Mars—On the Path or In the Way?

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Explore Mars may not be the highest and best use of government-funded human space flight. However, Explore Mars is pervasively accepted as the ultimate goal for human space flight. This meme has become refractory within the human space flight community despite dramatic contextual changes since Apollo: human space flight is no longer central to commonly-held national priorities, NASA's fraction of the federal budget has diminished 8 fold, over 60 enabling technology challenges have been identified, and the stunning achievements of robotic Mars exploration have accelerated. The *Explore Mars* vision has not kept pace with these changes.

An unprecedented budgetary commitment would have to be sustained for an unprecedented number of decades to achieve the *Explore Mars* goal. Further, the goal's justification as uniquely able to definitively determine Mars habitability is brittle, and not driving current planning in any case; yet NASA owns the choice of this goal and has authority to change it. Three alternative goals for government investment in human space flight meet NASA's own expressed rationale at least as well as *Explore Mars*, some with far greater capacity to regain the cultural centrality of human space flight and to grow by attracting private capital. At a minimum the human space flight advocacy community should address the pragmatics of choosing such a vulnerable goal.

I. INTRODUCTION[1]

Explore Mars is a refractory meme, but is it a vision or a dream?

Human space flight (HSF) became a valid social meme when von Braun wrote *Das Marsprojekt* in 1948—about three generations ago [1]. For most of the subsequent ⅔ of a century, the NASA community has accepted as axiomatic that the core goal of HSF is to *Explore Mars*.

As recently as 2009 the Augustine Committee used the strong term "ultimate destination" to characterize the relationship between Mars and HSF [2], and humans-to-Mars remains the common benchmark for judging all proposed HSF ambitions, missions, systems, and technologies. *Explore Mars* is the conceptual center of mass around which the government HSF value system revolves: ISS can be used as a testbed for Mars-class challenges; asteroids are stepping stones to Mars; the Moon is begrudged a role as proving ground for Mars surface operations, yet feared as an expensive programmatic eddy that might trap us en route to Mars.

Inside our community the *Explore Mars* meme is refractory. It survives despite the reality that NASA's spending power has halved since the peak of Apollo, as NASA's share of the federal budget has diminished eight-fold [3]. It survives despite contemporary, informed appreciation for the physiological and technological obstacles that all need to be overcome. It survives despite continuous scientific revelations about Mars by explorers using ever-better robots, who are now directly investigating the planet's habitability. It survives despite generations of HSF systems proposed and operated, successful and catastrophic, ascendant and canceled. And it survives within our community despite clear evidence of an evolving social milieu that no longer sees space as the "final" frontier. By the time we could overcome the technical hurdles to have humans first set foot on Mars, what would "exploration" even mean for them and for that era?

In addition, *Explore Mars* does not have a clean pedigree as the purpose of HSF. Even during HSF's defining period—the decade that culminated with men on the Moon, and which casts a shadow NASA has never escaped—investment was motivated clearly and simply by geopolitical showmanship. Ironically, the NASA human-exploration community mistook the means for the end, and has been trying ever since Apollo to recapture the glory, focus, momentum, and commitment that enabled it, by promoting a goal *that did not even underpin it.* When pressed today for rationale, *Explore Mars* advocates assert relevance and urgency by turning to a set of vague goals. Some of these, few could argue with (inspiration, international collaboration) but are not unique to human space flight. The rest are self-referential (public engagement, preparation for exploration) and thus moot as justifications. So which are we actually committed to: the fuzzy rationale or *Explore Mars* itself—which is the purpose, and which is the cover?

The march of history and the perspective it affords—that the halcyon days of HSF were not motivated by

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Explore Mars; that the nature of exploration is changing faster than is HSF progress; and that the societal benefits of *Explore Mars* are hard to pin down—demonstrate that our grip on the HSF value proposition is slippery. *Explore Mars* is a vulnerable goal; it behooves our community to apprehend this circumstance and manage our future accordingly.

The paper analyzes two dimensions of the *Explore Mars* value proposition and finds them unmanageably weak:

- First, by the time it could happen, human "exploration" cannot be as typically envisioned. Robotic capabilities, detailed mapping, and fundamental discoveries at Mars are all highly likely to have progressed too much for astronauts to deliver value through activities historically envisioned as exploring. As this becomes more clear over the intervening decades, the validity of the grand mission purpose could fray.
- Second, other HSF goals—having nothing to do with *Explore Mars*—are at least as capable of meeting the rationale put forward by advocates. Indeed, two of these alternative goals hold the potential to be more centrally relevant to today's popular interests and to critical global challenges, and therefore more able to attract the private capital needed for HSF to grow beyond the supply-side constraint of NASA's budget.

The paper concludes that *Explore Mars* is a boutique pursuit for human space flight: unlikely to secure or sustain the deep societal and financial support it needs and seeks, and not as aligned with major trends in societal interests and civilization's urgent needs as other goals it could adopt.

II. FAR IN THE FUTURE

Humans-to-Mars is far off, and far harder than Apollo to accomplish.

The earliest epoch proposed by contemporary NASA planning for a first human mission to the surface of Mars is at least 2040, and appears to be quietly slipping out to ~2050. A few iconoclasts argue that it could occur much sooner, but make these arguments without authoritative understanding of either the total technological challenge or the risk-management calculus of a federal agency. And since *Explore Mars* requires a level of funding accessible only to governments, government constraints matter. To soften the blow of the culminating event being four decades distant, the current Administration's challenge and NASA public discussion both carefully emphasize humans reaching "the vicinity" of Mars "in the 2030s."

Future history in this regard will be a function of several parameters. Two of the principals, both highly uncertain, are: level and sustainment of appropriated budgets, and technology readiness.

Budget Supply and Demand Are Both Unpredictable

Absent the type of urgent geopolitical motive that could conceivably restore the NASA HSF budget to its Apollo peak, NASA analysis shows that *Explore Mars* would require the current level of HSF spending ($\$10^{10}$/yr) to be sustained, aimed at that goal, for 3–4 decades to achieve it. Something to give advocates pause is how unprecedented such a commitment to a unitary, peacetime investment project would be in modern times. Even the Apollo push was sustained over just eight years, and Shuttle development also took less than a decade.

Development of the ISS (International Space Station) is the closest analogue. At first (in 1984), the space station was a peacetime HSF investment, albeit one with overtones of nationalistic pride on the world stage. In the end, it was accomplished by a genuine international partnership, and attained a cost scale comparable to what is contemplated for *Explore Mars*. Anticipated in 1984 to cost $\$10^{10}$ over a decade, it ended up requiring $\$10^{11}$ over almost three. So at first glance the reality of ISS seems to imply that the *Explore Mars* program could unfold as hoped.

However, fully applying the ISS-history analogy—including growth to the budget and schedule actuals—implies also that the current program projections for *Explore Mars* are highly optimistic. After all, ISS projections were low by an order of magnitude in cost and a factor of three in schedule. The project's investment of $\$10^{11}$ over three decades, spanning more than seven Administrations and fourteen Congresses, has happened only once. In today's societal and economic climate, potential analogous growth (to $\$10^{12}$ through 2100, for example) would put the project far beyond proven experience. Such analogy-based potential for growth might seem patently implausible, but a valid question is whether the interrelated technical, management, and budgetary challenges of getting humans to the surface of Mars are more or less predictable and manageable than the challenges that got ISS to assembly-complete. NASA's total programmatic resume of HSF programs (Apollo, Shuttle, and ISS)—and even of robotic projects orders of magnitude smaller, as noted by multiple independent reviews over the past half decade—indicates that our professional community's ability to predict cost and schedule is fraught with uncertainty. Thus any prediction of sustaining sufficient budget to enable the 2040–2050 target date is highly questionable.

Technology Readiness is Unpredictable

The technology agenda identified by NASA as necessary to initiate human Mars surface missions is daunting in scope and scale. Table 1 summarizes the challenges that would need to be resolved (beyond other types of deep-space missions) to enable Mars Design Reference Architecture DRA 5.0, a representative example from 2009 [4]. Table 2 shows a more recent snapshot of the agency's definition of the technology agenda needed to enable a Mars-surface expedition. Each line represents an individually managed technology project.

Technology development is inherently an uncertain enterprise. In the case of *Explore Mars* the sheer number of enabling technologies is large (60–80 depending on the architecture), many require major breakthroughs before their feasibility can confidently even be "baked into" program plans, and several require multi-step, decadal-scale development before they could be put into practice for human lives to depend on. So while a precedence roadmap can be defined, a reliable schedule cannot. Each individual technology program's schedule would be subject to its own uncertainties; convolving them all together would yield a schedule variance for the total technology program so large as to be non-usable, thus rendering any anticipated completion date soft. Since that date is a precondition even for selecting the inaugural Mars landing opportunity, the timing of that history-making event is technically, literally impossible to predict until much later in the *Explore Mars* program development lifecycle.

Combining the technical schedule uncertainty with the budget uncertainty discussed above means that the probability distribution for the date of a first human landing on Mars is both subject to a large spread, and skewed to the right. Thus the actual date could easily be much later than any target date identified now (2040, 2050, or some other). Here however, the target date is academic; for the argument that follows it is sufficient to establish simply that the date is highly unlikely to occur *before* 2040.

III. EXPLORATION NOT AS PORTRAYED

By 2040, human "exploration" cannot be as historically and typically envisioned.

In the world of robotic space exploration, three decades is a long time. Particularly if Mars remains the focusing objective of HSF, the exploration of Mars is not likely to remain in a static state awaiting the arrival of humans. Indeed, dramatic findings have accelerated recently, and the MSL mission set to land in August

Table 1: Technology areas needed for humans to *Explore Mars* pose a daunting, diverse array.

Functional Area	Capability
System Cross-Cutting	• Cryogenic fluid storage, transfer, and in situ production • Common subsystems across the architecture • Unsupported system operation for 300–1200 days
Human health	• 900-day remote medical, dental, urgent care • Radiation forecasting, protection, and mitigation • Micro-gravity countermeasures • Life support loop closure
In-Space Operations	• 300+ day LEO loiter and modular assembly • Large deep-space flight systems: o 110–124 t for trans-Mars injection, ~50 t roundtrip o Advanced interplanetary propulsion o Aeroassist for capture at Mars o 40–50-t payload to Mars surface • Abort-to-surface at Mars • ISRU-compatible (oxygen, methane) propulsion • +12 km/s Earth return speed
Surface Operations	• 30+ kWe nuclear power • Planetary protection systems, verifiable in situ • Dust mitigation • In situ analytical laboratory • Auto-deployment and checkout of complex systems • 100 km+ roving range • Drilling (10+ m depth access) • Lightweight, dexterous, maintainable EVA
Use of Mars resources	• Production of 24 t oxygen for Mars ascent • Production and verification of breathing O_2 (2 t) and H_2O (3.5 t)

Table 2: Technology needs, when resolved into discrete technology-development projects, introduce significant schedule uncertainty into readiness for a first human mission to the surface of Mars.

Required
LOX/LH_2 reduced-boiloff flight demo
Cryo Propulsion Stage, multiple technologies
LOX/LH_2 zero-boiloff development
Energy storage
Electrolysis for life-support O_2 generation
8-psi fire prevention, detection, & suppression
Environmental monitoring & control
High-reliability life support systems
Proximity communications
In-space timing and navigation for autonomy
High data-rate forward link
Behavioral health
Optimized exercise countermeasures equipment
Human factors and habitability
Long-duration medical care
Biomedical countermeasures
GCR radiation protection
SPE radiation protection
Radiation shielding
Vehicle systems management
Crew autonomy
Mission-control autonomy
Common avionics
Advanced SW development tools
Thermal management subsystems
Long-duration, deep-space mechanisms
Launch vehicle lightweight structures and materials
In-space lightweight structures and materials
Suited-crew-compatible robotics
Telerobotic control with time delay
Surface mobility
Surface suit
Autonomously deployable very large solar arrays
Solar Electric Propulsion demo
SEP stage
Fission power for surface missions
In Situ Resource Utilization
Thermal Protection System (<11.5 km/s)
Autonomous rendezvous, prox ops
Entry, Descent, and Landing, including terrain-relative navigation, precision landing, and ~20-t systems
Probably Required
Closed-loop life support
Suitport
Inflatable habitat flight demo
Inflatable habitat development
TPS (high speed)
Supportability and logistics
LOX/methane RCS
LOX/methane pressure-fed stage
LOX/methane pump-fed stage
Oxygen-rich staged-combustion launch vehicle engine
Architecture-dependent
Asteroid surface operations
Deep-space suit
Fission power for electric propulsion
Nuclear thermal propulsion
In-space non-toxic RCS

2012 puts us on the cusp of investigating conditions for life deep into Mars' past. Two reasonable questions are: what Mars-exploration progress might occur before humans arrive; and what "exploration" could even mean by the time humans arrive to conduct it in situ.

Another 30 Years Raises the Bar

Mars exploration has been underway for a half century already. At accelerating rates of accomplishment, even the next 30 years (an interval 60% as long as what is behind us) is likely to set a formidable science benchmark. For comparative reference, Table 3 summarizes the history of NASA robotic Mars exploration, including highlights of progress in both capability and discovery. Figure 1 maps these milestones on a timeline, graphically depicting the periods and gaps of achievement in the context of the interval remaining until 2040.

Figure 2 shows two quantitative measures supporting this portrait of progress: the data returned by, and major publications based on, NASA's orbital and surface Mars missions to date. The geometrically increase in information generated, and the significant effect of mission longevity (e.g., MGS orbiter and the MER rovers), are both readily apparent in the data.

Key conclusions from the record include: (1) presence at Mars is now continuous; (2) robotic mission longevity routinely exceeds design life; (3) resolution, sensitivity, data volume, and flexibility are all increasing; (4) scientific results now go beyond simple discovery, routinely using long mission durations to perform iterative investigations; (5) insight is increasingly synoptic in the spatial and time domains; (6) contemporary and future missions are programmatically sequenced around fundamental questions, and include focusing the full power of terrestrial laboratories on returned samples; (7) these questions culminate in learning whether Mars has ever had, or does still have, life, and understanding how similar such life might be to terrestrial life. In short, Mars exploration, already underway for a half century, has progressed to the point of testing specific, sophisticated hypotheses by using increasingly capable machines and instruments, in specified places and over very long times.

This situation changes the game for human exploration as conventionally envisioned in four key ways.

The first implication is that trends in the robotic exploration program already set a high bar for in situ human activity to perform the type of "exploration" that could justify such a program either pre or post facto. Hopping and driving around, taking photos, collecting rocks in sample bags for return to Earth, and hand-deploying instruments (as in Apollo) would not come close to matching the scientific return of 2040s

Table 3. Summary history of Mars-exploration achievements establishes the foundation for understanding what the exploration of Mars means [5, 6].

NASA Project	Epoch	Mission and Payload Highlights	Discovery Highlights
Mariner 3, 4	1964	• First flyby: 9,846-km altitude. Mariner 3 launch failed; Mariner 4 lasted 4x design life of 8 mo. • Payload: TV camera, Helium magnetometer, ionization chamber/particle detector, cosmic dust detector, cosmic ray telescope, trapped radiation detector, solar plasma probe.	• 22 images (~1% of the planet) transmitted over four days. • Dispelled notion that Mars was Earth-like: thin atmosphere; cratered, rust-colored surface.
Mariner 6, 7	1969	• Dual Flyby: 3,430-km altitude (equator and southern hemisphere), 4 d apart. • First onboard-reprogrammable computer. Payload included wide-angle and high-res cameras, showing features as small as 300 m.	• 143 images on approach; 55 close-up images (~20% of the planet in total). • Dark surface features not canals; cratered surface not like the Moon. Deserts, craterless depressions, huge concentric terraced impact regions, collapsed ridges. First data about atmosphere composition.
Mariner 8, 9	1971	• First orbiter: Mariner 8 launch failed; Mariner 9 lasted 349 d. • Payload: wide- and narrow-angle TV cameras, IR and UV spectrometers, IR radiometer. • 3 months after orbit insertion, first successful Russian orbiters arrived (Mars 2 and Mars 3).	• 7,329 images, covering >80% of planet. Imaged Phobos and Deimos. • Global dust storm, ancient riverbeds, massive extinct volcanoes, 4,000-km Valles Marineris canyon system. Wind and water erosion and deposition, weather fronts, fogs. Laid groundwork for Viking.
Viking 1, 2	1975	• Dual Orbiter/Landers. • Orbiters lasted 4-8x design life of landing + 90 d (V2 orbited 1,489 times). • Orbiter payload: cameras, IR thermal mapper, water vapor mapper, relay for Landers. • Landers entered from orbit after sites selected based on Orbiter imagery.	• 52,000 images, covering 97% of the planet. V1 imaged Phobos from 90 km. • From orbit: Evolution of global dust storm. Details of wind- and water-formed features. Hemispheric dichotomy (northern low plains and southern cratered highlands). Tharsis and Elysium volcanic bulges. Seasonal 30% atmosphere density variation; higher ancient density based on isotopic composition. • On the surface: 360° color panoramas. Collected and analyzed regolith samples, monitored temperature, wind direction, and wind speed. Seismic and biology experiments inconclusive. Iron-rich clay regolith devoid of life signs. Surface temperature 150–250 K with 30–50 K diurnal variation; surface frost.
Mars Observer	1992	• Orbiter	• Failed
Mars Global Surveyor	1996	• Orbiter: after capture, aerobraked into 400-km circular polar science orbit; lasted almost 2.5x design life of 4 yr. • Payload: High-res camera, thermal emission spectrometer, laser altimeter, magnetometer, relay for surface missions.	• More data than all previous Mars missions combined: thousands of high-res images; global mineralogical, magnetic and gravity field maps; 3-D views of topography; atmosphere; daily and seasonal weather patterns. Identified safe landing sites rich in minerals including hematite (formed in liquid water) for subsequent rover missions. • Gullies and debris-flow features suggesting current sources of liquid water near the surface.

NASA Project	Epoch	Mission and Payload Highlights	Discovery Highlights
Mars Pathfinder	1996	• Lander with first planetary Rover. Direct entry, airbag touchdown. Lander lasted ~3x design life of 30 sols. 10-kg *Sojourner* micro-rover lasted 12x design life of 7 sols. • Payload: Alpha Proton X-ray Spectrometer, dual sets of stereo cameras.	• 2.3 Mb of data: >16,500 images (Lander), 550 images (Rover), 15 chemical analyses of rocks and soil. Atmosphere structure; surface meteorology; wind abrasion of rocks by sand-size particles, dune-shaped deposits. Diverse rock types, generally higher silica content than Mars meteorites. Dust very fine (~1 µm), includes magnetic particles. Mars likely warm and wet, with thicker atmosphere, at one time.
MCO	1998	• Mars Climate Orbiter	• Failed
DS2	1999	• Deep Space 2 Microprobes (released from MPL)	• Failed
MPL	1999	• Mars Polar Lander	• Failed
Mars Odyssey	2001	• Orbiter, aerobraked into science orbit. Still active as of April 2012. • Gamma-ray spectrometer, thermal emission spectrometer, data relay for surface missions (relayed 85% of MER data).	• Thousands of images. Geology, climate (e.g., morphological record of ancient floods), surface temperature. Global mineralogy to 1 m depth. Discovered large amounts of buried ice; discovered radiation in low Mars orbit is 2x that in LEO.
MARSIS and ASPERA-3 instruments	2003	• Two payloads hosted on ESA Mars Express Orbiter: – Radar – Space-plasma	• Surface elevation and roughness; subsurface profiles to almost 5 km depth; profiles of subsurface layered ice deposits • Interaction between solar wind and upper atmosphere of Mars.
Mars Exploration Rovers	2003	• Twin Rovers on Lander pallets. Direct entry, airbag touchdown. • *Spirit* lasted 24x design life of 90 sols, roved 7.73 km; *Opportunity* still active at 32x design life, roved 34.4 km, as of April 2012. • Payload: multiple cameras (stereo panoramic, navigational, microscopic imager); instruments for analyzing composition and mineralogy (thermal emission spectrometer, Mossbauer spectrometer for Fe-bearing minerals, alpha particle x-ray spectrometer for chemical composition); rock abrasion tool to penetrate weathering rind.	• Thousands of stereo color images over long traverses; motion pictures of dust devils. Evidence of past interaction with briny water: 5-mm hematite concretions that formed inside deposits soaked with groundwater, layers of sedimentary rock containing minerals (e.g., sulfites and jarosite), and chemicals (e.g., chlorine and bromine) resulting from considerable interaction with water. *Opportunity* landing site likely once the shoreline of a salty sea.
Mars Recon-naissance Orbiter	2005	• Orbiter. Still active as of April 2012 (2.4x design life of 2.5 yr) for science and Ka-band data relay for other missions. • High-resolution camera (able to image landers descending and resting on the surface, and dust-devil shadows); mid-resolution camera for context. IR radiometer climate sounder for subsurface water. Navigation camera demonstration.	• 161 Tb of data as of April 2012. Global mapping, regional surveying, high-res targeting of specific surface features (including MER EDL systems and Rovers, and Phoenix). Detailed surface morphology (e.g., rock abundance of candidate landing sites for other missions, ancient shorelines, periodic seasonal gully flow features, evidence of fluids having circulated through fractured terrain, lava tube openings). Surface minerals. Dust and water transport in the atmosphere. Equilibrium state of subsurface ice deposits. • Discovered that liquid water played a large role shaping the surface over time; opal minerals formed in rivers or small ponds over time.

NASA Project	Epoch	Mission and Payload Highlights	Discovery Highlights
Phoenix	2007	• Lander. Direct entry, propulsive touchdown in north circumpolar layered plain. Lasted 3x design life of 50 sols. • Payload: robotic arm to excavate and transfer samples to onboard laboratory; soil-analysis chemistry instruments; microscopic camera; stereo panoramic cameras; meteorology station with microphone.	• Exposed ice just beneath the surface. Perchlorate in regolith. Falling snow. Microscopic analysis of mineral grains.
MSL	2011	• Nuclear-powered Rover. Landed by skycrane descent system (capacity 1 metric ton to the surface). Lands on August 5, 2012. • Roving range up to 200 m/sol. Payload 10x heavier than MER: will analyze scooped and cored samples as Rover climbs central mountain of Gale Crater; chemical analysis of rocks without contact; differentiation of atmospheric and evolved-gas isotopes with ppb accuracy.	• Investigate past and present habitability of Mars (potential to support microbial life): – Identify any organic carbon compounds – Inventory the key building blocks of life – Identify features representative of biological processes – Examine rocks and soils at and near the surface to interpret their formation and modification – Assess how Mars' atmosphere has changed over billions of years – Determine current distribution and cycles of water and carbon dioxide (frozen, liquid, gaseous)
MAVEN	2013	• Orbiter; "Mars Atmosphere and Volatile Evolution Mission" • Payload: Particles and Fields Package (six instruments), Remote Sensing Package, Neutral Gas and Ion Mass Spectrometer.	• Upper atmosphere, ionosphere and interactions with the sun and solar wind. Role that loss of volatile compounds (e.g., CO_2, NO_2, H_2O) played through time, giving insight into the history of Mars atmosphere and climate, liquid water, and planetary habitability.

era robotic exploration capabilities, much less provide comparable value (return per unit cost). To be justified on the basis of science, human presence would need to enable types of exploration unlike those that can be reasonably anticipated for machines three decades hence. Examples might include deep drilling (i.e., assembly of long, segmented drill strings; resolution of anomalies like stuck bits, broken drill pipe, clogged drill-mud lines; and dissection of extracted cores) and complex in situ analysis (i.e., requiring an appropriately equipped in situ laboratory; deep training of a small expedition crew; and diverse capabilities for sample collection from multiple sites, with long-distance sample retrieval to the laboratory).

And therein lies a conceptual break. Regarding the drilling example, there is no precedent for astronauts, operating in space suits in a lethal environment millions of kilometers from help, performing heavy work like deep drilling; only an audacious NASA risk-management milieu could allow it. Regarding the second example, such a sophisticated, well-outfitted laboratory is nowhere to be found in planning or budgeting for the human exploration of Mars [7]. Table 3 contains no line item even for an ISS *Destiny*-like laboratory module, let alone something pertinent to planet-surface investigations that could rival multi-disciplinary sample-analysis capabilities on Earth. *Explore Mars* planning has not yet acknowledged or adopted the type of science performance expectations that could justify it in practice.

A second implication is that by the time humans could set foot on Mars, the model of what it means to "explore" a remote place would be thoroughly undercut by interim achievements. Every rock, every promising locale, and every dynamic site of peculiar interest (at least, the ones accessible by a safety-accessible human crew) would have already been mapped in detail from orbit. Surface and subsurface mineralogy and volatile resources will likely be mapped globally. Locations related to astrobiological "special regions," such as outflow aprons beneath seasonal flows, will likely have been extensively sampled, or be off-limits to direct human investigation, or both. Pursuing the troubling question of what humans would actually do in lieu of the traditional portrayal of planetary exploration leads inexorably to the type of sophisticated tasks outlined above. Some might argue that since fewer than ten Mars launch opportunities occur between 2018 and 2040, robotic exploration is unlikely to outstrip human potential for sophisticated science at Mars, particularly given contemporary

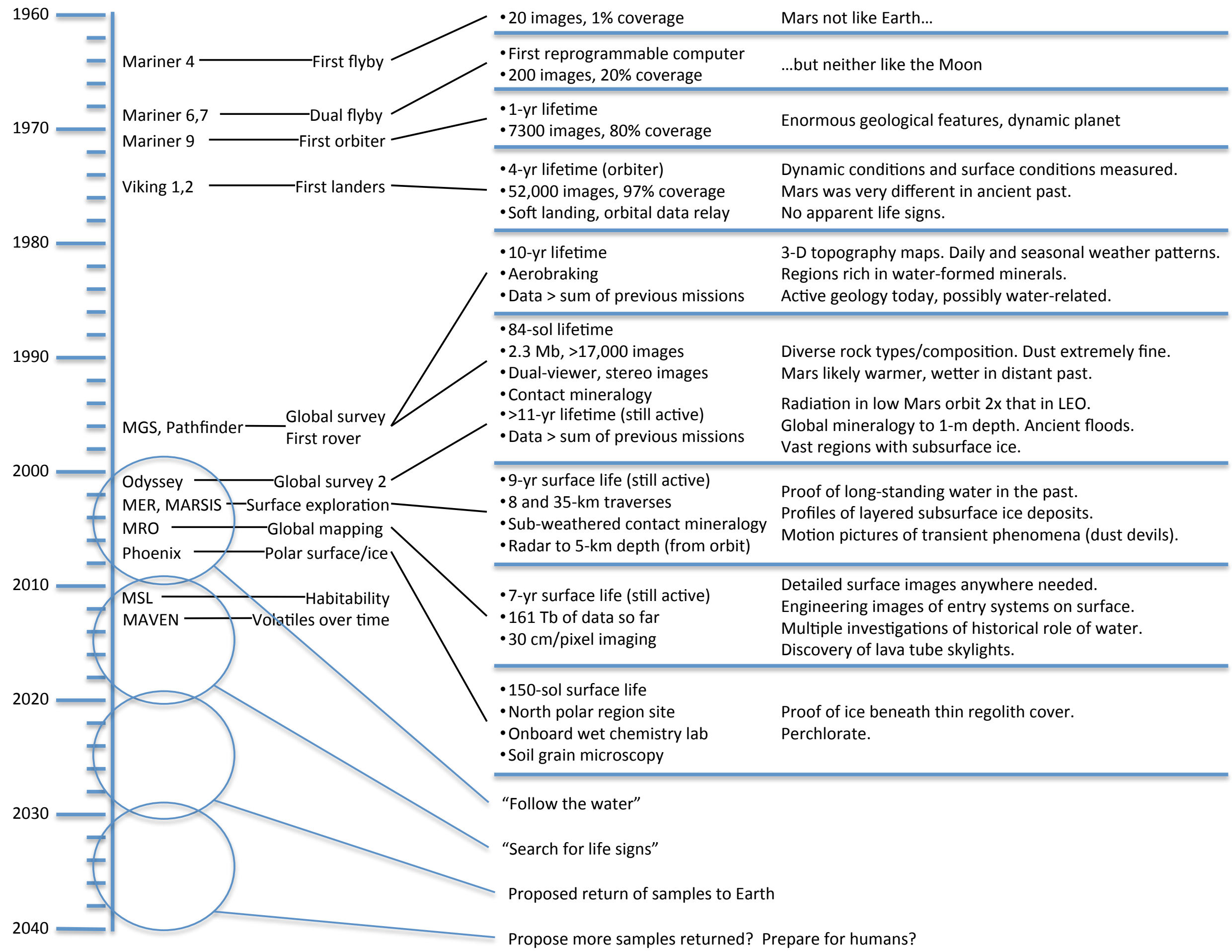

Figure 1. Time-series of NASA Mars exploration reveals pace, trends, and goals of achievement over 80 years.

federal budget challenges. But this argument is specious: for the cost of the human initiative, 50 MSL-class robotic missions could be done. To get a sense of what that could mean, imagine five MSLs *per launch opportunity*, benefiting iteratively from at least four generations of learning. Human exploration of Mars could not look like Apollo exploration of the Moon, even though a linear extrapolation of exactly this type of scenario underlies current planning for it.

A third implication is that discoveries accessible to a continued robotic program pose an active "wild card" to the hope that human exploration will make the epochal determination of Mars as an abode of life. The paradox here is that a well-planned human program would inevitably include an expanded array of robotic demonstrations, precursors, and adjunct missions—to provide key planning information, to manage the risk of unknowns, to target human missions to places that maximize the probability of significant return, and to maximize their operational efficiency. But those same robotic missions hold real potential to "take the wind out of the sails" of the human program by making the epochal discoveries themselves. The only way to curtail this significant program-sustainability risk would be to purposefully avoid robotic exploration, which makes no sense. This dilemma is akin to the one faced by space-flight advocates invoking the threat of an asteroid impact to justify human exploration of NEOs (near-Earth objects): continued progress in discovering, cataloguing, tracking, and characterizing NEOs is rapidly bounding the probability of finding a sufficiently threatening PHO (potentially hazardous object). Thorough planning always considers potential threats—whether it be PHOs or the ascendancy of Chinese HSF—but viable planning cannot hope for them. With respect to human exploration of Mars, accelerating progress by robotic science exploration poses a direct actuarial threat to the most compelling argument for the human initiative.

A fourth implication is that, should robotic missions fail to rule out indigenous biology at Mars, a planetary protection paradox will interfere with actual planning for human missions [8]. Human systems are biologically

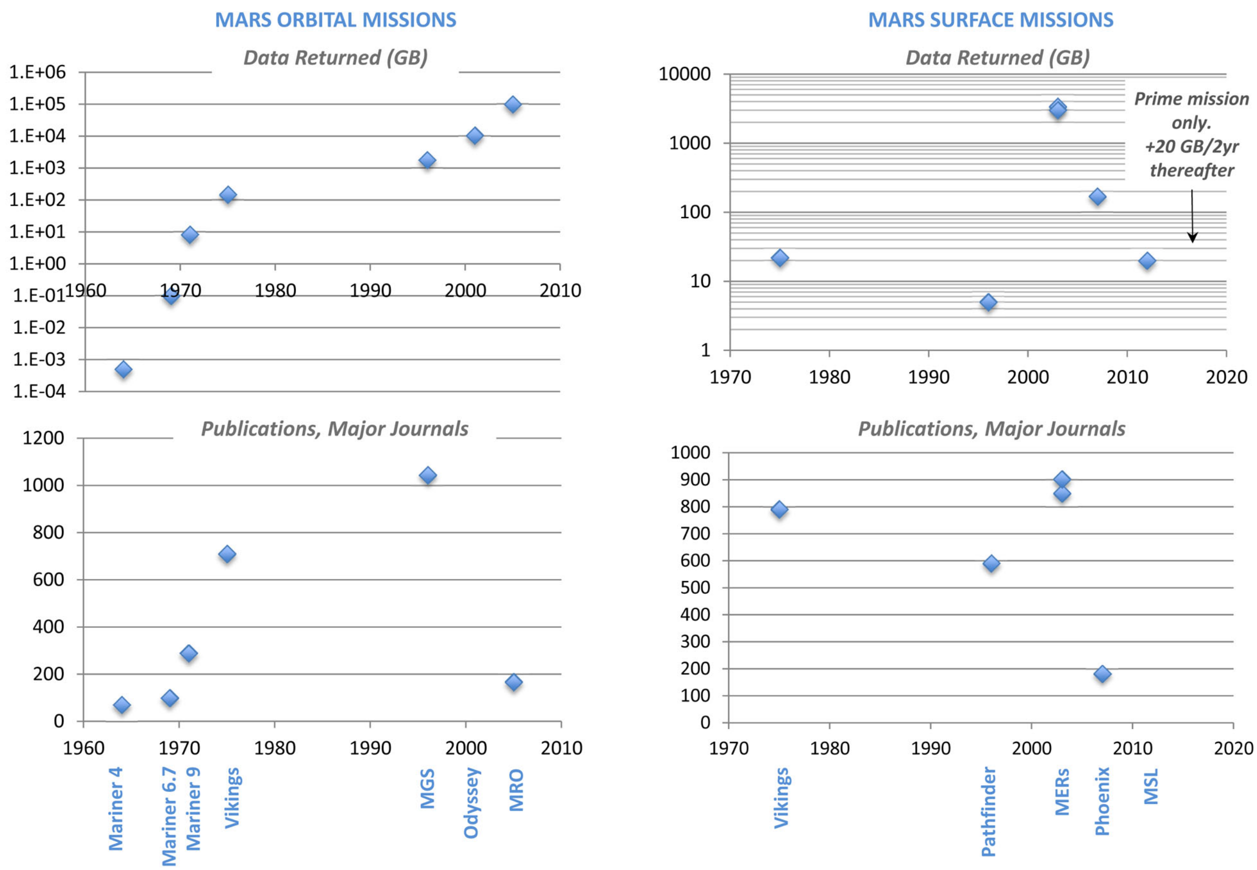

Figure 2. History of data returned by robotic missions, and major publications, sets expectations for future robotic missions and a high bar for science return from human missions. Note the log scale of the top graphs.

the "dirtiest" systems flown today; they cannot be sterilized and they release copious micro-flora into the external environment. In LEO or on the Moon or asteroids this is moot, but not on Mars. A sophisticated human exploration agenda would yearn to focus on detailed investigation of astrobiological special regions, yet these microclimates and other places of interest are precisely where human systems should not be sent—and would not be permitted. This paradox, which by international agreement and NASA's own policy could curtail human Mars exploration, is resolvable in favor of human exploration only through methodical, verifiable development of an integrated human-system architecture fundamentally driven by forward-contamination planetary protection requirements. Current planning for development of new systems does not embed such requirements into their technologies, concepts, or budget projections. Human Mars exploration, whether robotic precursors confirm habitability or fail to rule it out, cannot occur as envisioned today.

Together these implications mean that current thinking, based as it is on concepts rooted in historical assumptions about how humans would explore planets, and in the face of continued scientific progress and significant paradoxes, is planning the "wrong" exploration program. The right one, for the reasons outlined, would take longer and cost more than proposed by advocates of *Explore Mars*.

IV. OTHER OPTIONS FOR HSF

Why do we insist that *Explore Mars* is the right path?

NASA efforts to promote HSF as relevant and timely have evolved over the decades. Originally "the conquest of space" made perfect sense to Americans, because this phrase captured simultaneously the ethos of geopolitical competition and the heroic taming of a lethal frontier.

But with the geopolitical motivation resolved, only the "frontier" component remained. The HSF community reframed its raison d'être for continuance as "exploration," consistent with von Braun's long-standing personal vision. However, NASA's spending power had declined far below the threshold capable of implementing NASA's late-1960s, expansionist vision of shuttles, space stations, Moon bases, and Mars expeditions. The headliner slogans attached to each glacially paced step became prosaic to avoid highlighting the receding grand goal: we were "going to work in space" with the Shuttle, and then ISS was "the next logical step."

To still be seen as the "final frontier" space must now compete with diverse frontier alternatives. Genetic engineering, nanotechnology, artificial intelligence, networks, and sustainable energy are a few of the technological frontiers that command attention today. Each provides a clear, advancing front between what is understood and what is not, and between what can be used and what cannot. Each supplies a steady flow of challenges, achievements, and benefits. They attract capital, government regulatory attention, international competition, press, university programs, and young talent—all the things that the conquest of space used to.

Why does it seem that nobody will pay "enough" attention to HSF? Why must we repeatedly plead our case so hard? Is the problem that human exploration's true importance is somehow not being communicated effectively enough to gain traction—a common lament—or is the real problem that there is something fundamental about today's world that precludes this from even being feasible? If we seek attention in today's competitive clamor, followed by robust, widespread societal support and commitment, should we be focused on tuning the message, or rather on assuring that the message itself makes sense for today's world?

Four Strikingly Different Paths

Just as with the history of Apollo, key insights arise from analyzing what underpins the *Explore Mars* meme—and what does not. By examining the basis for our insistence on *Explore Mars* we could consider the potential value of alternative paths. Table 4 outlines four alternative options for government investment in HSF, each of which aims at a distinct purpose, taps a distinct vein of sociological aspiration, requires distinct enablers and builds a distinct foundation of capabilities, and results in a unique type of HSF achievement [9]. The four possible futures appeal to different motivations that might underlie the U.S. sense of identity in this century ("core myth"), and they trigger different assessments of the relevance and purpose of HSF: to explore, to settle, to create new possibilities for recreation, or to address a present and looming global crisis. Diverse people "see themselves" to greater or lesser degrees in each future, resonating—or not—based on their own sense of value returned by investing at NASA's contemporary budget rate for the next several decades. Usage of this conceptual framework since 2010 has indicated anecdotally to the author that the *Explore Mars* option, the course NASA has set, is actually the least attractive to public audiences, while the *Enable Space Power* option resonates most strongly. Perhaps what we have been pleading for society to support is not in fact what society is most likely to want or need after all.

NASA Not Required to *Explore Mars*

In a conceptual error that reverses cause and consequence, advocates of *Explore Mars* have come to see their agenda uniquely in the policy objectives NASA exists to support. But this correspondence can be tested. Everything NASA and other agencies and government departments do in space supports U.S. National Space Policy [10]. Its goals, refined most recently by the executive branch in 2010, begin with broad policy interests like industrial competitiveness, international cooperation, and peace through security; then remind us that both HSF and robotic means are components; and only get specific in the singular area of using space to observe the Earth and Sun:

- Energize competitive domestic industries
- Expand international cooperation
- Strengthen stability in space
- Increase assurance and resilience of mission-essential functions
- Pursue human and robotic initiatives
- Improve space-based Earth and solar observation.

While *Explore Mars* is certainly compatible with this framework, nothing in the National Space Policy explicitly requires this goal.

The legal framework for NASA, as a federal agency, is set by legislation. The NASA Authorization Act of 2010, Section 202, states (emphasis added):

- LONG TERM GOAL. The long term goal of the human space flight and exploration efforts of NASA shall be to **expand permanent human presence beyond low-Earth orbit** and to do so, where practical, in a manner involving international partners.
- KEY OBJECTIVES. The key objectives of the United States for human expansion into space shall be
    1. to sustain the capability for long-duration presence in low-Earth orbit, initially through continuation of the ISS … and through assisting and enabling an expanded commercial presence … as elements of a LEO infrastructure;
    2. to determine if humans can live in an extended manner in space with decreasing reliance on Earth, starting with utilization of low-Earth orbit infrastructure, **to identify potential roles**

Table 4. Government-funded investment in HSF could hypothetically be vectored to open any of four futures. *(Adapted from ref. 9)*

HSF Option	Purpose	Core Myth	Needs (+ $\$10^{11}$ over 30 yr)	Yields	Space Population ~2040
Explore Mars	• Extend direct human experience as far as possible • Understand potential of Mars to support life	Hero (Lewis and Clark)	• Public commitment sustained over several decades • International co-investment partnerships, sustained	• Cultural achievement: setting foot on Mars • Lagrange and asteroid destinations • High-tech international interdependence • Highly reliable space systems, advanced propulsion, deep-space human systems	Six international civil servants on a distant planet
Settle the Moon	• Establish humanity as a two-planet species	Pioneer (Heinlein)	• Public-private partnerships • Routine heavy traffic to lunar surface • Use of lunar resources • Broad range of technical skills and social services	• Cultural achievement: permanent human presence off-world • "Living off the land" in space • Lunar exports to Earth: REE, ^{3}He, tourism	10^3 mixed-demographic citizens raising families off-world
Accelerate space passenger travel	• Open space to citizens • Create new travel-related industries • Extend spacefaring perceptual shift to large population	Jet set (Branson)	• Public-private partnerships • "Four 9s" reliability launch and entry • Commercial space workers	• Highly reliable, reusable space vehicles • Space hotels and resort destinations • Routine in-space service industries (e.g., food, maintenance, medical) • 1-hr intercontinental travel	10^3 crew + 10^5 citizens visiting low Earth orbit every year
Enable space solar power for Earth	• Minimally disruptive transition to post-petroleum age • Create new energy-related industries • Become global exporter of unlimited clean energy	Green	• Public-private and inter-Agency partnerships • Power beaming protocols • Commercial space workers	• Cultural achievement: energy-abundant future • Changed land-use patterns • Economical heavy-lift launch • Routine in-space high-tech industries (e.g., construction, robotics, habitation	10^2 skilled workers on extended duty tours in high Earth orbit

that space resources such as energy and materials may play, to meet national and global needs and challenges … and to explore the viability of and lay the foundation for sustainable economic activities in space;

3. to maximize the role that human exploration of space can play in advancing overall knowledge of the universe, supporting United States national and economic security and the United States global competitive posture, and inspiring young people in their educational pursuits; and
4. to build upon the cooperative and mutually beneficial framework established by the ISS partnership agreements and experience.

Explore Mars is not called out explicitly here either. It is compatible with objective #3, but as analyzed above, maximizing HSF's role in advancing knowledge of Mars does not drive human exploration planning in fact. Interestingly, while *Explore Mars* must be inferred from the text of law, development of space resources, and specifically energy, is explicitly specified and with priority. Yet the *Enable Space Power* future is not a core part of NASA's own vision.

NASA Defines Itself

After policy and law, the next lower step is NASA's self-determination of its identity as an enterprise, and here we find that NASA is itself the source of our community's insistence on the *Explore Mars* option.

NASA's vision statement is "To reach for new heights and reveal the unknown, so that what we do and learn will benefit all humankind." While certainly compatible with *Explore Mars*, this vision statement does not specify it, let alone uniquely.

Proceeding deeper, we find the first hint of *Explore Mars* in NASA's current set of self-defined Strategic Goals (emphasis added), where the agency interprets the law's direction to "expand permanent human presence beyond low-Earth orbit" to mean very far away:

- Extend and sustain human activities **across the solar system**
- Expand scientific understanding of the Earth and the universe in which we live
- Create the innovative new space technologies for our exploration, science, and economic future
- Advance aeronautics research for societal benefit
- Enable program and institutional capabilities to conduct NASA's aeronautics and space activities
- Share NASA with the public, educators, and students to provide opportunities to participate in our mission, foster innovation, and contribute to a strong national economy.

Finally we reach the root. NASA has defined its organizational elements according to its view of what its mission is. Thus we find HEOMD (Human Exploration and Operations Mission Directorate), sibling to SMD (Science Mission Directorate) and a few others. Here NASA explicitly equates the purpose of HSF with exploration by conjoining the terms. As defined by HSF's founding fathers in the 1940s, shaped by the Apollo rush, habituated by the succession of HSF development programs gradually implementing the von Braun paradigm, secured by Congressional patterns of resource allocation, and reinforced by numerous blue-ribbon advisory panels, NASA now perceives HSF-cum-exploration to be inextricable with its institutional identity, and it projects its place in history thus (Figure 3).

Negotiating with its international partners from its dominant position of funding primacy, HEOMD has led the ISECG (International Space Exploration Coordination Group) to define five consolidated themes as the purpose of HSF:

- New knowledge in science and technology
- Sustained presence—**extending human frontiers**
- Economic expansion
- Global partnership
- Inspiration and education.

Each ISECG partner then chooses its respective focus among a common set of goals:

- Search for Life
- Extend Human Presence
- Perform Space, Earth, and Applied Science
- Perform Science to Support Human Exploration
- Develop Exploration Technologies and Capabilities
- Stimulate Economic Expansion

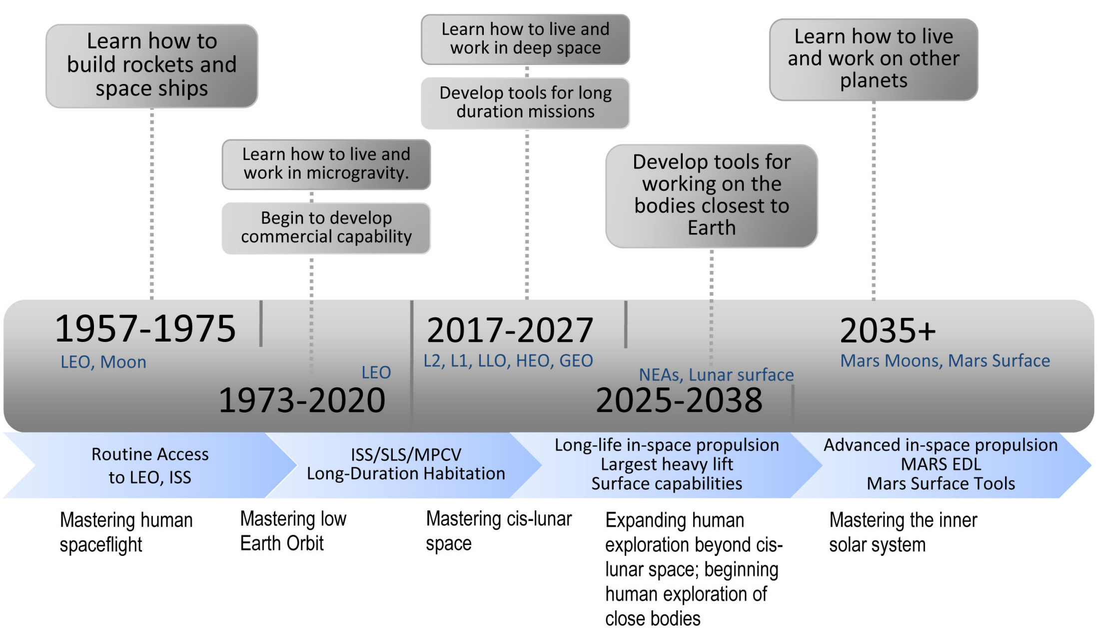

Figure 3. NASA's past and future "History of Human Space Exploration" shows how planned objectives in the present decade would lock in the *Explore Mars* future.

Table 5. Only 60% of the goals used by ISECG to justify HSF are relevant beyond HSF itself.

Self-Referential	Independent
• Perform Science to Support Human Exploration • Develop Exploration Technologies and Capabilities • Engage the Public in Exploration	• Search for Life • Extend Human Presence • Perform Space, Earth, and Applied Science • Stimulate Economic Expansion • Enhance Earth Safety

- Enhance Earth Safety
- Engage the Public in Exploration.

Table 5 parses this list of specific goals into five that are independently meaningful and three that are self-referential (i.e., they have only circular significance and thus are moot as justifying purpose). Uniqueness tests can be conducted on the five genuine goals. Most of the considerable attention devoted inside NASA to polishing these goals has been focused on asking to what degree *Explore Mars* might help attain them. But we should also ask two revealing questions: to what degree the other three HSF options could not attain them (Table 6); and the degree to which non-HSF means could. Among the options available to NASA, how unique and how effective is *Explore Mars* as judged by NASA's own criteria?

All four options Extend Human Presence, albeit in different ways that highlight variations in people's vision of humanity's future in space. Each can be seen as a valid definition of "extension:" reaching out as far as possible (*Explore Mars*); establishing a beachhead of civilization in another place (*Settle the Moon*); enlarging the spacefaring population by orders of magnitude (*Accelerating Passenger Travel*); or expanding the sphere of direct human work out to where resources can be obtained (*Enable Space Power for Earth*).

Of the four options, clearly only *Explore Mars* would tackle the Search for Life. Yet as discussed above, robotic techniques are already addressing this quest and are uniquely able to sidestep the forward-contamination paradox. *Explore Mars* would be the weakest at Stimulating Economic Expansion because it would not attract private capital; its supply side is essentially capped by the NASA budget appropriated to it, and there is little basis for anticipating either budget growth or significant change in names or nature of its industrial consumers. *Explore Mars* is also weak at delivering Earth Safety, an ironic result since this goal was written as code language for mitigating the threat of future asteroid impact. Because NEO exploration is proffered a stepping-stone to Mars, partial credit is justified. However, only robotic telescope missions can discover and track PHOs; subsequent robotic in situ missions could respond to emergent knowledge of PHOs, reaching them and characterizing them, far quicker than could HSF missions; and early intervention with robotic "gravity tractor" missions appears to offer the cleanest, most assured way of preventing PHOs from entering collisional keyholes on subsequent orbital encounters. The case for HSF being required to manage the impact threat is weak.

Settle the Moon would support terrestrial-planet science and, in particular, understanding early solar system evolution and the origin of the Earth-Moon system. But as with the Search for Life, HSF is not uniquely required to do this. Lunar science objectives are already thoroughly specified by the National Research Council, and robotic means can address all of them. Indeed, in contemporary planning discussions the telerobotic supervision of Farside surface machines is proposed as a key activity for human crews testing deep-space systems in a halo orbit around Earth-Moon L2. *Settle the Moon* deserves a nominally positive score for Stimulate Economic Expansion because of high-value lunar material resources that conceivably could generate value for the terrestrial economy: rare-Earth

Table 6. Four HSF options are mapped to NASA's rationale for HSF. All four options would extend human presence; all but "Explore Mars" could stimulate economic expansion by attracting private capital to the human development of space.

HSF Option	Search for Life	Extend Human Presence	Space, Earth, and Applied Science	Stimulate Economic Expansion	Earth Safety
Explore Mars	✓	✓	✓	–	–
Settle the Moon	–	✓	✓	✓	✓
Accelerate space passenger travel	–	✓	–	✓✓	–
Enable space solar power for Earth	–	✓	–	✓✓	✓✓

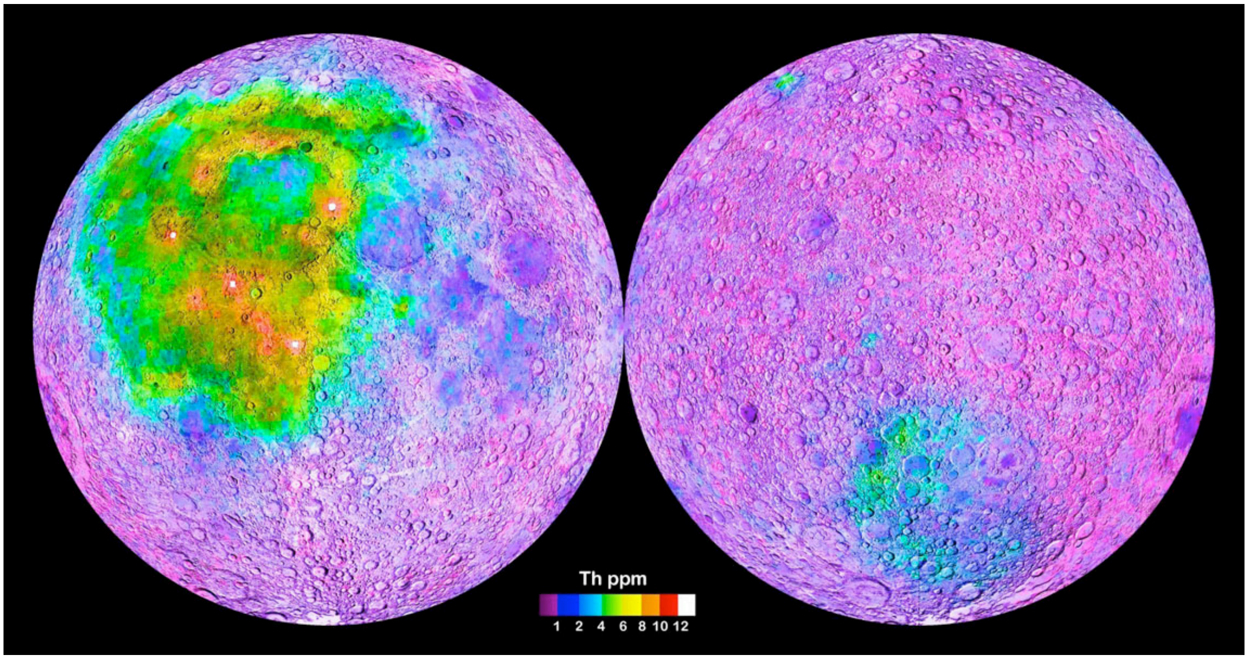

Figure 4. Thorium abundance map implies location of 10x-relative concentrations of Rare Earth Elements on the lunar nearside —a potential material resource for Earth?

elements known to be in the Procellarum Basin (Figure 4) [11], and ^{3}He embedded by the solar wind throughout the regolith. In addition, the Moon is an obvious long-term destination option for space tourism businesses. *Settle the Moon* also gets a positive score for Earth Safety, if we interpret the Moon's material-resources potential as helping the security of Earth civilization in a broad sense.

Accelerate Space Passenger Travel is not about Science or Earth Safety (although fast intercontinental travel ushered in by high-reliability commercial LEO travel would have major security implications). Rather, its purpose would be to Stimulate Economic Expansion, creating wealth by leveraging private capital to add new businesses to the 21st century economy. This pattern would be analogous to the way commercial air travel (enabled by NASA's predecessor the NACA) spawned multiple core and supporting industries throughout the 20th century.

Enable Space Power for Earth would also Stimulate Economic Expansion (albeit with a different mix of industries, balanced more toward energy distribution, land use, mass production of space systems, and high-throughput launch). Industrialization of GEO, because it merely "uses" space for a critical terrestrial need rather than being about space per se, has the greatest potential for rapid economic growth among the four options. Furthermore, because of its role in opening an energy-abundant future and in rebalancing the geopolitics of energy provision, it has the greatest potential among the four options to promote global economic and ecological stability. In short, *Enable Space Power for Earth* is the option most likely to embed extensive space operations deeply into mainstream terrestrial economy, governance, and society.

The second uniqueness test is even starker. Using Applied Science, Stimulate Economic Expansion, and Earth Safety as metrics, *Explore Mars* is found to be quite poor compared even just to the other contemporary technology frontiers listed earlier: genetic engineering, nanotechnology, artificial intelligence, networks, and sustainable energy. All have direct, apparent, and present impact on the three metrics. As catalysts for progress and shaping the future of human civilization they are far more powerful and relevant than *Explore Mars*. To a somewhat lesser degree this same non-centrality would likely be the case for Settle the Moon and Accelerate Space Passenger Travel. *Enable Space Power* for Earth appears to fare better; its potential to become centrally important is high because of the deep societal dilemma of energy supply, let alone abundance, as the 21st century unfolds; however its role would be prey to unforeseen, competing breakthroughs like the taming of fusion power.

At the least, the comparison to today's other high-technology frontiers highlights the degree to which the ISECG goals for HSF are in fact rationalizations rather than deep rationale.

Long before NASA existed, a technically knowledgeable and visionary international community of advocates calculated that interplanetary travel should be possible, and their assessment of feasibility morphed into a vision and commitment. Von Braun demonstrated how real this vision could be made to appear, lofted by the funding and sociological support of a cold-war-era geopolitical need. But while the rocket scientists' core vision did not sustain traction among political decision-makers on its own merits, the HSF community nonetheless interpreted the means for the end, concluding that *Explore Mars* was indeed the purpose rather than the tool. After the geopolitical agenda fell away, a mature "government-industrial complex" imbued with a geography of jobs and infrastructure began to represent the HSF tool as its own purpose. Assimilation of the *Explore Mars* meme into our community's sense of its own identity was the natural result.

By assuming or asserting that HSF equals exploration, and thus by insisting that *Explore Mars* is its raison d'être, NASA puts HSF on soft ground. The explicit value proposition contained in NASA's own justifying language is neither uniquely nor thoroughly compelling—other options are at least as capable of meeting the stated objectives. Because the value proposition of human space exploration is inherently weak, it should be neither surprising nor frustrating to our community that sociological and political enthusiasm is neither apparent nor forthcoming.

If we seek to have vibrant, expanding HSF, including proliferation of new industries that embed HSF into 21^{st}-century culture, then no matter why we "believe in" it, we might pragmatically consider how HSF—not human exploration—could be made attractive to and even fundamental to humanity's future. The answer may be one of the other three options.

V. CONCLUSION

Explore Mars may not be the highest and best use of HSF in the 21^{st} century. Since Apollo the human-exploration meme has lithified into an unexamined axiom, which has now run aground in its ability to motivate the kind of deep and widespread popular and political support that could establish and sustain the investment to retire the technical risks and fulfill the vision.

However, by re-examining the "HSF = exploration" axiom, particularly in light of modern societal aspirations, urgent global needs, and what could be accomplished technologically under reasonable funding scenarios, we can escape our predicament.

Explore Mars has a high opportunity cost. $\$10^{10}$ per year for NASA HSF is a precious resource in today's world, not guaranteed to continue indefinitely. At this point, sustaining the resource, let alone increasing it, hinges on securing an unprecedented commitment of long-term vision. But because of its weak value proposition *Explore Mars* may be unable to catalyze that commitment. Other options for NASA's level of HSF investment offer alternative futures, characterized by different combinations of extending human presence, stimulating economic expansion, and assuring a safe future for civilization.

What is the right conversation to have? Debates about "choosing a destination" are moot if HSF is perceived as a discretionary investment that provides only soft power and soft-perception benefits to American or global society, rather than capabilities and products critical to citizen interests or urgent needs. The right debate to have is what societal benefits we expect from our HSF investment, not which object in the sky we want to send a few astronauts to. Were NASA to adopt addressing core, current challenges as its driving HSF requirement rather than planetary exploration, the agency could begin to make HSF directly relevant to urgent priorities, popular interests, and unconstrained opportunities for economic growth.

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