Comments On The NAS Report *Pathways to Exploration* (Released June 2014)

Preface

This essay is a personal commentary on the prepublication draft of a report titled *Pathways to Exploration–Rationales and Approaches for a U.S. Program of Human Space Exploration* obtained from The National Academies Press via PDF download in June 2014 at http://www.nap.edu/catalog.php?record_id=18801 (accessed 20 July 2014). The essay author's opinions as an unaffiliated astrodynamics consultant are expressed herein with intent to stimulate further discussion among colleagues and the public of what this author views to be open issues or ambiguities in the report's findings or recommendations.

These topics are organized in subsequent paragraphs according to major themes or concepts documented in the report or absent from it. Page references to the report are therefore not in any ordered numeric sequence. Despite arguments made subsequently herein, this author on the whole regards *Pathways to Exploration* as scholarly research, a valuable contribution to U.S. human space exploration policy deliberation, and a worthwhile reference.

The Surface Of Mars As "Horizon Goal"

The "**Horizon Goal**" paragraph at the top of p. S-3 is ambiguously worded. Rationale for the surface of Mars being the most difficult plausible human spaceflight (HSF) destination is provided. But the paragraph is summarized, "the horizon goal for human space exploration is Mars". That leaves open an alternative in which humans in Mars orbit, perhaps stationed on Deimos or Phobos, explore the surface of Mars via telepresence. Subsequent report narrative indicates this is not intended, and the surface of Mars is assumed to be the report's horizon goal throughout this essay. Nonetheless, the report appears to recognize the possibility of telepresence being an effective exploration mode in the "*Scientific discovery*" paragraph on p. S-2 (robotic payload names italicized by this author).

> The current capabilities of robotic planetary explorers such as *Curiosity* and *Cassini* are such that although they can go farther sooner and at much lower cost than human missions to the same location, they cannot match the flexibility of humans to function in complex environments, to improvise, and to respond quickly to new discoveries. This constraint may change at some indeterminate time in the future.

Returning to the "**Horizon Goal**" paragraph, the report finds "the Moon, asteroids, Mars, and the moons of Mars" to be a "small set of plausible goals for human space exploration". This statement indicates an unawareness of the number, diversity, and range of HSF accessibilities associated with asteroids. At best, it is unintentionally misleading to readers. At worst, it could result in a wasteful and flawed selection of Mars surface landings as the horizon goal based simply on limited data, "gut feel", and romantic fiction literary influences extending back to Edgar Rice Burroughs and his conception of Barsoom circa 1912.

On p. S-4, high-priority technology development capabilities enabling HSF to reach its horizon goal are listed as "entry, descent, and landing for Mars; radiation safety; and advanced in-space propulsion and power". With the surface of Mars its horizon goal, the report implicitly assumes exposure to one-third *g* (*g* signifies the acceleration of Earth's gravity measured at its surface, 9.8 m/s^2) is of no concern to human health or productivity over intervals from less than 30 days to 500 days (see Figure 1.9 on p. 1-30). In fact, we have no data on Mars gravity's debilitating effects on humans over any relevant exposure interval. Until we do, learning about those effects and their mitigation should be a high-priority technology development effort for HSF with the surface of Mars as its horizon goal. But NASA has no plans to learn about one-third *g*'s effects on humans before a protracted a stay on the surface of Mars[*], and the report ignores this omission. Likewise, NASA and the report ignore the unknown effects of direct atmospheric entry accelerations on humans after months in microgravity for which no data or countermeasures currently exist.

"Dead-End" Mission Elements

Subparagraph **VI.d** on p. S-5 recommends an exploration pathway that "minimizes the use of dead-end mission elements that do not contribute to later destinations on the pathway". But this pathway principle is violated if the lunar surface is a prerequisite destination to the surface of Mars. Mission elements required to land on, inhabit/explore, and launch from either the Moon or Mars are among the most complex and expensive, plus they tend to demand the utmost performance per unit mass because they operate deep in a gravity well at a mission's end destination[†]. If such elements are developed for the lunar surface, they will be inapplicable to the surface of Mars because of differences in the two environments. Mars has an appreciable atmosphere (the Moon does not), Mars surface gravity acceleration is one-third *g* (the Moon's is one-sixth *g*), and ISRU prospects will be significantly different on the Moon and Mars[‡]. But no lunar-specific mission element is deemed to be a dead-end in the report's Figure 4.9 on p. 4-27.

Some rationale for Figure 4.9's dead-end mission elements is documented in the report's Section 4.2.8.4 "**Minimize Dead-End Mission Elements**" on p. 4-62. It states, "The ***Moon-to-Mars*** pathway has only a single dead-end mission element, the disposable descent stage for lunar sorties." This statement is troublesome in multiple respects. First, the disposable descent stage would presumably also support lunar surface outpost logistics associated with the Moon-to-Mars pathway on p. 4-2 and in pathway timelines such as Figure 1.11 on p. 1-35. What guarantees the outpost's viability in perpetuity? Second, why is this descent stage a dead-end while its companion ascent stage and all the lunar surface infrastructure required to support sortie missions and an outpost are not?

Indeed, the entire concept of dead-end technology is open to question because the report leaves it undefined. According to Section 4.2.8.4, "The goal of 'minimizing dead-end mission elements' is to maximize the logical feed-forward of systems and make the best use of constrained

[*] The report's Figure 1.9 shows less propulsive change-in-velocity (Δv) is required to support more protracted stays on the surface of Mars. Initial HSF missions to the surface of Mars are therefore likely to involve 1.4 years of one-third *g* exposure.
[†] Performance criticality associated with Moon or Mars surface logistics could be reduced if pertinent in-situ resource utilization (ISRU) techniques are found practical.
[‡] A similar list of differences between surface environments on the Moon and Mars appear in the report's footnote #46 on p. 4-22.

resources." But the degree of feed-forward exhibited by a mission element is highly dependent on how the report defines exploration pathways. The report apparently regards elements developed for use in reaching and exploring the lunar surface to be readily applicable to reaching and exploring the surface of Mars, but interplanetary in-space logistics capabilities enabled by the proposed Asteroid Redirect Mission (ARM) are considered dead-end.

Section 4.2.8.4 justifiably contains two disclaimers. First, the moons of Mars are recognized to have an unknown influence on pathway characteristics such as program development risk. The second disclaimer states, "the nation is unlikely to adopt any of the pathways exactly as they are presented in this report". In light of these disclaimers, it is hard to justify any report finding on whether or not a mission element is dead-end. Such a finding implies a specific pathway has been selected, which the report is unable to do. Recommending a specific exploration pathway over other alternatives in the report is beyond the current state of knowledge in astronautics and related fields. The dead-end mission element metric has intrinsic merit, but the report does not concisely define it and appears unable to evaluate it with confidence.

Pathway "Off-Ramps"

The off-ramp concept is introduced with Decision Rule B on p. S-5. "If a budget profile does not permit the chosen pathway, even if NASA is well down it, then take an 'off-ramp.' " Only one of the report's pathways, ***Moon-to-Mars***, is explicitly associated with only one off-ramp on p. 4-14 as follows (the moons of Mars are never mentioned explicitly in the report as a potential off-ramp).

> To proceed to the true destination, Mars, as soon as is practical, after an appropriate time for examining hardware, operational, and human health issues [with lunar surface missions], the lunar assets will be retired from government service and optionally maintained and leveraged by future commercial endeavors. Alternatively, should the actual crewed exploration of Mars prove to be infeasible for financial, technical, or crew health reasons, the ***Moon-to-Mars*** pathway presents a natural off-ramp, leaving the United States to lead global exploration and exploitation of the Moon.

The forgoing strategy suffers from two unsupported leaps of faith. The first is that NASA-owned infrastructure on the lunar surface can be transitioned to commercial interests capable of generating viable return on investment. Similar transitions were proposed for the Space Shuttle before its retirement, but they were never seriously attempted even with the U.S. as sole owner. Likewise, the ISS gives every indication it will remain the property of multiple partnered nations until it is retired through intentional atmospheric incineration. If lunar surface infrastructure elements serve as an intermediate HSF destination to Mars exploration, NASA and its international partners would be well advised to agree on terms under which they will disengage from operating and funding this infrastructure *long before* deployment. Space history teaches us lunar surface infrastructure will otherwise become a fiscal millstone forever impeding progress toward other HSF destinations. Ability to gracefully disengage from established lunar surface infrastructure will be further frustrated if highly speculative commercial ISRU enterprises foreseen by some advocates fail to materialize.

The second leap of faith with the lunar surface as an off-ramp on a pathway to the surface of Mars is human adaptation to one-sixth *g* reduced gravity as noted previously in this essay. Consider the following statement on report p. 4-24.

> The ISS has proven to be an essential platform to investigate and enhance the ability of humans to survive most of the hardships of space exploration. However, some unknowns remain, particularly with regard to the long-term effects of space radiation and the partial gravity present on the Moon and Mars.

Instead of recommending NASA establish a reduced gravity centrifuge facility in low Earth orbit (LEO) to assess human adaptability at one-third *g* and one-sixth *g*, the report appears to be advocating a "sink or swim" strategy to fill this knowledge gap. If the strategy fails, it will be at a cost many times that of the LEO facility not proposed. The report's strategy could also produce encouraging results on the lunar surface but fail to reveal potentially lethal human adaptation problems at one-third *g* on Mars, where Earth return could be a year or more away.

A contrasting off-ramp strategy was advocated when the Review of U.S. Human Space Flight Plans Committee (known informally as the Augustine Commission) introduced its Flexible Path exploration option in 2009. In the Augustine Commission's view, off-ramps are optional destination paths to be taken as future circumstances warrant. In its report titled *Seeking A Human Spaceflight Program Worthy Of A Great Nation*, the 2009 Augustine Commission defines off-ramps as follows on p. 40[§].

> The Flexible Path is a road toward Mars, with intermediate destinations. At several points along the way, the off-ramp from the Flexible Path to a Moon exploration program could be taken. Alternatively, if new discoveries drew us to Mars, the lunar stop could be bypassed, leading directly to a Mars landing.

The Augustine Commission's off-ramp concept is not a headlong, sink or swim strategy. On the contrary, these off-ramps are not essential to following the Flexible Path. They are merely options to be exercised based on in-situ robotic or other cost-effective remote sensing evidence of a compelling HSF destination.

Small Bodies As HSF Destinations

On p. S-6, the report states, "Given the expense of any human spaceflight program and the significant risk to the crews involved, in the committee's view the only pathways that fit these criteria are those that ultimately place humans on other worlds." Unfortunately, the report never clearly defines what is meant by "other worlds" and whether they include small bodies like near-Earth asteroids (NEAs) and the moons of Mars.

The only other occurrence of the word "worlds" in the report is within an abridged quote from Carl Sagan's *Pale Blue Dot* (published in 1994) appearing on p. 2-27. The footnote for this quote

[§] The Augustine Commission's report may be downloaded from http://www.nasa.gov/pdf/396093main_HSF_Cmte_FinalReport.pdf (accessed 28 June 2014).

references p. 371, but the Ballantine Books paperback copy in this author's possession has these words in completely separate passages on p. 306 and p. 310[**]. These passages are reproduced below from this author's copy of *Pale Blue Dot*, adding context to clarify Sagan's meaning for "worlds". Italicized text indicates narrative not quoted in the report.

> p. 306
> Every surviving civilization is obliged to become spacefaring—not because of exploratory or romantic zeal, but for the most practical reason imaginable: staying alive. *And once you're out there in space for centuries and millennia, moving little worlds around and engineering planets, your species has been pried loose from its cradle.*

> p. 310
> The more of us beyond the Earth, the greater the diversity of worlds we inhabit*, the more varied the planetary engineering, the greater the range of societal standards and values—* then the safer the human species will be. *If you grow up living underground in a world with a hundredth of an Earth gravity and black skies through the portals, you have a very different set of perceptions, interests, prejudices, and predispositions than someone who lives on the surface of the home planet. Likewise if you live on the surface of Mars during the throes of terraforming, or Venus, or Titan.*

In *Pale Blue Dot*, Sagan doesn't restrict "worlds" to mean major bodies like the Moon or Mars. This book remains one of the most compelling arguments in favor of humans exploring NEAs to achieve scientific knowledge, colonization, and planetary defense goals. Arguably, *Pale Blue Dot* is one of the earliest Flexible Path proposals, as indicated by the following quote from p. 248. This passage also confirms what Sagan means by "little world".

> If we are ever going to send humans to Mars, near-Earth asteroids provide a convenient and appropriate intermediate goal—to test out the equipment and exploratory protocols while studying an almost wholly unknown little world. Here's a way to get our feet wet again when we're ready to re-enter the cosmic ocean.

Sagan also documents a HSF role in planetary defense from Earth impacts by NEAs on p. 264.

> The asteroid hazard forces our hand. Eventually, we must establish a formidable human presence throughout the inner Solar System. On an issue of this importance I do not think we will be content with purely robotic means of mitigation. To do so safely we must make changes in our political and international systems. While much about our future is cloudy, this conclusion seems a little more robust, and independent of the vagaries of human institutions.

Contrary to Sagan's view, the report fails to document planetary defense as rationale for HSF in Section 1.4.2 on p. 1-20 and p. 1-21. This rationale is unique to NEAs among all near-term potential HSF destinations. Undocumented planetary defense HSF rationale is all the more perplexing because the report's description of an "**Asteroid in Native Orbit**" design reference

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[**] Due to this discrepancy, all subsequent *Pale Blue Dot* references use page numbers from this author's Ballantine Books first edition dated September 1997.

mission (DRM) in Section 4.2.2.6 on p. 4-10 states, "The asteroid for the mission is selected based on scientific interest (or relevance to planetary defense)". Failure to connect HSF with planetary defense could be a major contributing factor to lackluster public interest in HSF as documented in the report's Section 1.5.1.1 on p. 1-22.

Many planetary defense experts find HSF offers little to mitigating Earth impacts by NEAs. But averting an impact scenario likely will call for the highest performance launch and in-space propulsion systems then in operation. It is HSF that tends to develop and routinely utilize these high-performance reliable systems because it requires relatively massive payloads safely delivered over minimal transit time. Until autonomous robotic systems are greatly improved, it is also HSF visits to NEAs that will provide the most comprehensive data on characterizing these potential threats and understanding prospects for mitigating them.

The DRM described in Section 4.2.2.7 "**Mars's Moons**" on pp. 4-10 and 4-11 suffers from an arbitrary pedigree discrediting Phobos and Deimos as viable HSF destinations. Because an opposition class mission plan is associated with this DRM, humans can only "spend up to 60 days at Phobos and Deimos" before initiating Earth return. As a consequence of this plan, the crew is exposed to harmful radiation "from the deep space environment for most of the 700-day mission", a dose "more than three times that expected for the Mars Surface mission". But the "**Mars Surface**" DRM described in Section 4.2.2.8 on pp. 4-11 and 4-12 uses a conjunction mission plan spending "approximately 500 days" on the surface of Mars and enjoying shorter interplanetary transits than an opposition class mission. Comparing radiation doses between the two DRMs therefore leads to an invalid conclusion because the difference in those doses has nothing to do with the associated destinations. An opposition class mission to the surface of Mars could easily incur the same radiation exposure Section 4.2.2.7 documents.

The report has an unsubstantiated requirement that a horizon goal for HSF be associated with a significant gravity well. This requirement, plus other rationale for Mars as the horizon goal, is documented in the opening sentences of Section 1.6.1 on p. 1-28 as follows.

> Within the limits of foreseeable technologies, there are a limited number of places humans can go beyond LEO and only two of them have significant gravitational wells: the Moon and Mars. Mars is the farthest practical exploration “horizon” for the foreseeable future—the most distant goal that is consistent with human physiological limits under likely future technologies (Chapter 4). Mars is a goal most compatible with the committee’s enduring questions, and the intrinsic fascination that Mars has held in the popular imagination for well more than a century makes it an attractive target.

Distant goals are important in the report because the first of its two "enduring questions", initially documented on p. S-1 is, "How far from Earth can humans go?" But descending to the bottom of a "significant gravitational well" and climbing back out to reach a planetary surface and return to Earth requires complex, specialized systems. These systems take significant time and funding to develop. One metric measuring their performance is change-in-velocity Δv, equivalent to the vertical axis of Figure 1.9 on p. 1-30. From Figure 1.9, a roundtrip from Earth to the surface of Mars requires about 23 km/s of Δv. A plot equivalent to Figure 1.9 with a uniformly consistent and thoroughly documented pedigree can be downloaded from http://www.lpi.usra.edu/sbag/science/NHATS_Accessible_NEAs_Summary.png (accessed 1 July 2014). This NEA HSF Accessible Targets Study (NHATS) plot places Mars surface roundtrip Δv at no more than 16 km/s. Adopting roundtrip Δv = 16 km/s for the surface of Mars, a crew would find itself no farther from Earth than 1.0 + 1.7 = 2.7 AU when Mars reaches aphelion on the opposite side of the Sun from home. Under NHATS mission design criteria consistent with those for Δv = 16 km/s to the surface of Mars, an asteroid without an appreciable gravity well could be reached in a nearly circular orbit of heliocentric radius 2.7 AU, placing human visitors in the main asteroid belt up to 3.7 AU from Earth, 37% farther than Mars. Without a specialized asteroid lander to develop, this hypothetical asteroid very likely could be visited by humans sooner, with less risk, and at less expense than reaching the surface of Mars.

Evaluating the report's other p. S-1 enduring question, "What can humans discover and achieve when we get there?" is highly speculative, even for a relatively well-explored destination like Mars. But consider this. A 1 July 2014 search of catalogued asteroids with absolute magnitude $H < +20$, heliocentric semi-major axis 2.5 AU $\leq a \leq$ 2.7 AU, eccentricity $e \leq 0.1$, and ecliptic inclination $i \leq 5°$ returned 11,766 results[††]. Among these asteroids with HSF accessibility equivalent to the surface of Mars are eight with known diameters ranging from 15.78 km to 94.8 km (Phobos, the larger moon of Mars, has an average diameter near 22 km). What human visitors could discover and achieve at these myriad destinations is beyond speculation. It is certainly arguable this asteroid population offers prospects to human knowledge and enterprise eclipsing those of Mars. These asteroids could end up being more habitable than is the surface of Mars because we already know the fundamentals of adapting to the microgravity there. As noted previously, prospects for long-term human adaptation to reduced gravity on the Moon or Mars are open questions. If living in a rotating habitat is shown to be the ideal "gravity prescription" for humans, such infrastructure will be far more effective operating in microgravity than on the surface of the Moon or Mars.

In summary, the assertion that "Mars is a goal most compatible with the committee’s enduring questions" is highly debatable. If that rationale for selecting Mars as the horizon goal is set aside, the report can only support its assertion with "intrinsic fascination" and "popular imagination" associated largely with science fiction. Although science fiction can be a great motivator, U.S. HSF strategy should reflect a more factually informed awareness of accessible destinations including small bodies, nearly all of which were unknown a century ago. Perhaps a better HSF policy mindset to take forward from science fiction is Arthur C. Clarke's remark in *2001: A Space Odyssey*, "But please remember: this is only a work of fiction. The truth, as always, will be far stranger."

Value From International Partnerships

On p. 1-14, the report states that, despite concerns regarding unintended U.S technology transfer, "international collaboration is still thought to provide resilience to long-term, large-scale programs and space missions such as the ISS." This "thought" is backed by historic example the report fails to document. After first element launch in November 1998, ISS has been continually crewed since November 2000. A few months after loss of Space Shuttle *Columbia* in February

[††] Similar searches can be conducted at http://ssd.jpl.nasa.gov/sbdb_query.cgi (accessed 4 July 2014).

2003, this continuous human presence would have been interrupted until *Discovery*'s return-to-flight in July 2005 without redundant human logistics capability provided by Russia's *Soyuz* spacecraft. Following the Space Shuttle's final flight in July 2011, *Soyuz* has become the only ISS crew logistics capability, as noted on p. 1-10, a monopoly expected to persist until at least 2017.

If ISS is a representative example, major international partners in cooperative HSF will not long tolerate dependencies on each other for critical systems such as propulsion, communications, avionics, and life support. Unfortunately, these elements tend to be among the most expensive. If mission element monopolies are mandated to reduce costs for other partners who then become dependent, programmatic robustness from redundant capabilities is lost.

The overhead of redundant capabilities, international travel, and critically accurate coordination/documentation in multiple languages can easily outweigh apparent cost savings from international cooperation in major HSF programs. The report seems to share this viewpoint in the following excerpt from p. 1-13.

> There is an assumption that if the partners contribute capability, the whole can be greater than the sum of the parts, and the cost can be shared among the partners. A space project is potentially more affordable for each individual partner, and the pool of scientific and technological expertise brought to bear on the project is enriched. However, the evidence that international collaboration reduces costs for the lead partner, e.g., the United States, remains inconclusive. Indeed, senior NASA officials reported to this committee that international collaboration does not reduce costs.

Compared to the foregoing "assumption", the experience of "senior NASA officials" appears to carry little weight in the report after p. 1-13. On p. 1-19, the report finds, "Given the scale of the endeavor of a mission to Mars, contributions by international partners would have to be of unprecedented magnitude to defray a significant portion of the cost." This seems to suggest that, if NASA will simply "double down" on international partnerships, cost savings to U.S. taxpayers that never materialized during ISS will finally be realized in future, more expensive HSF programs.

Bottom line, if reduced costs are the primary U.S. motivation for future international partnerships in HSF, those savings will be realized at a two-fold expense. First, the U.S. must willingly tolerate foreign monopolies of critical capabilities. Such tolerance with Russia as the sole source provider of crew logistics for ISS and of RD-180 engines for the *Atlas 5* first stage has recently proven to be politically untanable. Second, sole source providers are also single points of failure reducing programmatic robustness.

Conclusions

The *Pathways to Exploration* report documents multiple useful concepts for policy and strategy governing future HSF. These include enduring questions, a horizon goal, modifiable (indistinguishable from "flexible" to this author) pathways composed of stepping stone incremental destinations, and an acute awareness of fiscal realities leading to pathway principles along with decision rules governing pathway conduct.

Unfortunately, specific pathway recommendations by the report extend decades into the future and must rely on highly speculative or unsupplied rationale arising from assumed critical advances in planetary science and astronautics. Such speculation is usually qualified as such in the report, but it leads readers to wonder what credence to place in recommendations so weakly supported. This is likely why the 2009 Augustine Commission was directed to provide options but no recommendations in its report.

The report's heavy reliance on NASA-provided DRMs leads to poorly supported generalizations from limited single-case mission designs. Under humanity's currently profound state of ignorance regarding the report's well conceived enduring questions, little credibility should be associated with *Pathways to Exploration*'s specific recommendations. When the Corps of Discovery set out to find the Northwest Passage in 1804, President Jefferson's orders didn't include the pathway to be taken.