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Approaches To Humans-Mars Both Safe and Affordable

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Abstract

The fundamental differences regarding the Moon vs. Mars for humans include far longer missions and greater resources required for Mars. In humans-Mars planning, thus far the extant technologies and approaches have not enabled missions which are both fully safe/healthy for humans and affordable. Cost reductions are required to afford health and safety and to reduce their costs. This report suggests and examines a wide spectrum of approaches to improve the affordability of humans-Mars approaches to ensure human safety and health during long distance space exploration and pioneering-on-the-way to colonization with humans-Mars as the exemplar.

Introduction

After over 60 years of launching humans into Earth orbit, along with a few early-on short expeditions to the Moon, humans are seriously considering becoming a two-planet society by colonizing another solar system planet that has a wide array of resources – Mars [refs. 1-3]. Some of the reasons for this evolving desire include the usual “because it is there”, and the several possible “natural” and human engendered happenstances that might-to-could end human society on Earth, including sizable asteroid impacts and solar storm effects on a society now wholly dependent upon electrons. There are also concerns regarding biohacking, resulting in a particularly deadly pathogen, super volcanoes, and a veritable litany of other possible disasters [ref. 4]. Compared to the ongoing humans-in-space activities, humans-Mars involves much greater distances and much greater costs, along with serious-to-deadly health and safety issues. Thus far, using near term technologies and approaches, the costs of humans-Mars are usually considered too large to fully enable excellent safety and health for humans. There are, however, many technologies and approaches (some nascent but developable) within the nominal NASA humans-Mars development time scale of ten years of R&D with beyond that system execution [ref. 5].

The first order of business is to address the major cost centers, which are nominally space access, in space round trip, habitats, on-surface operations and development, facilities, operations, and support. For cost reduction considerations, these cost centers can be addressed as individual issues and combinatorially at the systems, configuration, and architecture level. Some technologies and approaches can reduce the trip/on planet per se costs, some can reduce the costs of approaches to ensure greater crew health and safety, and some can do both. The combination of these approaches for humans-Mars activities would result in humans-Mars being far more affordable, safer, and healthier.

In many cases, past experiences and demonstration tests in relevant environments help guide those assessments and decisions. For humans-Moon, we can reasonably base our evaluations and assessments regarding health and safety on past experiences during the Apollo Program (although with some limitations), as well as during the thousands of days astronauts have lived in low Earth orbit, especially on the International Space Station. However, humans-Mars is far more difficult than the Apollo Program due to the greatly increased distance and mission time. Also, astronaut costs are 100X or more than the cost of robots in space due to the requisite safety and life support measures that must be implemented. Unlike most technologies and equipage, humans are not shrinking/miniaturizing and the equipage to keep humans healthy is mostly not reducing, especially “life support”.

Major Cost and Safety/Health Issues and Targets

The major fundamental metrics for viable humans-Mars, and indeed any human space exploration or operations, are cost and safety, health, and reliability. As currently identified, the major human crew health issues are related to reduced gravity and radiation, whose health impacts are much amplified by increasing time in space and can affect nearly every physiological and neurological aspect of human health. Additional mission health/safety concerns include EDL (entry, descent, and landing), psychological issues, and reliability. Nominal estimates for projected missions using chemical propulsion indicate up to a three-year round trip to Mars and the order of some 900 metric tons in LEO.

Human space flight health hazards are categorized by NASA's Human Research Program that identifies and catalogues risks tied to those hazards [refs. 6-9]. There are five major hazard categories presently, as illustrated in Figure 1: 1) Altered Gravity; 2) Radiation; 3) Distance from Earth; 4) Isolation; and 5) Hostile/Closed Environment-Spacecraft Design. The HRP continues to define standards aimed at mitigating risks to crew [refs. 10, 11].

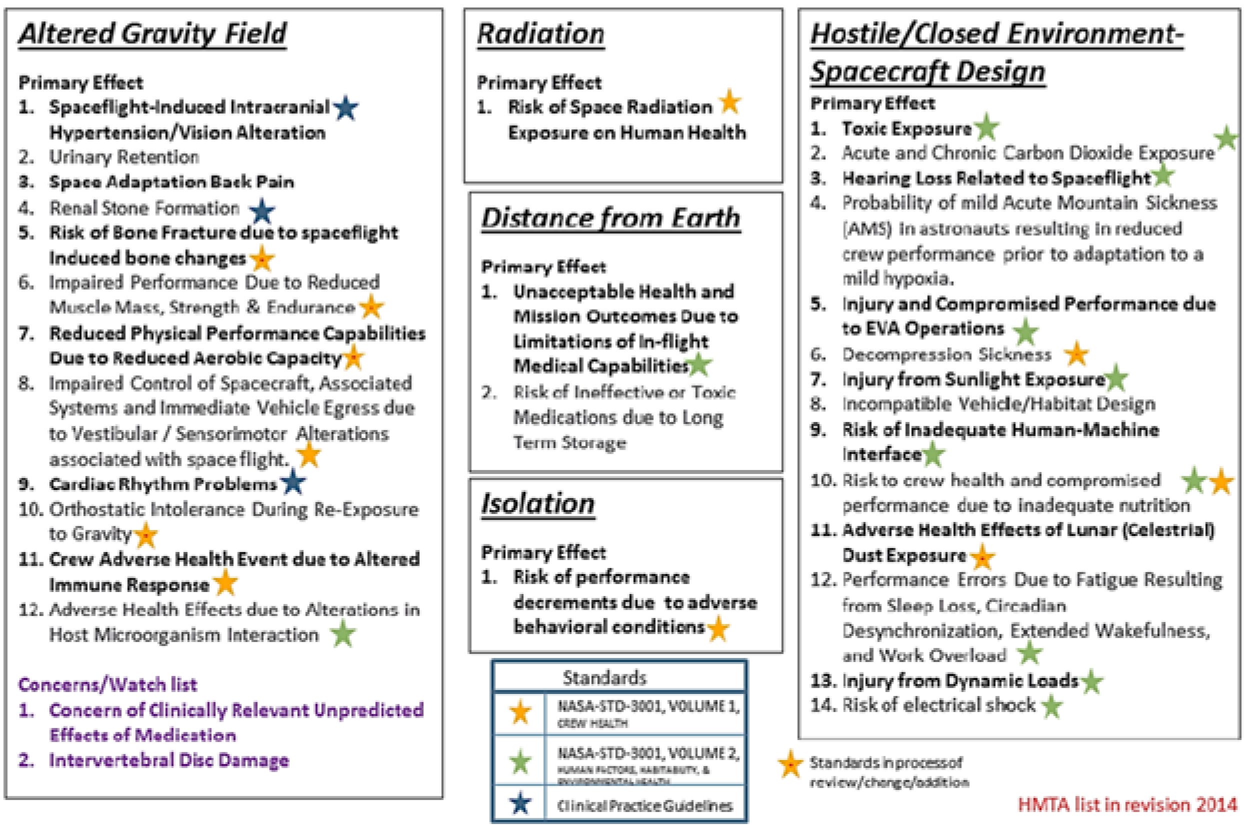

Figure 1: 30 Human Risks, 2 Concern/Watch List Items, Which the HRP Aims to Mitigate [ref. 6]

"Maintaining Human Health for Humans-Mars" provides an examination of the health issues and illustrates the enormous challenges facing roundtrip missions to Mars [ref. 12]. That analysis suggests that if the three years could be reduced to the order of a 200-day round trip via enabling energetics and propulsion, that the effects of the mission on human health would be greatly mitigated, as would most of the other major humans-Mars issues including cost, EDL, safety, psychological issues, and reliability [ref. 12]. The results of that analysis were based on a proxy dose limit for radiation at 150 mSv, well below the new limit of 600 mSv. Based on that analysis, increasing the dose limit by a factor of four may relax the speed of the fast transit scenarios studies, but it may not eliminate the need for galactic cosmic ray (GCR) shielding during the surface stays.

A recent cost estimate for "flags and footprints" style mission to Mars identifies the cost drivers for that mission type [ref. 13]. There are many similar studies for similar design reference missions that land a crew on Mars and returns that crew to Earth [ref. 14]. Those missions do not include sufficient considerations for crew safety and health hazards mitigation. Those missions are Apollo-like, aim to minimize mission duration by limiting surface stays and return the crew back to Earth as quickly as possible, subject to constraints on orbital mechanics stemming from possible conjunction and opposition class interplanetary trajectories. Tapping the vast resources of Mars and using fast transits may offer a far better risk and safety posture [ref. 12].

Affording Safety

The cost of a humans-Mars mission is estimated in the 100s of billions [ref. 13].

The costs are spread among the capabilities (see Figure 2), stemming from a design reference architecture that has not materially changed much in nearly 30 years.

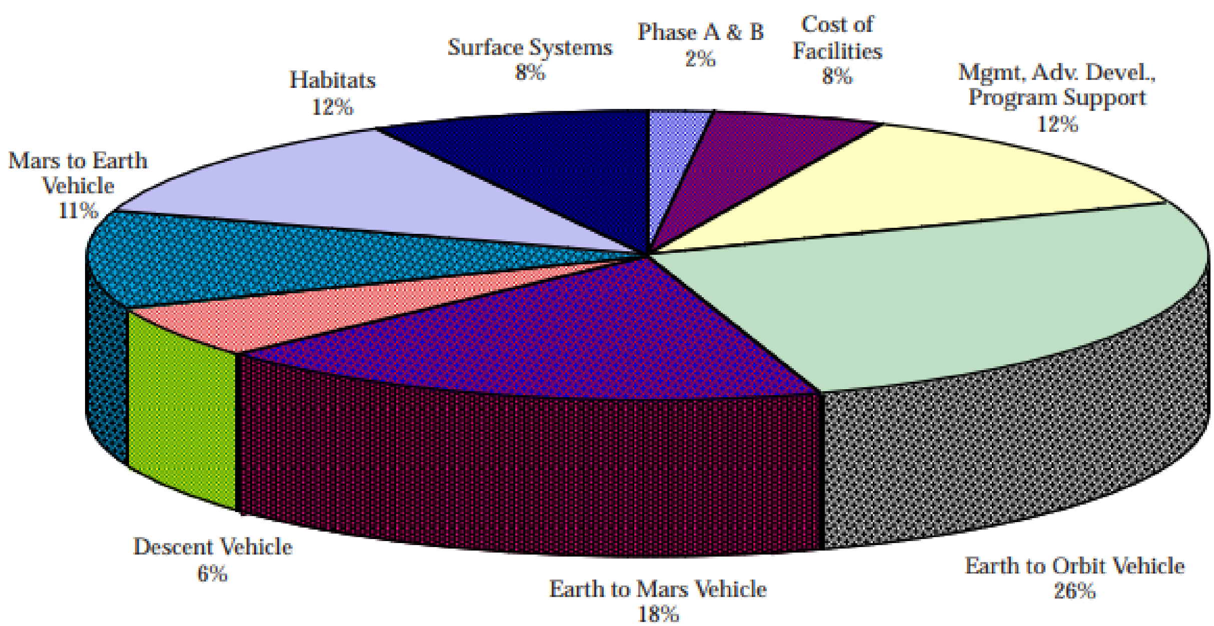

Figure 2: Distribution of Reference Mission Costs [ref. 14]

The top 5 cost drivers (see Figure 2) are: Earth to Orbit Vehicle (26%); Earth to Mars Vehicle (18%); Mars to Earth Vehicle (11%); Habitats (12%); and Management of Advanced Development Program Support (12%), which is nearly 80% of the total. The Surface Systems (8%) and Descent Vehicle (6%) make up another 14%.

Ref. 7 suggests that safety for humans-Mars requires GCR shielding and artificial gravity wherever possible. If those cannot be accommodated, then we need mission durations lasting less than one year, which does not seem to be doable even with the advanced nuclear in-space propulsion currently in development by NASA. Simplistically, GCR shielding and artificial gravity could be included by drastically reducing the costs of the systems already on the list or removing one or two of them.

Major Putative Cost Reduction and Safety/ Human Health Improvement Technologies and Approaches for Humans-Mars

There are a variety of opportunities to reduce cost so that additional capabilities aimed at improving safety and human health can be explored more seriously. Some of the additional capabilities in the following list are more advanced and higher technology readiness levels (TRL) than others.

<u>Systems and Architecture Level Cost Reduction Approaches</u> – These approaches posit major cost reductions but often require major changes in technology and mission planning.

A. Make it there, instead of taking it there – Mars has a vast array of resources including nickel, titanium, iron, sulfur, magnesium, calcium, phosphorus, chlorine, bromine, aluminum, silicon, oxygen, hydrogen, carbon, nitrogen, sodium, manganese, potassium, chromium, and deuterium. Overall mission costs scale to the requisite mass launched into LEO. Nominally for initial small-crew missions such as Apollo, they take everything needed, which is some 900 metric tons. Much of this could, via sending autonomous robots years before the humans go on inexpensive slowboats propelled by various varieties of sails, be produced via ISRU. This includes fuels and propulsive mass and would be checked out at on-planet conditions before the humans get there. The expensive tonnage is then much reduced.
B. Being Energy Rich – Much of the requisite tonnage is associated with power and energy. Switching to the new NASA high energy density nuclear battery would greatly reduce the weight associated with power and energy and enable energy rich operation of essentially everything along with much greater mission flexibility and safety. This enables atmospheric breathing powered EDL to greatly improve safety and reduce cost of such. It also enables microwaving the regolith to release water for life support, fuels, and plastics along with powering refrigeration to solve the cryo fuel storage boiloff problem, as examples.
C. Fast Transits – Very inexpensive chemical fuels could, via brute force chemical, greatly reduce the in-space transit times. Variable Specific Impulse Magnetoplasma Rocket (VASIMR), a high thrust Magneto Hydrodynamic [MHD] propulsion approach with a specific impulse (I_{sp}) greater than an order of magnitude better than chemical and powered by nuclear thermionic avalanche cells [NTAC], could enable 200-day Earth-Mars-Earth round trips, which would be very fast transits. Such fast transits essentially “solve” in-space micro gravity and radiation health issues, reduce logistics quantities, increase reliability, and reduce costs.
D. “Ditch and Bury” – Inflatable, rigidizable habitats buried under some four plus meters of regolith for radiation and micrometeoroid protection and thermal insulation. Obviates freighting expensive, heavy surface habitats with inadequate radiation protection.

Cheap space access - The breakthroughs associated with serious space access cost reductions are due to Space X and their pioneering development of reusable rockets, along with reduced manufacturing and operational costs. [ref.5] Factors of 6 to 14 cost reductions are being discussed, with projections for the Space X Starship of 100 metric tons for $2 million, some
$10/lb. to orbit, far below the usual thousands of dollars. Even greater values may be in the offing from continued artificial intelligence [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 may enable reduced dry weight and payload weight, providing additional cost reductions.

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 [ref. 5]. In general, shielding requires low atomic number materials to minimize very concerning secondary radiation. Protection approaches include magnetics, fast transits, biological countermeasures (BCMs), four 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 mitigation has altered over these last years from problematic/unaffordable to several potentially viable solution spaces across the TRL spectrum. These breakthroughs include inexpensive space access via reusable rockets discussed above, a low kg/KW (Alpha) scalable to many Mega Watts [MW] class nuclear battery, high energy particle reflection via silicon crystals, and the synthetic biology/gene editing revolution as applied to biological/medical countermeasures.

In decreasing order of TRL:

For on Moon, planet etc., ~ four plus meters of regolith.

For in-space:

1. Fast transits (200-day round trips to Mars) via inexpensive Chemical Fuel

2. Three-meter reusable polyethylene spacecraft overcoat via inexpensive chemical fuel

3. Biological/medical countermeasures [a partial solution in space thus far, but effectiveness is improving]

4. Fast transits (200-day Mars round trip) via 6,000 sec. I_{sp} 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 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 [ref. 16] - As in aviation, by far the most prevalent cause of accidents in space is human factors. Due to the IT/AI/Robotics tech revolutions, 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 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 and 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.

AI/Autonomous Robotics – This is the key to effective, efficient, and low-cost deep space operations for all purposes [ref. 17]. 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 quasi-random combinatorials. Such capabilities could enable, via ISRU, the production, prehuman arrival, of most of what humans will need on Mars. This greatly reduces the some 900 metrics tons in LEO estimated for the initial human missions to Mars required for an Apollo-class, bring-everything-with-you human campaign. This would also increase safety and reliability via proving out functionality at on-body conditions before human arrival.

Artificial Gravity - Produced via spinning, artificial gravity is a useful approximation to terrestrial gravity effects on human health. Artificial gravity changes the habitat design and at one time was a capability 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, especially for humans-Mars.

Fast Transits [ref. 12] - 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. The much-reduced cost of space access proffers fast transits via brute force, via low-cost chemical fuels. An alternative is the alpha of order one new nuclear batteries to enable the VASIMR, 6,000 secs of I_{sp} high thrust MHD propulsion system. Estimates for the latter are 200-day round trips to Mars instead of nearly three years.

Detailed On-Body Resources Data [ref. 15] - Data is needed regarding what, where, and how much of what regarding planetary resources are 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 regarding the details, and thus the commercial value concerning Moon water near the poles, illustrates how dependent the development of a business case and evaluating the benefits/utilization of ISRU are 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 for efficient mission optimization.

Materials/Printing Manufacture – Printing is becoming the most efficacious in-space manufacturing approach. Also, recent printing at the nano scale has produced 5x better materials via superb microstructures with greatly reduced dislocations and grain boundary issues resulting in up to 10x potential. Nanotube composites are being worked with an upside of 11x impact regarding materials. These materials could possibly greatly reduce payload weight and rocket dry weight, further reducing space access costs. Going forward on-planet/body printing should reduce the cost and weight of materials processing.

Synthetic Biology [Synbio] – Synthetic biology could provide food, materials, electronics, biocement, biopolymers, bioadhesives, life support, biofuels, biomining, pharma and biophotovoltaics.

Inflatables and Membranes – Inflatables, including rigidization, imbedded sensors, actuators, and AI for localized shape changing for applications include antennas, sails, heat exchangers, solar photovoltaics, filtration, mirrors, light buckets, solar concentrators, structures/habitats, telescopes, cushions, radiators, and sunshades. Inflatables and membranes could reduce weight and increase functionalities and capabilities.

Optical and Quantum Communication – Increasing utilization of free space optical communication for greatly increased bandwidth. Quantum vector/scaler potential communication is patented but nascent, and purportedly is applicable to planetary distances at high band width.

Powered EDL – For Mars, the current state of the art for EDL is inflatable heat shields to increase drag area. With reusable rockets/ “cheap space”, or VASIMR, with 6,000 seconds of specific impulse (I_{sp}), missions could perhaps afford direct propulsive deceleration such as is used on planets and bodies without atmospheres. The other propulsive EDL for Mars is ingested CO_2 heated by nuclear batteries and ejected.

Dust Control - Moon and Mars dust is a major health and operational problem for on-body activities. Mitigating and controlling dust is a first order issue which needs to be researched with mitigation approaches designed into the mission. The dust is abrasive, electrostatic, magnetic, oxidative, chemically reactive, and contains silicates and gypsum. On Mars, it contains perchlorates, which affects the thyroid, and arsenic, cadmium, and beryllium. There is concern that the dust could become much more corrosive, a greater problem once inside habitats at their higher pressure, temperature, and oxygen content.

Surface Mobility - It has been noted that the topogrpahy of Mars is mostly sufficiently rugged such that flying vice driving is probably required for other than very local environs. Such off-surface mobility capability has long been studied, including helicopters, aircraft, balloons, and rockets. Given the sizable amount of magnesium in the Mars regolith, magnesium-CO_2 rockets may be efficacious. The alternative is CO_2 breathing nuclear battery powered propulsion.

Advanced Nuclear Batteries – Advanced nuclear batteries have three major benefits/improvements over earlier versions and reactors: on the order of 25 to a factor of 1000 times less weight for the same power, far more power density than previous nuclear batteries, and scalability from milliwatts to tens of megawatts. Their lightweight enables viable high thrust and high I_{sp} electromagnetic propulsion. They could also be used to power energy beaming as well as thermal or electric propulsion. Additional in-space uses include powering in-space and on-planet habitats, ISRU writ large, on-body transportation and utilization of propulsive mass such as regolith and water vice fuels and employing conductivity enhancement approaches or via heating [refs 12, 18]. For on Mars transportation with its variegated typography, flying would be useful in general for beyond walking distances. The advanced nuclear batteries could provide energy for CO_2 breathing for both longer ranges (via heated ingested CO_2), and shorter ranges via a surface effect airborne approach, where the nuclear batteries power lift fans. They could also enable CO_2 breathing for low-cost powered entry, descent, and landing, a possibly major safety and other metrics advancement.

Refueling Depots [ref. 5] - The fuel to supply such depots could be sourced from Earth, the Moon, Mars, asteroids, etc., anywhere that provides the fuel at lowest cost. These depots could be in Earth orbit/Earth environs, anywhere suitable/convenient/required in space or on “bodies.” The fuel could be chemical of various flavors including methane, H_2/O_2, nuclear reactor, or nuclear battery “fuel.” Where propulsive mass and energy have been and can be separated, such as utilization of nuclear, solar, or beamed energy using the various flavors of nuclear energy including positrons, propulsive mass for propulsion utilizing external energy addition could be supplied. The total refueling depot system architecture includes fuel sourcing, production, transportation, storage, and disbursement.

Energy Beamers - Devices beaming power/ energy could be nuclear or solar powered, including by positrons, the cheap anti-matter. These could be located on bodies, in orbit or in space, and provide an alternative energy/powering source, perhaps involving less cost than producing and handling fuel. This would still require propulsive mass for utilization of beamed energy for propulsion. There are the many other uses of beamed energy including asteroid defense, mass drivers, on body/spacecraft power and energy, space manufacturing, and other industrial/commercial activities.

Engineering For Reusability - Perhaps the most obvious difference aside from major cost savings between the design of one-time use products and reusable ones is the increased service life duration [refs.19, 20] This gives rise to greater durability and damage tolerance considerations. Also, the increased service life necessitates that the product design enables detailed inspection, and to the extent possible, ease of repair with an overall eye to minimizing refurbishment requirements. Experience indicates that reusability should be designed in initially and throughout up to the systems of systems level. Design information required for safety and reliability includes the operational parameters and conditions for all envisaged missions. The extended operational service requires augmentation of the appropriate testing regime. An additional aspect of reusability is utilizing materials in mission equipage that can be recycled into other or similar uses. Then there is repurposing of piece parts.

ISRU Writ Large – ISRU is a result of the panoply of on-body resources, and the AI, robotics, energetics, sensors, and printing technologies ultimately enabling Earth independence, especially for Mars [ref. 21]. There are massive resources on Mars obtainable from the atmosphere and extractable from the regolith. These can support human colonization and viable industry/commercialization on and beyond Mars. Using these resources, existing ISRU technologies could supply water, oxygen, nitrogen, fuels, and building materials on Mars to increasingly reduce the dependence on Earth during the buildup of colonization. As technologies in the areas of additive manufacturing, energetics, and AI/robotics are developed, habitat, and mobility systems, fuel, life support, and building materials become available in quantities capable of building and supporting colonies on Mars and crew return to Earth, missions to go elsewhere in the solar system and fostering space tourism in the inner solar system. Starting with the pre-deployment of robotic ISRU and habitat systems to prepare Mars for the arrival of the first crew, each successful mission within the pioneering campaign yields greater confidence in this ISRU approach, enables functionality checkouts at on planet conditions and sustainable colonization that is both safe and affordable. Then, and only then, will colonization of Mars realize its Earth independence. Of especial and early interest for early humans-Mars ISRU is, using energy from nuclear batteries, microwaving regolith to release/collect water and cooling a surface to collect CO_2. Having C, H_2, and O_2 enables manufacturing of a wide variety of plastics for equipage, fuels, and life support.

<u>Protection from Non-thermal Electromagnetic [E-M] Health Effects</u> - Humans in spacecraft or on other bodies are no longer exposed to non-thermal radiation Earth background levels. Instead, along with (mitigated) GCR, and other ionizing radiation they are subjected to non-thermal radiation from internal electronics, etc. Some 4,000 studies over more than five decades indicate, especially if pulsed, that such low-level, microwatts/cm2, nonthermal E-M can have appreciable neurological effects due to alteration of voltage-gated calcium channels and opening the blood-brain barrier among other physiological impacts. Therefore, it is probably useful to determine the habitats/spacecraft interior non-thermal E-M environment and employ faraday cages if necessary to minimize that portion which could be problematic.

<u>Underground Operations</u> – Utilizing “ditch and bury” or inhabiting extant lava tubes, living and working underground is the least expensive and most rapid way to attain human health/safety and effective humans/Mars. Lightweight inflatable habitats and labs with some built in furnishings buried beneath some four meters plus of regolith would provide excellent protection from GCR radiation and micrometeoroids, along with providing thermal insulation. Thereby saving the major costs, and for current designs, inadequate radiation protection, of surface buildings. Thick ice igloos are also a form of underground living, are protective.

<u>Laboratory Produced Foods</u> [ref. 22] – Due to technology advancements and the need to reduce climate change impacts, there is an ongoing near revolution in lab-grown foods, also termed cellular agriculture. The efforts were initially focused on meats and other proteins but are expanding across most foods. Using molecular biologics, tissue engineering, Syn-Bio, bacteria, etc. foods could be manufactured on Mars with a smallish footprint and less resources and effort. Cyanobacteria and insects are suggested as food resources. Then there is dark food, and other bioproducts not produced by photosynthesis but instead by chemotropic single-celled organisms. Projections indicate orders of magnitude reductions in the energy, water, and costs required to produce food by photosynthesis.

Combinatorial Precepts/Technologies for Less Costly and Safer, Healthier Humans on Moon/Mars

The fundamental issue for humans in space is the rapidly developing capability of autonomous robotics/AI and their reducing cost including miniaturization versus the orders of magnitude costs and human health issues associated with in-space/onsite humans. Humans are not miniaturizing and the equipage to keep them healthy is weighty. However, the desire for humans to become a multiplanet society and hedge the bets of the species regarding asteroid impacts, and other existential threats drive the human's space goals of, nearer term, humans-moon and humans-mars travel. The fundamental metrics and issue with humans to Mars have been cost and safety with what is safe is not affordable and what is affordable is not safe/healthy. Given the technologies for the capabilities summarized herein, that situation is changing rapidly. This section summarizes some major cost reduction and enhanced safety/human health combinational technology possibilities.

The cost centers for humans to/on Moon/Mars are the following:

- Overall Mass in LEO
- LEO Launch
- Infrastructures to Keep Humans Healthy
- Exploration "Equipment"
- Power and Energy
- In-Space Propulsion
- Architecture(s)/System(s) approaches

Overall Mass in LEO – The major ongoing cost reductions in LEO access alters greatly this cost center and changes the entire mission architecture possibilities. Alternative technology related approaches to reduce total mass in LEO include sending autonomous robotics to mars years before humans go to utilize Martian resources and ISRU precepts/printing etc. to manufacture much of the required human equipage and verify such at on-planet conditions before the humans leave Earth, making it there instead of hauling it there and having to put it in LEO. Advanced lightweight materials would reduce the mass of both rocket and payload, increasing payload fraction and reducing payload weight. The nuclear batteries would replace heavy solar energy and nuclear reactor equipment. Living and operating underground would eliminate the weight of above ground living/laboratory spaces. The latter would be replaced by lightweight inflatables. Utilization of on-planet synbio for many operations/functions/supplies would further reduce what must be put in LEO. VASIMR powered by nuclear batteries with an I_{sp} of some 6,000 secs would greatly reduce the fuel weight lofted. The major new nuclear battery weight advantage/enabler is the Alpha [Kgs/Kw] of the order of one vs. vaues of 35 to 100 for a nuclear reactor.

LEO Launch – The cost of fuel to launch to LEO is only a few percent of the extant launch costs. The other costs can be or are being greatly mitigated by reusability, printing, automation, AI, replacing expensive human labor for manufacture and launch operations with machines, economies of scale, and less expensive materials. The now vastly reduced launch costs are a MAJOR enabler for making humans-Mars travel both safe and affordable.

Equipage to Keep Humans Safe and Healthy – The major in-space human health issue is GCR, including fully ionized iron nuclei at GEV energy levels of particle radiation. The only data we have on GCR health effects on humans is the short exposure times in the Apollo program and the some 50% of deep space exposure within the Van Allen belts on the ISS for up to a year or so. Humans-Mars exposure to nearer full GCR during transit and 50% or so on Mars is far longer. Other, non-particle radiation data from Hiroshima and Nagasaki are used, at lower than GCR energy levels, as allowable exposure metrics. This is optimistic; the GCR effects are apparently more serious. The human health impacts of GCR are far more than carcinogenesis. They include Spaceflight-Associated Neuro-Ocular Syndrome (SANS), Cyclic Vomiting Syndrome (CVS), and others [ref. 12]. The lowest cost approaches to GCR exposure protection include fast transits, curved silicon crystals, and underground living/operating. The next most serious human health space related issue is low to microgravity, again with a spectrum of adverse impacts. Exercise is helpful for alleviation of some impacts. Artificial gravity during transit to Mars, which would impact the design of the spacecraft, would be required.

Exploration "Equipment" – This includes everything on planet used by humans and for humans such as habitats, rovers, ISRU, manufacturing equipment, etc. Underground living/operating equipment would be cheaper than above ground equipment via such as using inflatables, with the regolith providing the mass/cost for radiation protection, structure, etc. The resources on Mars and ISRU printing/manufacturing as the source of much of the equipage would reduce their total cost, including transportation expenses. The use of autonomous robotics for most on planet activities would reduce health and safety concerns compared to human labor.

Power and Energy – Weight, cost, and convenience-wise the least expensive on-planet and in-space power and energy source, which is essentially scalable and sufficiently lightweight for all purposes, is the advanced, light weight, and scalable nuclear batteries. Living underground would reduce the human environmental system energy requirements.

In-space Propulsion – At this juncture, there are two types of in-space propulsion for the high thrust needed for human transport: nuclear and chemical. Cheap space access reduces much of the cost of chemical propulsion to the point where fast transits might be affordable. For nuclear propulsion, there is a large weight reduction for nuclear batteries vs. reactors. Also, their capability to use a propulsion cycle, VASIMR, with 6,000 secs of I_{sp} vs the order of 800 plus using nuclear reactor powering both enables fast transits, with a long list of benefits, and much reduced fuel weight.

Mission Architectures – Current Mars mission architectures utilize chemical fuels and require many launches to loft the requisite amount of such. Also, the equipage is transported from Earth, partially along with the crewed mission. There is a current dearth for Mars of GCR protection. The mission times, mostly in space transit at micro g and nearly full space GCR, are nearly three years. Power and energy are mostly chemical and solar. The projected overall cost is not small. The technologies and mission architecture changes under development and possible discussed herein would enable a much lower cost mission and colonization, while improving the overall impacts on human health and safety.

Concluding Remarks

A huge percentage of cost is baked into projects in the initial planning stages. As projects mature, costs always increase as the work is accomplished at increasing detail and involves systems of systems level issues. Therefore, it is necessary to begin projects with large positive cost margins. For humans to Mars travel, the cost margins are negative, even at the outset and before adequate human health and safety are accommodated. Approaches such as those given herein regarding ways to seriously reduce costs and improve health/safety are required to ensure a successful mission, one that is both safe and affordable for humans-Mars. Approaches with the greatest cost reduction/health improvement leverage, that enable missions both safe and affordable, include the massive Starship LEO access cost reductions, the many enablements provided by the new advanced nuclear batteries, ditch and bury using inflatable/rigidizable habitats, fast transits (using either nuclear batteries/VASIMR or cheap chemical fuel), autonomous robotics/ISRU writ large including prehuman arrival, in-space artificial gravity, and synthetic biology/cellular agriculture for food. Regarding crew health and safety, what has not yet been adequately addressed is in-habitat dust protection. At this point, the effects of the reactive Mars dust on health in the presence of elevated oxygen, pressure, and temperature inside the habitat is unknown. Also unknown are the health impacts of the Martian .38G, and the combinational health effects of radiation, partial g, and diet, other changes such as isolation, which could perhaps be serious.

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