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# Futures of Deep Space Exploration, Commercialization, and Colonization: The Frontiers of the Responsibly Imaginable

*Dennis M. Bushnell*
*Langley Research Center, Hampton, Virginia*

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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**Futures of Deep Space Exploration, Commercialization, and Colonization:**
**The Frontiers of the Responsibly Imaginable**

Dennis M. Bushnell

**Abstract**

The reusable rocket, printing, automation engendered reductions in space access costs are rapidly opening up deep space, beyond GEO, to commercialization. Report addresses the related issues, technologies, approaches, opportunities for the key requirement, closed business cases, in the context of the longer than usual decade or less business outlook. Report also addresses the requirements and approaches, options for humans in deep space on the way to colonization. Martian colonization has moved from extremely difficult to increasingly feasible with regard to radiation, cost, and safety, in just a few years, due to space access cost reductions.

## Introduction

For many decades now, the home planet has developed an almost exclusively Geosynchronous Equatorial Orbit (GEO) and below commercial space industry, currently evaluated at some $320 B/yr. It's composed to a great degree of positional Earth utilities, various manifestations of telecommunication, navigation, and imaging. The other 100B of some $420 B total current space economy [ ref. 1] includes mainly government activities such as space exploration, including humans in Low-Earth Orbit (LEO), space science, and national security space. There is a veritable LEO application revolution occurring, with thousands of small satellites being lofted to supply high speed internet world-wide along with possibly the capability to stare and capture images of anywhere on the planet constantly. We are also in the midst of ongoing technology revolutions including IT as a whole, enabling miniaturization and cost reductions, and other technology improvements producing major space access and space faring cost reductions.

The present report considers the opportunities, issues, and outlook for space activities beyond GEO, referred to herein as deep space. Deep space includes commercial activities, human exploration and, in due course, colonization [refs. 2 – 12]. The major enabler for serious deep space development is ongoing reductions in LEO access costs from a combination of reusable rockets, improved manufacturing (including printing), and optimization of launch operations. Current cost reductions are a factor of six [ ref. 13], with factors up to 14 being worked and probably more in the offing compared to NASA space launch system [SLS] projected costs. The space access cost floor is the cost of fuel, which is less than 1% of conventional, historical space access levels. Artificial Intelligence (AI) and autonomous robotics for manufacturing and operations will produce further launch cost reductions. Given more affordable space access, it is time to consider potential deep space developments, including the issues, potential goals, technologies, solution spaces, and possible ways forward. For commercial deep space, the zeroth order issue is a closed business case what, aside from privatization of government activities, beyond GEO, are the best business opportunities and ways to make a profit in deep space. Given viable business cases and activities, there is a plethora of business services and support activities that would be necessary

For humans in deep space outside of Earth's protective magnetic fields, the major issue is human health [ref. 8], especially radiation with myriad adverse impacts including carcinogenesis, cardio-vascular and central nervous system issues, and other physiological impacts. Of especial concern is Galactic Cosmic Radiation (GCR), which is particle radiation composed of fully ionized heavy elements at energy levels well into the Giga Electron Volt (GEV) range. Then there are the many physiological effects of partial and micro g. Via ISS activities, we have evolved approaches to mitigate some of the micro g effects. However, the impacts of various levels of partial g on the Moon, Mars, etc., over extended time periods are, at this point, essentially unknown.

The development of deep space, commercially, robotic and human exploration and eventual colonization will occur over many decades, well beyond the usual business horizons of five years or less. During these decades, the many ongoing and combinatorial technology revolutions (e.g., IT, Bio, Nano, Quantum, Energetics, etc.) will continue, changing technical capabilities and enabling improved options and ways forward. What will also continue are the many concomitant serious to possibly existential societal issues, including climate change, the crashing ecosystem, machines taking the jobs, etc., and the massive societal shifts to tele-everything (e.g., work, shopping, travel, education, medicine, commerce, politics, manufacturing-local printing). Then there is ultra-low-cost renewable energy, which is producing a tremendous shift to electrification of everything including transportation. Deep space developments going forward require advanced technology and associated putative impacts including human level AI including ideation, autonomous robotics, molecular manufacturing, and the rapid human evolution of the humans (e.g., increasing cyborgism and brain augmentations). Basic drivers for eventual human colonization of Mars, which has the resources to support such deep space developments listed above, include concerns regarding impacts on Earth of solar storms, asteroid impacts, and other potentially existential issues (e.g., climate, calderas, biohacking, etc.) to, as some opine, ensure the survivability of the human species via becoming a multi-planet society.

**What is Out There?**

- Vast to unimaginable space(s)
- Vacuum
- Low temperatures
- Solar energy
- Solar and GCR radiation
- Micro g

- Minerals, volatiles, oxides, etc., on planets, moons, asteroids, meteorites, dust
- Magnetic fields
- Photons
- Gravity fields
- "Position," the source of the economic and societal value of the current commercial space industry at GEO and below
- Interstellar space, the rest of the galaxy and universe

The number of asteroids, many of which are in the asteroid belt past Mars, is estimated at 150 million. Their diameter ranges from 33 feet to 530 miles. Their total mass is less than that of the Earth's moon. There are approximately 15,000 near-Earth asteroids, with 900 of them over a Km in size. Asteroids are classified as C type, chondrites, S type, silicates and M type, metals and can contain water and many other elements. In terms of space object composition, aside from Earth we know the most about the Moon and Mars. Resources available on Mars include nickel, titanium, iron, sulfur, magnesium, calcium, phosphorus, chlorine, bromine, aluminum, silicon, oxygen, hydrogen, carbon, nitrogen, sodium, manganese, potassium, chromium, deuterium, aluminum, lithium, cobalt, copper, zinc, niobium, and tungsten [refs. 14, 15].

**Why Go Beyond GEO?**

1. Exploration and science determine what is out there, try to infer how it became the way it is, and how it is developing. Of especial interest is the discovery of "life" elsewhere than on Earth. Such life could possibly be silicon or sulfur as well as carbon based. Space science includes determination of explications for the far too many and serious unsolved problems in physics including cosmological physics, dark matter, dark energy, the 120 orders of magnitude difference with regard to quantum predictions and the cosmological constant, what happened to the anti-matter, the physics that explains the measured greater than 10,000 times the speed of light for quantum entanglement, etc.

2. Space solar power, 24/7/365 energy, but currently more expensive than the terrestrial renewables which, with storage, are undergoing major further cost reductions and consequent utilization increases [ref. 16].

3. Mining asteroids, moons, and planets for utilization on Earth if deemed cost effective, otherwise in deep space, for In-Situ Resource Utilization (ISRU), space manufacturing and colonization, especially.

4. Micro g and other in-space/on-body manufacturing, initially GEO and below, but migrating out to exploration sites for ISRU/colonization/increased space operability and in part for unique products for use on Earth [ref. 17].

5. Colonization on Mars at least initially due to onsite resources and conditions. Other inner solar system potential sites include the poles of Mercury and the upper atmosphere of Venus. Beyond Mars there are several moons of interest for possible colonization [refs. 18-22].

6. Tourism, via both virtual/digital reality and physical presence. Again, initially below GEO, but there is already some consideration of the Moon/Mars along with commercial space station tourism going forward. Very dependent upon costs and mitigation of the adverse effects of space faring upon human health for physical tourism.

7. Asteroid Defense, which is a planet wide, governmental issue.

8. Growth of unique biologics and biologics in space due to micro g and radiation effects, whether changes can be beneficial and directed is TBD.

9. Enabling utilities, supplies for the above activities, functions, including transportation, manufacturing, communications, fuels, food, equipage, servicing, etc.

Of these, 2, 3, 4, 5, 6, 8 and 9 and combinations thereof are potential commercial deep space activities.

**The Issues**

- Costs of launch, research and development (R&D), manufacture, operations. These costs are dropping across the board due to miniaturization, reusability, printing, AI, and robotization. Overall, the launch metric is changing from dollars/pound to value/pound.
- Space debris is becoming ever more serious and will have to be addressed beyond just identifying/tracking/avoiding what is up there. Some suggest we are just one or two collisions from closing out LEO, which could close out much of our space access.
- Health issues for humans-The international space station [ISS] experience indicates that humans are, within the Van Allen belts in LEO at somewhat less than half of deep space GCR radiation, capable of withstanding six months in space. Astronaut Scott Kelly found twice that time in space much more worrisome. As stated, there exists the need to mitigate the impacts of radiation and micro g upon human health. For colonization, especially on Mars, over time we would morph into an altered species, changing to adapt to the different radiation and partial g conditions.
- Safety/reliability - Currently, rockets are unsuccessful every some 100 launches on average. This is orders of magnitude less safe than commercial aircraft [ref. 23]. Other safety concerns include the deadly in-space conditions (e.g., temperature, pressure, etc.) and the human health concerns. Spacecraft and space systems require the design precept, up to the system of systems level, of fail safe.
- Closed business case(s) are necessary of (non-government related) commercial deep space and require market creation/development over long time frames.
- Terrestrial competition, which is extant and evolving for such as space solar power, mining, manufacturing (including using terrestrial space simulators), and tourism (via

digital reality/immersive presence), is a serious consideration for nearly all potential deep space business areas.

- Technology shortfalls including autonomous robotics. Technology is the enabler for deep space development and can be applied to both deep space operations and terrestrially. What would favor deep space development would be technologies and their combinatorials which, financially in a total business sense, favored space. The costs of human operations in space are orders of magnitude greater than robotic operations. The technologies to enable serious autonomous robotics operation for mining, ISRU, etc. are under development and crucial to commercial deep space progress going forward.
- Legalities-Currently, legal issues are impeding the private development of space and cleaning up space debris. There is sizable literature addressing these issues.
- Power and Energy - Except for the outer planets where solar energy is too weak to be really useful, current space energy sources are largely chemical and solar. As described herein, there are under development far more capable approaches including a 100X times RTGs nuclear battery, miniature fission reactors, and stored positrons.
- Commercial deep space long lead/maturation times for business development - along with and part of a closed business case, is the necessarily long and costly technology and market development times which are factors greater than those prevalent in current terrestrial, or even GEO and below, commercial space business practices.
- Pollution from rocket launches is an increasing issue, due to the combination of an increasing number of launches and the increasing need to curb pollution of all sorts for sustainability and climate.
- Detailed data with regard to what, where, and how much is out there. We know somewhat the general makeup of the Moon and Mars, having sent orbiters and probes there, and we are sampling some asteroids. However, the current consternation with regard to the details, and thus the commercial value concerning moon water near the poles, illustrates how dependent the development of a business case is on having far more detailed resource data than we have thus far. Even though we know much more now than we did before, our knowledge is far from sufficient.
- Dust on the Moon, Mars, etc.-Mars dust can contain sulfur, chlorine, perchlorates, and cadmium. It is abrasive, electrostatic, magnetic, oxidative, and chemically reactive. There are concerns it could cause cognitive impairment, neuroinflammation, autoimmune diseases, depletion of gut microbiota and depletion of tryptophan production. Also, of concern are potential behaviors, impacts in the habitation conditions of increased temperature, density, and moisture. Moon dust is sharp and jagged, abrasive.

As a summary, the fundamental major issues with commercial deep space include high investment costs, it takes too long to realize a profit, the necessity to create markets, and prevalence of overall weak to less business cases.

**Putative Solution Spaces**

- Cheap space access-The breakthrough with regard to serious space access cost reductions are due to Space X and their pioneering development of reusable rockets, along with reduced manufacturing and operational costs [refs. 24, 25]. Factors of 6 to 14 reductions are being discussed, with perhaps even greater values in the offing from continued AI developments and subsequent further replacement of expensive human labor by autonomous robotics, along with increased launch rates providing economies of scale. Also, the efforts involving material printing at the nano scale to produce a much better material microstructure would enable much reduced dry weight and payload weight, providing additional cost reductions.

- Radiation protection-After cheap space access, and where humans in space are involved, GCR protection is the next level of importance with regards to deep space operational enablement. In terms of protection using mass, three plus meters of thickness is required, and the mass offering protection must be composed of significant hydrogen to minimize secondaries. Cheap space access can enable such protection, requiring only a reusable overcoat left in space between trips. Also enabled by cheap space access is cheap fuel in space. This enables fast transits (e.g., to Mars) which greatly reduce the exposure duration. There is also a breakthrough nuclear battery which could power Vasimir: the high thrust electric propulsion with 6,000 seconds of Isp for fast transits. There is a possibility that mm long curved silicon crystals could deflect the particle radiation.
- Over the past decades miniaturization has enabled major very favorable impacts upon the size, weight, and cost of space payloads. While miniaturization is continuing apace, the humans in space are not miniaturizing and require sustenance and conditions that scale with their size. This is a major reason (along with safety) for the orders of magnitude cost difference between robotic and human missions.
- E-M tethers - They can be powered by solar or nuclear battery to collect space debris for remanufacturing in space. While space debris is serious now and going to become far more so going forward, the current approach is detect and avoid, which will soon be insufficient. A major issue with cleaning up the debris is the cost of fuel to do so. Refs. 26 and 27 document the approach of using E-M tethers, powered by solar or the new nuclear battery to do the cleaning, essentially fuel less and affordable. In addition, rather than deorbiting the collected materials to burn up they could be put into a space junkyard for remanufacturing, repurposing, with ISS added to that collection as it is surplused.
- ISRU [in situ resource utilization] is THE enabler for colonization. Much of current Mars human expedition planning involves Martian ISRU return fuel. The resources on Mars are prodigious, with much water, $CO_2$, minerals, etc. Can with these make fuel, life support materials, and plastics for equipment. Then there are the asteroids and moons as well as possibly other planets to extract fuels and equipage from. Utilizing autonomous robotics such ISRU would not involve expensive onsite humans and would be far more affordable. From a National Research Council (NRC) review of the NASA Space Tech Roadmaps "Use of Martian derived Propellants could reduce launch masses by over 60%...A Game Changer for Exploration" [refs. 28-32].
- NTAC - NASA has recently invented a nuclear battery termed NTAC, Nuclear Thermionic Avalanche Cells [ ref. 8] with up to 22 kW/kg of isotope which is orders of magnitude greater energy density than RTGs with a weight that is 25 to 150 times lighter than fission reactors. This battery scales from powering PDAs to tens of megawatts and could

essentially power deep space including propulsion, space and on-body habitats, ISRU, and on-body transportation.

- AI/Autonomous robotics is the key to effective, efficient, and low-cost deep space operations for all purposes [ref. 33]. Nearly all of space faring thus far has been automatic versus involving local humans. However, the nano and AI technologies are enabling large capability improvements in robotics, up to the trusted autonomy level. Trusted autonomy, a key feature of which is the capability to handle unknown unknowns or surprises in real time, will be enabled by the IT capability to ideate via machine speed systems evaluation of quasirandom combinatorials. Such capabilities could enable, via ISRU, the production, pre human arrival, of most of what humans will need on Mars. This greatly reduces some 900 metrics tons in LEO estimated for human missions to mars, required for an Apollo class, bring everything with your human campaign. This would also increase safety and reliability via proving out functionality at on-body conditions before human arrival.
- Separating propulsive mass and energy is a very different propulsive paradigm related to solar and nuclear thermal propulsion, where a separate energy source is used to heat and energize propulsive mass. In the general case, energy beaming powered by solar or the new nuclear battery could be utilized to provide energy. The propulsive mass could be something other than a “fuel” that supplies additional energy. One could eliminate the need to produce and store fuels. Requisite conductivity can be attained via alkalines, which are present on Mars, and collected atmospheric gases or even regolith could be used as propulsive mass.
- Reusability, design for robotic repair and servicing. Presumably, if the Hubble space telescope had been designed to be serviced by robotics, then considerable resources could have been saved by obviation of the need for human space servicing missions. The technologies to perform robotic repair, servicing, and construction in space are developing rapidly. These are a key capability to reduce overall mission costs, and in many cases, increase capabilities.
- Space hardened humans-NASA is working on biological counter measures to reduce radiation health impacts, with some successes and possibilities for space hardening humans. This will be accomplished initially via diet/exercise/meds and, going forward, through genomics, crisper, and synbio. The particle nature of GCR radiation makes bioremediation more difficult, but the ensuing large injury field around the penetration can be mitigated.
- Artificial gravity, produced via spinning, is a useful approximation to terrestrial gravity effects on human health. Artificial gravity changes the hab design and was a capability at one time planned for ISS. Given that we have not yet determined how to mitigate all the micro g effects for human flights lasting longer than six months, this capability would be efficacious.
- Fast Transits-The benefits of advanced energetics enabled fast transits to Mars are well known and include reduced costs overall, reduced integrated radiation exposure, reduced micro g exposure, increased reliability due to reduced duty time, reduced durability concerns/issues, less boil off, reduced consumables, less psychological problems, and improved public engagement due to enhanced currency.

**Human Health In Deep Space [Ref. 8]**

- Due to current lack of definitive information, the following is an incomplete list of human health issues and concerns for a human mission to and from Mars. The basic differences in health related parameters between the ISS in LEO and the missions to and from Mars include a far longer time frame for the current some three year roundtrip duration versus six months on ISS, spacecraft exposed to full GCR versus 45% on ISS, and attendant increased time-related reliability, safety, psychological issues, and other health concerns.
- The detailed nature of the potential clinical health impacts at Mars-Mission conditions and their potential synergistic effects are largely unknown. Where the impacts are known, the effects appear to scale in severity with the exposed time in space to and from Mars. The potential effects of the .38 g on Mars are also unknown, but partial gravity is expected to relax the issues experienced on ISS during microgravity. The many and various adverse health mitigation approaches thus far are mainly directed at trying to establish conditions closer to those on Earth, conditions which resulted in current human physiology.
- The health and medical challenges expected in a human Mars mission are unlike any prior manned spacecraft experience. There is no analog on Earth that can fully represent conditions on Mars. The identified human health issues associated with Humans-Mars on site exploration include:

1. Mars dust which contains small, sharp, and highly oxidative particles that affects respiratory and cardio-pulmonary systems. Their health impacts at the high oxygen, high pressure conditions inside the hab are of concern.

2. Pathogens or biologics in space that appear to become more virulent at in-space conditions, in combination with immune system degradation, resulting in illnesses that medications could prove ineffective for. Other immune systems impacts are expected from weakened T-cell function and immune system due to a combination of radiation, micro gravity, and psychological, and diet/sleep issues.

3. Micro gravity allows fluid shifts that causes eye/vision changes that blurs vision upon abrupt motions, motion sickness, affects balance and appetite, causes dizziness, and stuffiness. It also can result in DNA damage such as double strand breaks, chromosome aberrations/mutations, attenuated repair process, down regulation of the P53 tumor suppressor protein, weakened T-Cells, 1% per month bone mineral loss (especially calcium) and early onset osteoporosis plus kidney stone propensity, muscle atrophy (up to 20% loss in 5-11 days), skin irritation, cardio-vascular deconditioning, cardio arrhythmia, heart degeneration including 30% to 50% decrease in maximal $O_2$ uptake due to blood cell and capillary altered interactions and blood volume loss, orthostatic hypotension and low blood pressure, neurologic, brain, cerebrovascular, and neurovestibular changes, reduced release of neuro-transmitters, effects on spinal fluid, sensory changes and dysfunction, increased homocysteine, liver damage (including long term scarring), and non-alcoholic fatty liver disease and fibrosis. Mitigation for many of these via exercise and other approaches has been pursued on ISS.

4. Space radiation present both in space and on planet/body causes radiation sickness, degenerative tissue effects, DNA damage, DNA repair process alterations, oxidative DNA damage, immune system degradation including significant reduced ability to produce blood cells, anemia, carcinogenesis including leukemia, tissue degeneration, respiratory effects, cataracts, heart, cardiovascular and digestive system impacts, neurologic effects, central nervous system, and cognitive impairment, Alzheimer's precursor (white matter hyperintensities of the brain) reduced length and area of dendrites, performance decrements and memory deficits, loss of awareness, focus, and cognition, collateral tissue damage to adjacent cells (called bystander cell damage from heavy nuclei) which could increase the cancer risk by some factor.

5. Psychiatric effects due to a combination of physiological effects already noted plus distance from Earth, diet changes, sleep deprivation, and proximity to other crew members.

6. Toxic chemical exposure from spacecraft components as well as from Martian dust.

7. Reliability/life support system failures, spacecraft/propulsion, and other mechanical failures including sensors.

8. The usual space conditions of cold, vacuum, and the presence of exhaled $CO_2$ which tends to stay near the face and be rebreathed.

There are also the potential synergistic effects of all of these, which at this point are an early stage work in progress. Thus far, only the Apollo crews have been subjected to micro g and full GCR and for only a few days. As stated, where examined, these mostly tend to become more worrisome with time in space, as evidenced by Kelly's comments with respect to changes and effects of his nearly one year versus the usual six months in space sojourn on ISS. Some of the effects, to the extent currently known, appear to be permanent. Then there is the potential interaction of effects.

**Radiation Protection**

There are three approaches to radiation mitigation which can be employed combinatorially: Spend less time in space, shield or deflect the incident radiation, and biological/medical counter measures to mitigate the resultant health impacts. In general, shielding requires low Z materials to minimize secondary radiation. Protection approaches include magnetics, fast transits, biological countermeasures (BCMs), three plus meters of regolith or ice igloos, and silicon crystals to divert the GCR away from humans. The latter may be able to provide protection while in space suits, albeit this may require an exoskeleton to carry the weight/handle the inertia, etc.

Overall, due to systems level and conceptual/technological breakthroughs, the outlook for GCR radiation mitigation has altered over these last years from problematical/unaffordable to a number of potentially viable solution spaces across the TRL spectrum. These breakthroughs include inexpensive space access via reusable rockets, a low Kw/Kg (Alpha) many MW class nuclear battery, high energy particle reflection via silicon crystals, and the syn bio/gene editing revolution as applied to biological/medical countermeasures.

In decreasing order of TRL:
For on moon, planet etc., ~ three meters of regolith

For in space:
1. Fast transits (200-day round trips to Mars) via inexpensive Chemical Fuel
2. Three-meter reusable polyethylene overcoat via inexpensive chemical fuel
3. Biological/medical countermeasures, a partial solution in space thus far, effectiveness improving
4. Fast transits (200-day Mars round trip) via 6,000 sec. Isp VASIMR high thrust MHD propulsion powered by an alpha of order one nuclear battery
5. Magnetic redirection of GCR particles via superconductive (S-C) magnets located extended distances from the spacecraft
6. Silicon crystal reflection of GCR particles plus shielding for Gamma secondaries

All of these approaches require extensive research and optimization with subsequent triage and development to determine the most efficacious for development/utilization. The current unsatisfactory status of GCR mitigation makes such investment necessary due to GCR being the agreed upon most serious human health deep space exploration/colonization issue.

**Safety and Reliability**

As in aviation, by far the most prevalent cause of accidents is human factors. Due to the IT/AI/Robotics tech revolutions, the major improvements in space safety and reliability (S&R) will probably develop as we increasingly utilize machines in lieu of humans for everything including design, manufacture, checkout, transportation, operations, etc. Compared to humans, machines have far less latency, know far more, are far less expensive, exclude operational human error (e.g., leaving rags in fuel lines, etc.), have a far longer duty cycle, are far faster, far more efficient, far more durable and patient, and operate where humans cannot.

The major general categories of safety and reliability issues include human factors including errors, mechanical equipment functionality, cyber, and environmental effects, all of which need to be addressed. The safety and reliability issues are combinatorial, including cascading failures. Little of safety and reliability is simple but much is insidious. A sampling of cogent get-well approaches includes redundancy/backup systems, certification/standards, inspections, margins, recovery designed in, emergency systems, reliability analyses, obviate single points of failure, fault tolerant systems, and graceful degradation. The NASA list of top technical risks include cyber security, shortfalls in ground and flight testing, and too heavy a reliance on analysis/modeling and simulation.

**Deep Space Manufacturing**

In-space manufacturing has been under study along with considerable associated experimental R&D for many years. The original impetus was the exploitation of micro g to produce unique products that could be worth the associated additional costs involved compared to terrestrial manufacture. The current litany of such unique products from micro g and vacuum processing include protein, other crystals, improved semiconductors, micro encapsulation, fibers and fiber optics, pharma, human organs, and improved metal alloys. Additionally, in-space manufacturing development has expanded beyond just production in space of terrestrial application products to include reuse and repurposing of space debris, ISRU, and real-time mission applications, along with the capabilities proffered by printing fabrication and for both in-space and on-bodies. The task expansion has also included fabrication, assembly, integration, maintenance, repair, and upgrades. Essentially, it's a combination of in-space and on-body manufacture and application that includes in-service aspects. Advantages of space manufacturing include mission proximity and convection control, no sedimentation, larger and higher quality crystal formation, increased material purity, defect free, and perfect roundness.

**Deep Space Mining**

Deep space mining can be utilized for either Earth or in space. There are three fundamental approaches for commercial mining in space for use on Earth: bring the mined material to Earth to be processed, process it in space then distribute the products, or bring the asteroid to Earth environment for processing. The economic competition for deep space mining for Earth includes alternative materials utilization, accessing the materials from the seabed or ocean water, and better detection, extraction and processing of extant availability. Initial efforts with regard to deep space mining concerned precious metals, notably platinum. There were thoughts that some asteroids might contain serious amounts of this and with its high current value there was apparently a solid closed business case. Other thoughts related to this included the potential effects on the market price of a large infusion of product, which could to would alter much the profit outlook. Also, some major uses of platinum are subject to alternative material utilization. Another approach to determining the possible business case for deep space mining for Earth is to consider the projected materials shortages here. Within the next several decades, shortages are slated in antimony. By the next 100 years, shortages are projected in molybdenum, rhenium, zinc and gold [ref. 34]. Note the absence of rare earths, which apparently are not rare, but some ores are easier to access/process than others. Also, there is material and function substitution ongoing with regard to rare earths, which is based upon cost issues. There is an excellent study [ref. 35] with regard to the occurrence of rare earths in deep space. They are present in deep space, notably on the Moon and Mars, but are assessed as not being of sufficient concentration to be exploitable. However, higher concentrations might be found near specific craters/locations deposited by an asteroid. That possibility also applies to all deep space materials and is TBD depending upon far better definition of what is in deep space, where, and how much of it exists.

Considering the avowed potential scarcities on Earth, molybdenum, zinc, and gold are contained in nodules on the ocean floor and in the ocean water. That leaves antimony, rhenium, and possibly indium. Indium is on the Moon and Mars has rhenium. Then there is water. There has been great interest in mining whatever water is at the poles of the Moon for rocket fuel. NASA computations indicate that it is much cheaper to bring water up from Earth than to mine it and bring it from the Moon, especially with reusable rocket econometrics. Except for indium and rhenium, deep space mining is apparently primarily for use in deep space within the next century or so.

**Deep Space Tourism**

Orbital space tourism began with the Russians, who in eight trips and after suitable training, took seven tourists to the International Space Station (ISS) from 2001 to 2009 on Soyuz. The nominal cost of such trips is now in the range of $20 M to $25 M, via Blue Origin, Virgin Galactic, Boeing, and Space X. The U.S. is planning for Space X Crew Dragon and Boeing Starliner to transport tourists (sometimes termed spacecraft participants) to the ISS, with an ISS accommodation cost of $35 K/day each. NASA is largely responsible for the reinvigorated emphasis upon private space travel. The NASA commercial crew program with Boeing and Space X has as one of its objectives fostering commercially supplied private human space access. With that program thus far a success, there are now serious plans to exploit that space access capability for space tourism [ref. 36]. Bigelow Aerospace and Orion Span have nascent luxury orbital hotel designs. Space X and Space Adventures plan Moon loop flights for $70 M to $100 M. A survey indicates that there is significant public interest in spending up to two weeks on the ISS with a spacewalk and some are desirous of a space hotel. Space Adventures plans to fly two tourists to the ISS in 2023 on Soyuz. Axion/Space X plan to fly three tourists to the ISS in 2021 for 10 days. Space Adventures and Space X plan a four to five-day space trip, no ISS visit, in the 2021-time frame. Axiom Space is planning a private module addition to ISS as a hotel.

There appears to be accelerating serious near-term interest in orbital space tourism. The current costs are, for most, daunting, but the activity, interest, and now emerging capabilities to do these trips plus the large Space X LEO access cost reductions bode well for the future of space tourism, providing that there are no accidents and loss of life. The projected mean number of missions for loss of crew on space shuttle was a factor of order two more than what was actually observed. However, shuttle was designed in the 1970's and built for half the projected cost due to budget cuts. We know more now and have more experience. Therefore, space tourism will probably experience at least the historical average on the order of 100 flights between failures. The extent to which rocket safety can be improved and its public acceptance is TBD. Serious space tourism is starting in Earth orbit over the next few years. Two weeks or less in space, from the available information, should not produce many of the adverse health effects that characterize longer stays. ISS is within the planetary magnetic fields that offer some protection from radiation (even though it's above the protective atmosphere). In fact, the radiation exposure is half of that which would be received in deep space (e.g., during trips to the Moon, Mars, and other destinations). Typical ISS duty periods for highly trained ISS astronauts are six months. In deep space with exposure to full radiation, serious radiation protection and artificial gravity will be needed for such as Martian trips and beyond.

With respect to the present status of virtual/digital space tourism, NASA has a number of immersive virtual tours of destinations such as the ISS and the planets. Companies offer virtual tours of the Moon, Mars, the planets, and the solar system. Google offers a tour of the

ISS, space tours are on YouTube, and the virtual reality companies are planning to offer live virtual tours of Earth from space. Digital reality will increasingly provide space tourism experience at some million times less expense and some thousand times safer.
After 60 years of highly trained astronauts going into space, space related technologies have advanced, and their costs have reduced to the point where increasing numbers of private citizens can become space tourists. Initially, space travel will be suborbital for minimal times and Earth orbital for up to two weeks, with nearer term plans by Space X to do lunar flybys. There has also developed a rapidly improving digital reality/immersive virtual presence technology providing space tourism experiences at minimal cost and available essentially to everyone. The safety aspects of physical space tourism, including the human health concerns, need further development. However, those that relate to the space environment are tolerable for a few weeks based off of the 60 years of manned space flight experience. As space tourism expands beyond Earth orbit to the Moon, Mars, asteroids, and other planets, the safety issues will need to be seriously worked, and that is doable. The apparent breakthrough in the resurgence of space tourism was the NASA commercial crew program, which was partially targeted on space tourism and has led to the transportation necessary to enable the nearer term, very few years out now, plans for a goodly expansion of physical space tourism. This is only a portion of what will become major opportunities and expansion of commercial space beyond providing positional Earth utilities/up to GEO into deep space, initially the Moon, Mars, asteroids, and near-Earth objects. There are projections that travelers that colonize Mars will, over time, due to the reduced g and radiation exposure, evolve into Martians.

**ISRU/Space Colonization**

Space Colonization is first order dependent upon onbody resources, efficient ISRU, and energy, even if colonization sites are in space [refs. 37-40]. The costs of serious resupply from Earth for sizable space colonies are probably prohibitive otherwise. The initial body of interest for colonization is Mars, due to its exceedingly rich resources. The Moon is perhaps next in line due to its proximity to Earth and the presence of some resources, although the amount of the most important Moon resource (water) is currently unknown.

ISRU can provide habs, return fuel, on planet fuel, EDL fuel, life support (e.g., water, $O_2$, atmospheric $N_2$, food, thermalization, pressurization, dust protection), radiation protection, equipage via printing from regolith minerals, volatile extraction, synthetic biology/bio fabrication, and printed plastics derived from $H_20$ and $CO_2$. Some notable advantages of ISRU include $O_2$ production for ascent and consumables, reduced initial MLEO [ mass in low earth orbit] and reduced number of launches, reduced lander size and volume, greater surface exploration capability, life support redundancy, lower risk via fewer launches, and lower life cycle cost.

The currently known resources on Mars are massive, including extensive quantities of water and $CO_2$ and therefore C, $H_2$, and $O_2$ for life support, fuels, plastics, and much else. Mars has very little water in the atmosphere, but estimates indicate much of the water that was ever on Mars is still there. Massive amounts of water ice in the north pole region, many Km thick, is enough to put an ocean on a flat Mars some 350 meters deep. There are major quantities of water ice and water adsorbed on minerals in the regolith, from 3% at the equator (up to 8+%

localized) to 40% plus at 60 degrees north, can microwave/heat to produce water vapor, capture and store as ice in container. A solar tent could produce sufficient heat to vaporize the regolith water ice. Water is also available from sulfates (22% $H_2O$), silicates, etc. A large crater near the equator purportedly has an ice lake the size of Lake Huron with similar or greater depth, and there have been discoveries of large ice lakes near the pole. The regolith is replete with all manner of minerals.

In Situ Resource Utilization (ISRU) applicable frontier technologies include robotics, machine intelligence, nanotechnology, synthetic biology, 3-D printing/additive manufacturing, and autonomy. These technologies, combined with the vast natural resources, should enable serious, pre- and post-human arrival ISRU to greatly increase reliability and safety and reduce cost for human colonization of Mars. Various system-level transportation concepts employing Mars-produced fuel would enable Mars resources to evolve into a primary center of trade for the solar system for eventually nearly everything required for space faring and colonization. Mars resources and their exploitation via extensive ISRU are the key to a viable, long-term, safe, and affordable human presence beyond Earth.

The major currently envisaged destinations for human missions and colonization include the Moon, Mars, poles of Mercury, upper atmosphere of Venus, Europa, Callisto, Enceladus, Titan, and Triton. The evaluative metrics for these destinations include temperature, radiation, water, atmospheric pressure, minerals, organics, volatiles, solar energy, atmospheric composition, and lava tubes, among many others. All of these destinations have water except Venus, where hydrogen could be extracted from the sulfuric acid rain and combined with oxygen from the $CO_2$ atmosphere. Venus uniquely has Earth-like gravity, temperature, pressure, and low radiation when living 50 km above the surface and floating in the atmosphere.

After Mars and Venus, the next most salubrious destination for humans is Titan with its low temperature and gravity, but with low radiation, high pressure, and organic lakes. Callisto also has low radiation, but shares cold temperatures, low gravity, and near vacuum pressure with the other destinations. All have minerals and at least some organics. Those destinations beyond Mars have low solar energy. Titan has copious hydrocarbons. The asteroids purportedly have precious metals and water. The required radiation protection on bodies is readily available via living, working under some 4 to 5 meters of regolith with such living quarters produced via ditch and bury or utilization of lava tubes as caverns.

Traveling beyond Mars would require use of nuclear power via batteries or fission reactors, with the goal of using fusion propulsion. Ongoing reductions in costs for space access will enable development of serious commercial deep space beyond GEO, eventually at the trillion dollar/year level. The technologies and infrastructures developed for commercial deep space will be efficacious for human solar system missions and colonization.

Suggested ISRU-related Research Areas:

- For energy: micro-fission reactors, radiation-hardened, manufacturable on Mars flat panel PV, NTAC nuclear battery, positrons, direct conversion, and storage approaches
- Habitat: lightweight inflatable habitat with molded-in air locks and furniture
- ISRU resource extraction and storage approaches
- Exploration of underground Mars for ice/water, lava tubes/caves, especially ice caves, geothermal energy, concentrated mineral ores

- Food production on Mars
- Autonomous robotics
- Fabrication/health effects at/of 0.38 g
- Evaluation of EDL approaches including using cheap space access/cheap fuel powered EDL and entry from low Mars orbit
- Solution spaces for corrosiveness of Mars dust at habitat interior conditions

As an ISRU example, Martian $CO_2$ could be utilized for shielding, fuel cells, $O_2$ production, carbon for CNT's, pressurized rockets, $CH_4$ fuel production, polyethylene production and in-atmosphere solar pumped $CO_2$ lasers.

**On-Body Transportation**

A major issue that dominates travel on the Moon, Mars, and beyond short ranges is the varied and sometimes extreme topography such as impact craters. While the northern portion of the northern Martian hemisphere has smoother portions, most of the planet has, often extreme, variations in surface morphology, including craters, chasms, and mountains. Flying is the most expeditious transport mode for mid to long distances.

The dominant Martian issue with regard to aeronautical flying is the very low atmospheric density, requiring huge lifting surface acreage for heavier loads (e.g., humans). What has been instead suggested for these conditions has been rockets. These could provide the needed Vertical Take Off and Landing (VTOL) capability dictated by the complex terrain, and could be chemical or nuclear, utilizing ISRU fuels or, with nuclear options, propulsive mass including regolith enriched by alkalines for conductivity. Thus far the nuclear energy power sources considered have been conventional, heat producing radiologics or reactors. The former has a nominal hopper range, using atmospheric $CO_2$ for propulsive mass, the order of a kilometer. The Zubrin nuclear reactor rocket option would provide planet wide access. Then there are chemical rockets including $CO/O_2$, magnesium/$CO_2$, methane/$CO_2$, etc., (i.e. ISRU propellants).

Recent invention of a nuclear thermionic battery with orders of magnitude greater energy density and much reduced overall weight (alpha of order one, 22 kW/kg of isotope, NTAC) which lasts for years, opens up an entirely different long range, large cargo trade space. There are three obvious possibilities for utilization of this new nuclear capability, lower speed, nuclear ramjets, and nuclear rockets. The energetics of the new nuclear rocket are such that propulsive lift could provide a long haul, as well as short haul, lower speed (subsonic) flying machine, and a Mars truck to and from low Mars orbit. $CO_2$ from the atmosphere could be pressurized by electric motors turning axial flow compressors and directed using ejector nozzles to provide lift and thrust. For higher speeds up to high supersonics, NTAC could provide heating and additional compression for an atmospheric ramjet or heating for a conventional rocket, with or without addition of chemical energy using on planet ISRU derived propellant or propulsive mass such as regolith.

**Separating Propulsive Mass and Energy**

One way to circumvent the rocket equation is to separate propulsive mass and energy using either onboard or beamed energy. This approach is utilized in solar thermal and nuclear thermal propulsion. If the energy source is sufficiently light weight for the onboard case and sufficiently energetic in either case, then propulsive mass can be anything that can be made conductive (usually with alkalines) including atmospheric constituents or regolith. This would obviate the need to manufacture and store fuels, which combine propulsive mass and energy. An example instantiation of the separation of propulsive mass and energy for planets with atmospheres is a systems-level approach which would obviate most of the huge percentage of the Human-Mars up-mass which is fuel. A rocket is sent to LEO and arrives with an empty tank. The rocket is de-orbited slightly and an inlet is opened to ingest far outer region atmospheric air. Once the tank is filled with this propulsive mass (estimates indicate three orbits should suffice), then the rocket moves to the vicinity of an orbiting beamer and MW/laser energy is beamed to the rectennas/PV on the rocket. This off-board energy powers an MHD accelerator which provides, using the alkaline-doped pressurized atmospheric air as propulsive mass, high thrust at ISP levels of up to 2000 seconds. A rapid acceleration is utilized due to beam diffraction issues, with some future possibility for major reductions in beam diffraction via soliton wave and meta-materials research. Several technologies, including much more efficient/ultra-lightweight rectennas, make this concept interesting. Such an approach could be utilized for orbit raising (LEO to MEO, HEO, GEO – low to medium, high and geosynchronous Earth orbit) as well as Moon, Mars, and other expeditions. If a beamer is pre-positioned around or possibly on Mars, then a similar approach could be used on the return trip, possibly using regolith as propulsive mass. The approach utilizes reusable in-space infrastructure, is very different from current approaches, and could possibly obviate much of the huge percentage of the upmass which is fuel. The new NASA nuclear battery NTAC scales from powering phones to tens of megawatts and could, at orders of magnitude less weight than nuclear reactors, power such an approach either via beamers or on board, as well as essentially all other space power requirements including in space and on-body habs, ISRU, and on-body transportation. An example of on rocket NTAC utilization is powering VASIMIR, a high thrust MHD propulsion approach that provides 6,000 seconds of Isp and 200-day round trips to Mars.

**Beyond the Solar System**

Currently, interstellar space beyond the solar system, with its apparent multitude of planets, many of which are Earthlike, is limited to virtual travel because the distances are simply too far for even the best of the current energetics, anti-matter, to enable speeds close enough to that of light for reasonable physical travel over the requisite distances. Therefore, we are up against physics limitations; however, those limitations have uncertainties. There are a large number of huge unsolved problems in physics, especially at cosmological and interstellar scales [ ref. 41]. These include the inability to experimentally and directly verify the concepts of dark matter and dark energy, which together are supposed to constitute some 95% of all matter-energy in the universe. Then there are 120 orders of magnitude discrepancy between the experimental measurements of the cosmological constant and the predictions of quantum theory, which otherwise is usually accurate to many significant figures. Also, we cannot find the massive amounts of antimatter that is supposed to be out there, and we lack cogent explications for the observed greater than 10,000 times the speed of light effective speed of quantum entanglement, which is the basis of much of the next big little thing beyond nano – quantum technology. In fact, natural quantum entanglement which is the utilization of materials that are entangled with whatever/wherever could conceptually, via the effects of natural or human actions on the other parts of the entangled system, alter the operational and safety aspects of space systems. There are many other issues with physics as we now know it, especially at cosmological scales. If we ever understand and can explain these many issues, there may be a possibility that such an altered physical understanding could enable useful human interstellar travel and colonization of not just the solar system but the universe.

**Concluding Remarks:**

What is needed in the nearer term/over the next few decades for development of commercial deep space and space colonization:
- Solutions to space debris, such as the E-M tether approach described herein
- Solutions to/mitigation of the many space-related human health issues, the foremost of which is radiation protection
- Inexpensive space access, in progress
- Reliability and safety improvements
- In-space/on-body resources mapped in detail
- Advanced power and energy options researched, developed, demonstrated, including fission and positrons
- Closed commercial deep space business plans, possible due to inexpensive space access
- Legalities solved with regard to both space debris and on-body resources, becoming ever more critical as deep space mining becomes real and the debris problem worsens
- Trusted AI developed, applied to reduce costs of deep space development via autonomous robotics
- Reusability writ large, a major enabler
- Moon/Mars dust control, a potential serious health and operability issue
- Optimization of ISRU writ large, including via AI/Robotics

Martian colonization has moved from extremely difficult to increasingly feasible with regard to radiation, cost, and safety, in just a few years. There are now several ways forward to an affordable and safe humans-Mars mission as a result of reusable rockets, serious ISRU, energetics/fast transits, achievable radiation protection, AI/robotics/printing, and ever greater knowledge of Martian resources, along with a solution for space debris.

Overall, technology is enabling going forward:
- Colonization of Moon, Mars, etc.
- Multi-trillion-dollar commercial deep space commercialization/industrial development

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The reusable rocket, printing, automation engendered reductions in space access costs are rapidly opening up deep space, beyond GEO, to commercialization. Report addresses the related issues, technologies, approaches, opportunities for the key requirement, closed business cases, in the context of the longer than usual decade or less business outlook. Report also addresses the requirements and approaches, options for humans in deep space on the way to colonization. Martian colonization has moved from extremely difficult to increasingly feasible with regard to radiation, cost, and safety, in just a few years, due to space access cost reductions.

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