Technology Investment Agendas to Expand Human Space Futures

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The paper develops four alternative core-technology advancement specifications, one for each of the four strategic goal options for government investment in human space flight. Already discussed in the literature, these are: *Explore Mars; Settle the Moon;* accelerate commercial development of *Space Passenger Travel;* and enable industrial scale-up of *Space Solar Power for Earth.* In the case of the Explore Mars goal, the paper starts with the contemporary NASA accounting of ~55 Mars-enabling technologies. The analysis decomposes that technology agenda into technologies applicable only to the *Explore Mars* goal, versus those applicable more broadly to the other three options. Salient technology needs of all four options are then elaborated to a comparable level of detail. The comparison differentiates how technologies or major developments that may seem the same at the level of budget lines or headlines (e.g., heavy-lift Earth launch) would in fact diverge widely if developed in the service of one or another of the HSF goals. The paper concludes that the explicit choice of human space flight goal matters greatly; an expensive portfolio of challenging technologies would not only enable a particular option, it would foreclose the others. Technologies essential to enable human exploration of Mars cannot prepare interchangeably for alternative futures; they would not allow us to choose later to *Settle the Moon,* unleash robust growth of *Space Passenger Travel* industries, or help the transition to a post-petroleum future with *Space Solar Power for Earth.* The paper concludes that a decades-long decision in the U.S.—whether made consciously or by default—to focus technology investment toward achieving human exploration of Mars someday would effectively preclude the alternative goals in our lifetime.

Nomenclature

CBM	=	Common Berthing Mechanism
DRA	=	Design Reference Architecture
EDL	=	entry, descent, landing
EM-L1	=	Earth-Moon L1 Lagrange Point
EM-L2	=	Earth-Moon L2 Lagrange Point
ESA	=	European Space Agency
EVA	=	ExtraVehicular Activity
EVR	=	ExtraVehicular Robotics
GCR	=	Galactic Cosmic Radiation
GEO	=	Geosynthronous Orbit
GNC	=	Guidance, Navigation, and Control
HEFT	=	Human Exploration Framework Team
HSF	=	human space flight
ISRU	=	In Situ Resource Utilization
ISS	=	International Space Station
JIMO	=	Jupiter Icy Moons Orbiter
KSC	=	Kennedy Space Center
LEO	=	Low Earth Orbit
LOC	=	Loss of Crew
LOM	=	Loss of Mission
LOX	=	Liquid Oxygen
LH2	=	Liquid Hydrogen
MSL	=	Mars Science Laboratory
NACA	=	National Advisory Council on Aeronautics
ORU	=	Orbital Replaceable Unit
PDR	=	Preliminary Design Review
R&D	=	Research & Development
RCS	=	Reaction Control System
REE	=	Rare Earth Elements
SEP	=	Solar Electric Propulsion
SLS	=	Space Launch System
SPE	=	Solar Proton Event
SPS	=	Space Solar Power
STEM	=	Science, Technology, Engineering, and Mathematics
WW I	=	World War I

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I. Introduction

International planning for human space flight (HSF) is focused toward eventual human exploration of Mars—what the Augustine Committee called the "ultimate destination"—with the only significant debate being about whether a "Moon first" or "asteroids first" path is the best warmup.[1] Declining spending power forces the needs of the *Explore Mars* goal to be used as a filter to determine the relevance and priority of proposed HSF-related technology investments.

NASA's HEFT (Human Exploration Framework Team) began such a prioritization in 2010 by cataloguing about 55 major technology development projects, all of which would have to reach flight readiness to make the *Explore Mars* theme feasible. Analogous technology development agendas were not elaborated to a comparable level for the three alternative objectives for government HSF investment (Table 1).[2] A natural question arises: Is the *Explore*

Table 1. Four alternative futures could be enabled by government investment in HSF.[2]

HSF Option	Purpose	Core Myth	Needs (+ $\$10^{11}$ over 40 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, 3He, 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 • "Five 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 • conomical 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

Mars technology agenda equally preparative for all four potential objectives? If so, then debate over the core value proposition for HSF is moot until retirement of the technology agenda is well underway. But if not, then the value-proposition debate is not academic.[3] In that case large investments in the *Explore Mars* technology agenda might foreclose the other pathways for a generation. Today's stakeholder community needs to know how irrevocable its current choices might be.

II. Technology Agenda to *Explore Mars*

Explore Mars "pulls" the default HSF technology agenda; consequently well-studied, this agenda has evolved significantly since the 1940s. Table 2 is a contemporary list, produced in 2010 by HEFT, of required and provisional technology-developments that together would enable *Explore Mars* technically. Two attributes are noteworthy. First, each item is a distinct technology-development project to be planned, funded, and managed to maturity. Taken together the list comprises a daunting development program, which indeed is partially responsible for the intrinsic unpredictability of both date and cost to achieve a first human Mars surface mission. Convolving the variances of only the 40 essential and 10 likely-essential technology projects precludes confident calendaring of the integrated program, no matter which architecture is chosen. *Explore Mars* is far harder than Apollo, and there is no basis for presuming a "blank check" to maintain schedule.

Second, each item opens a rich world of questions, options, tradeoffs, and uncertainty even regarding fundamental feasibility. "Biomedical countermeasures," "high-reliability life support systems," "EDL for 20 ton human systems," and "fission power for surface missions," among many others, are each as fraught with development risk as "lunar orbit rendezvous" was for Apollo. No one really knows whether they could be implemented reliably, so their presence on the critical path is sobering.

Still, technology advancement for its own sake is proffered as a core rationale of the *Explore Mars* value proposition, because of the Apollo spinoff experience and the strategic importance of STEM education and technology-sector jobs. So the daunting *Explore Mars* technology agenda has inherent value no matter how long it may take to complete, independent of actual attainment of the *Explore Mars* goal. This open-ended societal benefit can be weighed together with the intangible (finally, humans on Mars!) and tangible (six civil servants setting foot on Mars circa 2050) outcomes of the goal.

The question for the present analysis is to what degree the prosecution of the *Explore Mars* technology agenda might "bake in" that goal, precluding other HSF

Table 2. Technology development agenda to *Explore Mars* is a daunting list.

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

futures by not adequately preparing for them as well. This unexamined question is the subject of the present treatment.

Direct comparison across the four options requires a different list, for two reasons. First, Table 2 is too granular. It omits an intermediate layer of rationale because it is cast with *Explore Mars* as its axiomatic purpose. For example, beyond-LEO heavy-lift launch, and in-orbit loitering and assembly of deep-space vehicles, are key drivers behind several of the technologies listed, yet they do not appear explicitly and might be unneeded for alternative HSF goals. Second, no widely accepted DRAs exist for the other three HSF futures, so there is no basis yet for a detailed, quantified comparison.

To gain first-order comparative insight, we focus on just the dominating investment areas required; Table 3 shows a different view of the *Explore Mars* technology agenda. The technologies to enable the 2009 NASA Design Reference Architecture 5.0 are listed on the right. Albeit more architecture-specific than Table 2, it nonetheless suggests a taxonomy of major areas (listed on the left) at the appropriate level for comparison with technology agendas for the alternative goals. Assessed at that level, the technology agenda to *Explore Mars* is characterized by six major domains.

Human-system-scale, deep-space, advanced propulsion—Contemporary Mars mission concepts tend to accept that all-cryogenic propulsion is impractical to advocate. Hence concepts are now based on some combination of: aerobraking for planet-orbit capture (in less favor today than in the early 1990s); nuclear thermal rocket (episodically resurgent in popularity, but challenging to test under U.S. environmental laws); variable-Isp plasma rocket (laboratory progress in recent years, but would require nuclear reactor-class power); nuclear electric (also would require a nuclear power plant; the robotic JIMO precursor flight system development was canceled in 2004); solar electric (popular again today, but very large system size). Significant technology maturation would be required for any of them.

Maintenance of human health for long durations in deep space—Crews on *Explore Mars* missions (asteroids, Mars vicinity, or Mars surface) would operate out of reach of help from Earth and without any means to

Table 3. Binning technology areas allows broader comparison with other HSF options. Example shows technologies for *Explore Mars* DRA 5.0, vintage 2009.

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 • Microgravity countermeasures • Life support loop closure
In-Space Operations	• 300+ day LEO loiter and modular assembly – Large deep-space flight systems: – 110–124 t for trans-Mars injection, ~50 t roundtrip – Advanced interplanetary propulsion – Aeroassist for capture at Mars – 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)

return quickly. The ability to handle low-probability, high-consequence medical situations would require time-delay telemedicine, well-provisioned treatment facilities, and significant cross-certification of a very small crew. No protocols, systems, or practical implementation scenarios exist yet.

Human-system-scale Mars landing and ascent—MSL's Skycrane, the state-of-the-art EDL technology for landing heavy payloads on Mars, delivered almost a metric ton to the surface on August 5, 2012. Human-system payloads for *Explore Mars* scenarios typically range between 20–30 metric tons. Such payload mass is far outside the feasible range for parachutes; supersonic inflatable decelerators are just beginning development for MSL-class payloads. The remaining option is supersonic retropropulsion, an exhilarating approach whose feasibility is not universally accepted, and which has not been validated experimentally, converted into system requirements, or mainstreamed.

Planet-surface operations for complex science—Traditional *Explore Mars* surface-system and operations concepts are analogous to Apollo: suited crew EVAs, rovers for local mobility, sample collection, and experiment set-up. Most likely, human surface sites would be extensively mapped robotically before crew arrival; meanwhile, in situ Mars science leaps ahead with each robotic mission in the interim. To take full advantage of humans being onsite for months (e.g., conjunction-class stay time) would require an in situ laboratory at least on par with the ISS *Destiny* module; no such facility or equipment is included in *Explore Mars* planning.

Use of in situ resources for propellants and consumables—The opportunity to use oxygen derived from the Mars atmosphere for ascent and/or return propellant is tempting from the standpoint of propulsion "gear ratio." However, the likelihood of relying on this efficiency for a first human mission is not settled, calling into question ISRU as a significant basis for planning, and hence the overall "size" of the first mission campaign. Extraction and purification of water and breathing oxygen appear more tractable and reasonable, but would still require significant technology development and in situ validation.

Self-sufficient maintenance of human space systems—Analogous to the medical challenge for human crews, vehicle systems on which human lives could depend for three years (more if some elements, e.g., habitat modules, are to be re-used) would need to operate reliably without servicing or logistics from Earth. This is an unprecedented challenge, particularly for such a visible undertaking as the first human expedition to Mars; reliability and maintainability experience on ISS is a sobering counterpoint.

Each of these technology domains contains a host of individual technologies needing development, validation, maturation, and infusion before human crews could depend on them to Mars and back. Together, to first order, they comprise a technology agenda to *Explore Mars*.

Heavy-lift launch, of the type needed to support on-orbit assembly of modular, Mars-mission-class flight systems (e.g., a Saturn-V class vehicle), is not included in this short list because it is not intrinsically a new-technology development. This prominent example highlights a key distinction between system developments and fundamental breakthroughs. Whereas any 21st century launch system (e.g., SLS) would incorporate the most robust technologies available by the time of its PDR, the basic solution for this class of heavy-lift launch has been in hand since the 1960s. For the other domains this is not the case.

III. Technology Agenda to *Settle the Moon*

A goal of space settlement by pioneers would set a significantly different technology agenda than the default case of exploration by heroes (see again Table 1). The differences arise from three principal distinctions between the two scenarios. The first two greatly simplify the transportation challenge: the Moon is ~145 times closer than Mars ever is, and the Moon has no significant atmosphere. The third distinction adds complexity to everything else: supporting a population permanently in a lethal environment is a different type of problem than sustaining a tiny crew on a three-year expedition.

Routine heavy traffic between Earth and Moon—With respect to launch and transit, the reduced capacity to mount a single mission, and the absence of a need for breakthrough human-system propulsion technology, both mean that routine exchange of people and products between the Earth and Moon is orders of magnitude less impractical than for Mars. With respect to planetary landing and ascent, the solution space for lunar descent collapses to all-propulsive, tethered (rotor deposition or EM-L1 elevator), or impact-landing. The solution space for ascent collapses to all-propulsive, tethered, or mass-driver. Entry capsules, heat shields, aerodynamic decelerators, and fairings are not needed, which alleviates scaling challenges for heavy payloads compared to Mars. Single-stage systems are feasible for the Moon, which could facilitate fully-reusable architectures. EM-L1 and EM-L2 provide node options in addition to lunar orbit that, when coupled with in situ production of oxygen and single-stage reusable systems, offer efficiencies for a routine transportation network. So whereas small, one-way crews could conceivably settle Mars, settling the Moon by "building a railroad" between Earth and its moon would be far more

feasible. Technologies aimed at the viability of such a "railroad"—including use of in situ propellants, surface basing, system reuse and refurbishment, repetitive operations, modular solutions for both people and cargo, and system-level redundancy for schedule reliability—would matter most. However, these factors are not likely to be key driving requirements for government planning aiming for episodic lunar "exploration" on the way to Mars.

"Living off the land"—For scalable settlement, lunar resources would be essential for several classes of material product: propellant (oxygen, then hydrogen), interior atmosphere (nitrogen, oxygen); water; lightly processed construction materials (siteworks, sintered regolith, cast basalt, glass, and iron); manufactured construction materials (concrete, steel members, glass-fiber composites, aluminum and titanium members, elastomers, plastics, epoxies, semiconductors, and electrolytes); manufactured elements for assembly and outfitting, made from manufactured and organic materials (photovoltaics, fasteners, wires, ducts, insulation, fiber, fabric, foams, and coatings); consumables (plants and animals for food, renewable and recyclable products like paper, toner, clothing, and packaging); and finally complex manufactured assemblies and equipment (heavy machine parts, precision machine parts, and electronic devices) up to the limit of affordable self-sufficiency for the settlement. The technology network required to literally build civilization from the ground up in a remote, hostile environment is by far the most fundamental need and the most transformational benefit of the *Settle the Moon* scenario. It is unlike any of the other three HSF options in the diversity or scale of technical challenge; compared to them it offers the broadest set of opportunities for existing terrestrial industries to engage with HSF, the largest set of opportunities for small-business entrepreneurialism, and consequently the richest potential for technology spinoff back into terrestrial enterprises. This technology domain arises from the operations scale required for settlement; hence with two exceptions (radiation-shielding modular habitats, and experimental derivation of water and propellants from lunar polar ice), this domain is thin in traditional lunar "exploration" planning aimed at preparing for Mars.

Lunar civil engineering—A closely related technology domain would advance the industrial operations to create and use the aforementioned products throughout their respective lifecycles: mining, processing, manufacturing, construction, assembly, finishing, testing, certification, maintenance, disassembly, recycling, and disposal. The development of such integrated, "horizontal" lifecycle operations would be as comprehensive as the "vertical" product families themselves, with consequent significance for how fundamental both the challenge and benefit would be. A particular subset of this domain is civil engineering to enable even primitive settlement: building shelter. For lunar settlement there are three major sub-domains of civil engineering that would require significant, enabling technology development:

1) Siteworks—removal, grading, sorting, deposition and stabilization of native regolith for dust control, radiation shielding, roads, workyards, berms, foundations, and landing/launching pads.
2) Large-dimension pressure vessels—fabrication of elements, assembly into habitation-scale and community-scale enclosures; incorporation of engineering penetrations for utilities, hatches, windows, and connectors; sealing, testing, and certification for occupancy; outfitting with secondary structures; monitoring, maintenance, and repair; and deconstruction and recycling.
3) Industrial complexes—accommodation of industrial-scale equipment and operations for community-scale and export-scale mining, processing, and manufacturing; and husbandry, farming, and food production.

No significant technology investments have been made to date in these areas.

Community-scale life support and food—Means for refreshing breathing air, purifying water for potable uses, and producing food on a community scale are far outside the scope of traditional HSF investments. The technological challenge is daunting. It inevitably synthesizes physicochemical and biological means, and is subject to feasibility limits that remain uncharacterized. Extant examples are instructive because they represent three poles in the tradespace. First, life support and food on the ISS are totally engineered: respectively, machine-controlled and pre-packaged. Biological agents are treated as contaminants throughout the system. Second, state of the art research by NASA (particularly at KSC) and ESA (MELiSSA) takes a highly engineered approach to employing biological agents: e.g., bacteria for digesting waste and plants for revitalizing air and growing food. These organisms are contained, differentiated, cultured, monitored, and controlled. Third, the original Biosphere II experiment took the bold approach of hermetic but large-scale biological life support, in which biological agents occupied more natural niches in a broad-spectrum ecology, and were loosely tended by the crew.

Imagine each approach scaled to the capacity required to support a settlement community of thousands of people. It is doubtful that any such system should rely completely on either physicochemical or biological means—redundancy and the need for locally produced food suggest otherwise. The weaknesses of each contemporary approach even just for air and water indicate the scope and challenge of the technology development required: reliability, sustainability, logistics, contamination control, and "artificiality" of the ISS extreme are all incompatible with settlement-class implementation. The electromechanical complexity of MELiSSA is no simpler, and indeed increases complexity through dependency on microorganisms and plants. Yet the biological balance in Biosphere II

was observed to be delicate, complex, and highly sensitive (e.g., CO_2 buildup caused by higher-than-expected soil microbe metabolism). Even at the size of Biosphere II the "aquarium effect" occurs: managing the system to maintain a designed equilibrium requires constant attention and may not be fully controllable.

A few observations and conclusions are clear: (1) this is a rich, unsolved technology domain; (2) it is the most directly relevant for terrestrial sustainability challenges the world faces with or without HSF; (3) developing "closed ecological life support" for small exploration crews can only scratch the surface of the field; and (4) scalability is strictly enabling for space settlement, given practical limits on physicochemical means for community-scale biological systems, and given the need to produce food.

Broad spectrum of technical skills to support socially "normal" life—This domain is not as urgent as the prior four, but is included because of its necessary pervasiveness at the scale of settlement. It provides another source of opportunities for clever design, entrepreneurial development, and commercial service provision. For space architects it is a stimulating domain almost completely outside the realm of any HSF investment program to date. Appreciation for the need, challenge, potential for inspiration, and potential for terrestrial spinoff can be gained by isolating almost any aspect of civilized life and considering how it could be done on the Moon. Examples prosaic and diverse make the point: where toilet paper would come from, what the nominal 1/6-g ceiling and doorway height should be, how to make a maintenance garage for construction equipment, whether and how regolith could be adapted to soil, what a hermetic "outdoors" could be like, how citizens would carry their shopping around their community, what to do with corpses. Virtually all functions and activities underlying social life would require solutions to be adapted to lunar conditions or developed anew—and many of these would lead to technology invention with subsequent infusion back on Earth.

Mining for exports—Seven conceptual lunar exports are described in the literature: (1) oxygen for propellant; (2) construction materials for use in space; (3) tourism; (4) beamed power for Earth; (5) ^{3}He for terrestrial fusion reactors; (6) platinum-group metals; (7) rare-Earth elements. Of these, the first two are self-referential as a basis for economic growth, because they simply shift the burden of a business case to other HSF activities. The remaining five are at least theoretically viable as engines for growth of lunar settlement because they use the terrestrial economy to consume value produced by lunar work.

Developing lunar material or energy products for export would hinge on a network of technologies for prospecting, mining, extraction, beneficiation, processing, and transport at a minimum. Some laboratory development has been done on techniques for oxygen extraction from regolith and rocks (before recent confirmation of ice deposits at the lunar poles). Some conceptual approaches for mining have been published for the other products, and first-order scenarios have been published for large-scale implementation of lunar surface-based power beaming. However, the center of focus for the minor NASA investments in lunar ISRU has been self-use of oxygen to lower the per-mission cost of lunar "exploration." This scenario suffers from poor economy at small flight rates, if the costs to develop, validate, implement, verify, and utilize in situ oxygen are not treated as externalities. Fundamentally no NASA investments have been made toward industrial-scale export, either for oxygen or the other resources including tourism.

The value proposition for the five non-self-referential exports is highly uncertain, and is dependent on competing sources for analogous products. Prospects for lunar settlement would hinge on a combination of ineffable benefits (e.g., the sociological achievement of becoming a multi-planet species) and some or all of the material benefits listed here. While the latter may appear to be a fragile basis for investing $\$10^{11}$ of public resources and decades of technology development, the *Settle the Moon* option nonetheless could offer them; *Explore Mars* cannot, because of its astrodynamics barrier.

IV. Technology Agenda to *Accelerate Commercial Space Passenger Travel*

The technology needs to *Accelerate Passenger Travel* are as different from those to *Settle the Moon* as those are from the ones to *Explore Mars*. At the top level there are two driving differences: (1) the target spacefaring population in this case is very large but very close to Earth (as opposed to large but remote, or tiny but very remote as in the other two scenarios); and (2) the objective of government investment would not be directly to emplace or operate capabilities in the marketplace, but rather to "lower the bar" for entrepreneurs to attract private capital and create new industries.

The appropriate model for this option is NASA's predecessor the NACA. Created in the closing years of WW-I to yield a strategic U.S. military advantage, the NACA developed the fundamental technology base that still underpins the aerodynamics and propulsion capabilities enabling commercial and military air travel. Thus the NACA, albeit not in pursuit itself of a "mission" like Man on the Moon (or by analogy, *Explore Mars* or *Settle the Moon*), directly led to the creation of today's commercial aviation sector of the economy, and the enormous growth

of the air power segment of the military sector. Its value proposition is practically incalculable because of the orders-of-magnitude leveraging of capital, the creation of a network of businesses, and the transformational change air travel has wrought on civilization.

A 21st-century analogy could arise were NASA to invest in technologies needed for a network of industries to implement large-capacity passenger travel in Earth orbit. Today's space entrepreneurs who are already pioneering space passenger travel, both suborbital and orbital, have made great headway on the shoulders of pre-existing NASA technologies, by investing in targeted improvements in diverse areas like airframe architecture and design-for-manufacturing. Yet game-changing breakthroughs in aerospace tend to be expensive, and beyond a certain threshold such developments can be afforded only using public money. A worthy agenda can be assembled from such needs.

"Five 9s-reliable," reusable flight systems for launch and entry—The price elasticity of the space passenger travel market has been debated extensively, particularly with regard to "performance elasticity." That is, for minutes-long suborbital hops and (separately) for indefinite-duration orbital flights, how much would the market grow as the price declines? No one will really know until the actual marketplace develops. We may speculate, however, that a third elasticity dimension will come into play: "reliability elasticity." This is illustrated by bounding thought experiments: Is there any price—even free—at which an average traveler would fly into space if the probability of returning safely were only 95%? Conversely, how would the "knee" of the price-elasticity curve shift if space flight could be made as safe as commercial air travel?

The Shuttle experienced a LOC reliability of 133/135 (0.985, almost "two nines"); NASA's SLS/Orion system is designed for an order of magnitude improvement, approaching three nines. Contrast this with commercial air travel: about 50,000 commercial carrier flights occur per day globally, and among the 30 safest carriers, odds of fatality are about 1 in 30 million (3×10^{-8}, or "seven nines").[4] A goal of supporting routine traffic to and from LEO by hundreds of thousands of tourists per year would push launch and entry to become as airline-like as feasible: standardized flight systems, schedule reliability, rapid trips with short transfer times, substantial passenger throughput (through some combination of high flight rate and large cabin size), and perhaps five-nines flight reliability (10^{-5} LOC).

Nothing like this is in development today, and flight systems being developed for exploration do not establish an applicable technology foundation for it. Whether this combination of requirements is even achievable is not universally accepted among aerospace engineering professionals—a clear indication of its worthiness as a breakthrough capability and the reason why it would be beyond the reach of research funded by the commercial sector. Given a charter to achieve five-nines reliability, the government-contractor space flight community would be as challenged as they were in the 1960s, to make the seemingly impossible real. Governing assumptions for space flight applications other than tourism would shift as a result. An obvious example that might ripple quickly through the modern economy would be intercontinental "air travel" in under an hour.

Space hotels and resort destinations—The second-most critical technology domain to *Accelerate Passenger Travel* would enable the type of orbital destination amenities that a tourism industry would require. Among these are seven key elements:

1) Large habitable volumes assembled and verified in situ—"Squeezing" future space destination systems through the diameter of a launch vehicle shroud cannot work for resort applications beyond the very initial stages. Existing inflatable module technology provides only marginal relief from this constraint. Technology for forming or assembling, then testing and certifying for occupancy, large-dimension pressure vessels will become enabling for large-population uses. A reasonable mid-term benchmark might be the ability to fashion volumes comparable to the lobby and ballroom spaces of terrestrial hotels, i.e., able to assemble 50–400 people. Such volumes would be fundamental for many habitation, recreation, and industrial functions in microgravity.
2) Big windows—Windows in space habitats are a hard engineering problem. Yet the instant photogenic popularity of the ISS Cupola demonstrates how critical a need this will be for travelers. First, Earth is the most poignant, beautiful, and ever-changing view in the solar system. But beyond that, the dominating subtended field of view of Earth in LEO makes it possible to use overflight of the home planet as a "blue sky" surrogate in microgravity environments inverted so nadir is the overhead direction.[5] This illusion and many others could be done without windows by using large-area, flat screens showing camera views; however it seems likely that direct viewing will be demanded by high-paying travelers. Future large windows would require integrated solutions for strength, fracture resilience, structural integration, and radiation shielding.
3) Multi-use berthing mechanisms—ISS CBMs between modules were mated (and sometimes re-mated) only a few times. Today's smaller-diameter docking adapters may be used 10^2 times over the life of ISS, with margin. To certify mating systems for 10^3 cycles may require new technologies for seals, mechanisms, and in situ maintenance and refurbishment.

4) Kitchen science—"You can't have a space hotel until you can cook an omelet and mix a martini." On adventure-travel vacations to remote places on Earth, good food is an essential part of the experience. To date, essentially no research or development has been invested in learning microgravity techniques for genuine cooking and kitchen-waste recycling; food growth and especially food processing are infant fields. Behavior and transformation of foodstuffs in microgravity represent a startling gap in spacefaring knowledge; appropriate equipment for this most basic of human activities has not been designed or tested.
5) Leisure accommodations—Tourists should be anticipated to expect activities unique to their exotic travel destinations. In LEO this would include: viewing Earth, experiencing microgravity in groups (sports) and privately (sleep, repose, and sex), viewing facility engineering operations (including food production and maintenance or industrial activities), and going on EVA. Activity viewing requires, in addition to windows, structural solutions like galleries. Recreational EVA may seem a reckless oxymoron to experienced aerospace engineers and mission managers, but is likely to be a vital element of the orbital resort business model. Multiple technologies providing gradations of EVA would need development: flyaround "minivans," free-flying capsules, jetted suits, and tethered suits. The common element for a wide range of microgravity sports would be large habitable volumes, but water-body facilities analogous to pools would pose unique challenges for containment, momentum management, and breathing equipment.
6) Surgery—Invasive medical care in microgravity is an undeveloped field. Virtually every aspect (e.g., sterility protocols, imaging, anesthesia, retraction and restraint, reaction force for operating precision, perfusion, infusion, cleansing, and visibility, as well as the behavior in microgravity of bodies, systems, and organs under trauma) requires development, testing, and standardization. An even larger number of medical procedures less serious than open surgery also need to be adapted to in situ conditions and limitations.
7) Artificial gravity—Large-radius rotation (to avoid Coriolis- or vision-induced nausea) would introduce unprecedented system-design and operational complications for habitable spacecraft. Thus artificial gravity has, for many years, been the option that *Explore Mars* engineers hope they can avoid for multi-year deep-space missions. Recent data from ISS prophylaxis protocols provide the first encouraging indications that it may be possible to stabilize bone deconditioning; however, it remains unclear how a crew could arrive at Mars sufficiently conditioned for surface work in 3/8 g after a half year of microgravity. Without empirical physiology data from at least orbital-centrifuge and lunar-surface missions, no one even knows whether weight levels less than 1 g can prevent deconditioning. For mature tourism, though, uncertainty about what might be required to maintain health during long-duration spaceflight may be moot. High-paying passengers would likely consider variable gravity, and the bizarre perceptual shifts that occur in a rotating frame,[6] as fun features of the perfect vacation. The counter-intuitive trajectory of an object dropped or a ball thrown in a rotating habitat, and the weird pull experienced while climbing a ladder, for example, are sensations that may be expected by resort tourists. Significant technology development would be required to enable configuring, operating, and outfitting for rotating artificial weight.

All seven elements of this technology domain go far beyond the space-habitation knowledge put into practice so far by government programs in the U.S., Russia, Europe, Japan, and China; or being invested in going forward. Only dental and contingency surgery, and perhaps artificial gravity, are seen as essential to the *Explore Mars* goal; these might be advanced to some degree on the default path.

Commercial space workers—A commercial jet carrying hundreds of passengers might do so with only a handful of flight crew and flight attendants onboard. But resort destinations are quite different, where worker-to-guest ratios approaching 50:50 are common. So even if we expect space tourism operations to be more economically constrained than this, thousands of professional in-space workers would still be required to support a transient population of travelers totaling hundreds of thousands per year. Guests would be exposed to space radiation for only days to weeks, but workers on half-year duty tours would have exposure potential like today's civil-servant ISS crews. For workers' careers to last longer than just a few duty tours could easily require radiation mitigation technologies (shielding, prophylaxis, and remediation) exceeding anything NASA is likely to develop for deep-space expedition crews.

In addition, flight systems occupied by non-professional guests, possibly including children and risk-taking or misbehaving passengers, would need a suite of design and operations features to maintain human and system safety. These might extend to adaptive artificial intelligence as well as physical separation and security systems. A helpful analogy is today's automobiles: machines operating at intrinsically dangerous energies are nonetheless pervasive in society, routinely operated by lightly trained drivers. To enable this they are built full of safety technologies, and operation is monitored.

At a "micro level," diverse service industries would require technology development to be adapted to the space environment. Practically every operation done by space workers in providing routine services to passengers and

other crew (e.g., food, maintenance, medical, cleaning, entertainment, security) would require some degree of reinvention.

V. Technology Agenda to *Enable Space Solar Power for Earth*

This HSF option would be based on a staged scenario: government demonstration of the end-to-end power chain from collection of solar energy in GEO to supplying baseband power into the terrestrial grid; then development and demonstration by public-private partnerships of scale-up feasibility; then full-scale development by public-private utility partnerships.[7] As with commercial passenger travel, NASA's role would be catalyst, not capitalist. NASA would enable this new type of utility, but non-NASA public and corporate capital would fund implementation.

Industrializing GEO could leverage some technology domains derived from the other scenarios, for example: human launch (to GEO) reliable enough for career space workers; turnkey or commercially operated space habitation systems (in high orbit); routine EVA/EVR operations (outside the geomagnetic field); and routine orbit transfer of work crews. However, to *Enable Space Solar Power for Earth* a sequence of demonstration, scale-up, and implementation would require development of several unique technology domains:

High-power beaming protocols—Technical solutions implemented via international treaties would be required to implement large-scale, high-flux, trans-atmospheric power transmission and ground reception. SPS might use radio or laser frequencies; the most prevalent concepts assume 2.45 GHz microwaves, which couple efficiently to water molecules and thus pose the possibility of heating organisms (e.g., birds) passing through the beams. SPS rectennas would be compatible with other large-area, engineered land uses (e.g., farming), so effects on plants and livestock living under the rectennas would have to be considered as well. Radio interference is another possible effect. While protocols would be primarily a diplomatic challenge, being enabling for the scenario they would require significant technology demonstration underpinning.

High-capacity, economical, "green," heavy-lift launch to GEO—Assembling and servicing sufficient SPS capacity to make a difference to the terrestrial energy economy would require hauling vast amounts of payload up into high orbit. (The use of lunar material would theoretically reduce the mass to be lifted from Earth, but there is little doubt that launching a lot of mass is far less complex and could be implemented sooner than first developing lunar industry.) For effective scale-up scenarios both high per-launch capacity (heavy lift) and high throughput (high launch rate) would be essential. Economics would drive such launch systems to have the lowest recurring operations cost practicable, and likely therefore to be reusable. If reusable, the capital-cost economics would then drive these systems to be highly reliable as well—perhaps to within an order of magnitude of the reliability level appropriate for human launch even though the marginal value of a single cargo launch would be inconsequential. Finally, given the motivation for SPS in the first place, it would make no sense to use rocket propellants other than LOX-LH2; a sustainable energy future could not hinge on pouring vast amounts of toxic or climate-impacting rocket effluent into the atmosphere. No current launch technology development aims at this combination of requirements.

Hyper-modular SPS systems—Contemporary SPS architecture concepts[8] are "hyper-modular," comprising thousands of identical sun-tracking reflectors, thousands of identical gossamer structural elements, and thousands of identical solid-state conversion-transmission modules, all launched, deployed, assembled, verified, and operated identically. Each module would contain integrated functions for station-keeping, GNC, telecommunications, onboard power, and fault management. Power complexes distributed around the GEO ring, located over population centers, would be managed as large formation fleets of large platforms, in high orbit. They would have to be hyper-reliable for Earth to depend on them for uninterrupted electrical power, and thus likely be based on a sparing hierarchy of onboard hot spares, onboard cold spares, proximate-based spares for rapid changeout, and ground-based spares for replenishment.

Very large-scale implementation of advanced space robotics—SPS complexes comprising thousands of identical modules would be robotically assembled and maintained. While this could mean that onsite crews might be needed only episodically, to repair robots and refurbish power modules, it would require space-qualified robotic architectures and systems to be co-developed along with the SPS systems they operate on. The robots would have to be capable of autonomous positioning, assembly, verification, operation, inspection, troubleshooting, and ORU replacement of each other. Such an extensive, tightly coupled automation architecture is unprecedented, let alone in high orbit.

With the exception of SLS/Orion, if interpreted as establishing the basic capability to get humans outside the protection of the geomagnetic field, the technology agenda to Enable Space Solar Power has essentially no overlap with the default agenda to *Explore Mars*.

VI. Conclusion

Examining the end state in which technology investments would be put into practice provides a powerful lens for judging practical merit. This is the case even for such a thoroughly discussed technology agenda as the one to *Explore Mars*. For example, ecological life support technology is often justified as a pursuit based on its ability to minimize mass on long-duration missions compared to physicochemical approaches. Yet surely an additional launch's worth of equipment and spares is the better deal, given all the other challenges needed to land people on Mars someday—especially after considering just how many such missions are likely ever to occur. Laboratories working on biological life support approaches are actually working toward the *Settle the Moon* future, perhaps without differentiating it from *Explore Mars*, or thus appreciating scale-up rather than long-duration as the dominant driver for its end-state application. Similar judgments can be considered for all HSF technologies proffered for investment.

The *Explore Mars* technology agenda is not equally preparative for all possible HSF futures. The four HSF goal options available to us in the 21st century require very different core capabilities, and the technology agenda we pursue is highly diagnostic of our choice of goal. In a resource-constrained environment, a technology agenda that enables one option is, in practical terms, disabling for the other three. Thus the choices we make today about which technologies to invest in have a critical consequence: they fashion the channel in which we will sail for decades. Conscious consideration of our choice of goal is advisable.

Separate from the question of the value proposition intrinsic to each of the four alternative HSF goals, their respective technology portfolios also have distinct characteristics. Each has an aggregate profile: the *Explore Mars* and *Settle the Moon* agendas are the most complex; *Explore Mars* contains the largest number of potential showstoppers; *Settle the Moon* requires the greatest diversity and depth and is the most directly relatable to terrestrial society; Enable Space Power for Earth is the narrowest and least challenging overall, but leads directly to the largest scale of implementation; *Accelerate Space Passenger Travel* is the most natural extension of today's HSF programs, but contains perhaps the single hardest challenge (five-nines reliable launch and entry).

A technology agenda often seems like a dependent variable in discussions of HSF purpose, yet the technology sector differentiates what is possible from what is not. It is where program commitments really start, it consumes most of the financial resources and causes most of the schedule challenges, and in the end it provides the program's tangible legacy. The magnitude, complexity, and benefit of their respective technology agendas can be used to compare the feasibility, sustainability, productivity, and likelihood of eventual success of the four HSF future options.

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