by way of a Venus gravity assist. Such high-speed trajectories are confined to the opposition-class mission option eliminated from DRAv5.0. By virtue of its longer duration, the conjunction-class mission option adopted by DRAv5.0 can utilize optimal heliocentric phasing in departing Mars for Earth. This optimal phasing maintains Earth return entry speed under 12 km/s.

14) (p. 33) "*The descent stage is an all-propulsive, legged lander concept that uses four pump-fed LOX/LCH4 engines with the following reference characteristics: an Isp of 369 sec...*" The author's LSR research assumes a DM with LOX/LH2 propellant delivering an Isp of 450 sec. It may be possible to modify this initial DM concept to a LOX/LCH4 configuration, particularly if decreased propulsive efficiency is compensated through reduced structural mass because LCH4 is less bulky than LH2. If a reasonably accurate and scalable mass ratio between LOX/LCH4 propulsive systems and usable propellant can be specified, this modification's impact on LSR performance can easily be assessed. Should this

assessment prove viable, LSR feed-forward relevance to DRAv5.0 would be further enhanced.

15) (p. 34) "*An even more critical assumption is that the systems comprising the transit habitat (and SHAB) would be largely based on hardware design and reliability experience gained by ISS operations, as well as long-duration surface habitat operations on the lunar surface (i.e., lunar outpost), which would precede any Mars campaign.*" With regard to the transit habitat, this design and experience feed-forward would be enhanced in association with NEO missions as opposed to lunar surface habitats. Because NEO missions span a duration spectrum stretching from months to years, habitat *scalability* becomes an important design attribute. Particularly if lunar exploration strategy abandons the outpost concept in favor of sorties, surface and transit habitat scalability could become essential to DRAv5.0 feed-forward.

16) (p. 34, Table 4-4) A noteworthy item in this table is 7.94 mT dedicated to "*Food (Contingency)*". This mass is redundant to human consumables also landed on Mars, and it protects a Mars surface mission abort to the transit habitat in Mars orbit, where the crew awaits the next trans-Earth injection (TEI) opportunity. Along with zero human-specific Mars surface systems mass, an exploration mission confining humans to Mars orbit would not require this redundant mass.

17) (p. 34, Table 4-4) Mass associated with the CEV at TMI is assumed to be 10 mT. This value appears too small because it fails to cite service module (SM) mass, while only accounting for CEV *Orion* crew module (CM) mass. On p. 31, 9.227 mT is associated with "*the Orion lunar vehicle*", but this value excludes SM mass. A "*CEV/SM*" docked to a "*Transit Habitat*" is present in Figure 4-5 (p. 26). In Table 4-1 (p. 27), a "*CEV/SM + Crew*" payload element is valued at 10.6 mT. In Table 4-2 (p. 29), a "*CM + Crew*" payload mass item is valued at 10.6 mT, but no SM mass is explicitly cited. Suppose a lunar SM were scaled to provide 300 m/s Δv for MTV separation and entry interface targeting during the final 3 days of a DRAv5.0 Earth return. The resulting SM "wet" mass would be no less than 2.6 mT assuming specific impulse of 314 s and a CM mass of 11.1 mT (10.6 mT CM plus crew mass increased by 500 kg of Mars return science mass) obtained in consultation with NASA/SP-2009-566 editor Bret G. Drake in January 2010.

18) (p. 51, Table 6-2) "*Orion Earth return speed 'within Orion family' – 12 km/s (TPS implications).*" As previously noted, consultation with NASA/SP-2009-566 editor Bret G. Drake in January 2010 has confirmed selecting the conjunction-class mission option for DRAv5.0 establishes this Earth return speed limit. The alternative opposition-class option, excluded from DRAv5.0, is associated with Earth return speeds as high as 14 km/s.

19) (p. 59, Figure 6-6) Delivered mass, volume, and power trades among several ISRU options indicate tapping into Mars H2O could substantially reduce exploration mass transported from Earth. This strategy incurs additional risk with respect to

the CO2-only ISRU adopted for DRAv5.0 because it entails martian soil transport and processing. Given the dearth of macroscopic H2O deposits on the Moon, it is difficult to retire this risk there. Because a subset of NEOs is undoubtedly rich in H20 content, these exploration destinations may offer highly relevant ISRU feed-forward potential to Mars exploration.

20) (p. 62, Table 6-6) If humans are confined to Mars orbit during initial Mars exploration, many vulnerabilities of crew dependency on solar power (automated array deployment and suspended/deposited dust attenuation, for example) are diminished with respect to its use on the martian surface. If nuclear power is still preferred in support of robotic surface systems, power generation capacity, transmission distance, and shielding mass requirements will be greatly reduced if human explorers are confined to Mars orbit. Power-related payoffs from humans confined to Mars orbit are therefore likely to enable Mars exploration earlier and at less initial expense than would be the case with humans initially transported to the martian surface.

21) (p. 73) "*Note that the longest flight of stored cyrogens* [sic.] *is Titan Centaur-5, where the propellants were stored in orbit for a* [sic.] *9 hours.*" Storage problems associated with cryogenic propellant required for DRAv5.0 will be difficult to solve with the PoR because ISS and lunar exploration do not log appreciable time in deep space far from Earth/Moon thermal effects. Considerably more DRAv5.0 feed-forward on this problem's solution would be accumulated during NEO missions.

22) (p. 78) "*Given the large investments that are required and the risks that would be incurred in pursuit of human missions to Mars, public commitment over several decades will be critical to mission success.*" The HSFPC suggested this commitment could best be sustained by successfully achieving a series of human exploration milestones to progressively more remote destinations. Regular and progressively more challenging human missions to NEOs will provide these milestones. Supported by a robust NEO detection program already mandated by Congress, together with appropriate robotic precursor missions, each human mission to a NEO will bring the public to a unique and exotic new world while advancing the science and astronautics necessary to explore Mars and the entire solar system.