Maintaining Human Health for Humans-Mars

Robert W. Moses[1] Dennis M. Bushnell[2] David R. Komar[3] Sang H. Choi[4] and Robert C. Singleterry[5]
NASA Langley Research Center, Hampton, Virginia 23681, USA

Ronald J. Litchford[6]
NASA Headquarters, Washington DC 20546, USA

and
Franklin Chang-Diaz[7] and Mark D. Carter[8]
Ad Astra Rocket Company, 141 Bay Area Blvd, Houston, TX, 77598, USA

The Human Health Research Program states that Radiation is the most challenging hazard to human spaceflight beyond LEO. The International Space Station provides an analog for evaluating techniques for dealing with Altered Gravity, the Radiation Environment of the ISS is only about 45% of the deep space values where radiation due to Galactic Cosmic Rays (GCR) dominate the spectrum. The Moon and cis-lunar space are being considered as a Mars Analog training ground for preparing crews for human mission to Mars. Spending more than 200 days in deep space is considered unsafe based on our current proxy for lifetime radiation dose. The paper outlines a way forward for spending days training near the Moon and for completing roundtrip missions to Mars while remaining below the current proxy. In the first case, a GCR overcoat shields crews from radiation during cis-lunar activities before making fast transits without in-space GCR overcoats to and from Mars. This case requires continued maturation of low TRL propulsion and power technologies currently around 4 to 5 while depending on repeatable reductions in launch costs by a factor of 6 expected of current reusable rockets. The second case requires no new technology development except for the expectation that the next near-term generation of reusable rockets will reduce launch costs by a factor of around 14. Five trajectories and GCR overcoat sizes for all mission legs are presented herein to illustrate the opportunities to maintain human health for Humans-Mars missions.

I. Nomenclature

CRISPR = Clustered Regularly Interspaced Short Palindromic Repeats, a family of DNA sequences
GCR = Galactic Cosmic Rays
HRP = Human Research Program
LEO = Low Earth Orbit
MLEO = Mass in Low Earth Orbit
mSv = amount of radiation dose in millisievers
t = mass in metric ton or tonnes, equal to 1000 kilograms
g/cm^2 = grams per square centimeter; divide by density (g/cm^3) to obtain “thickness” in centimeters

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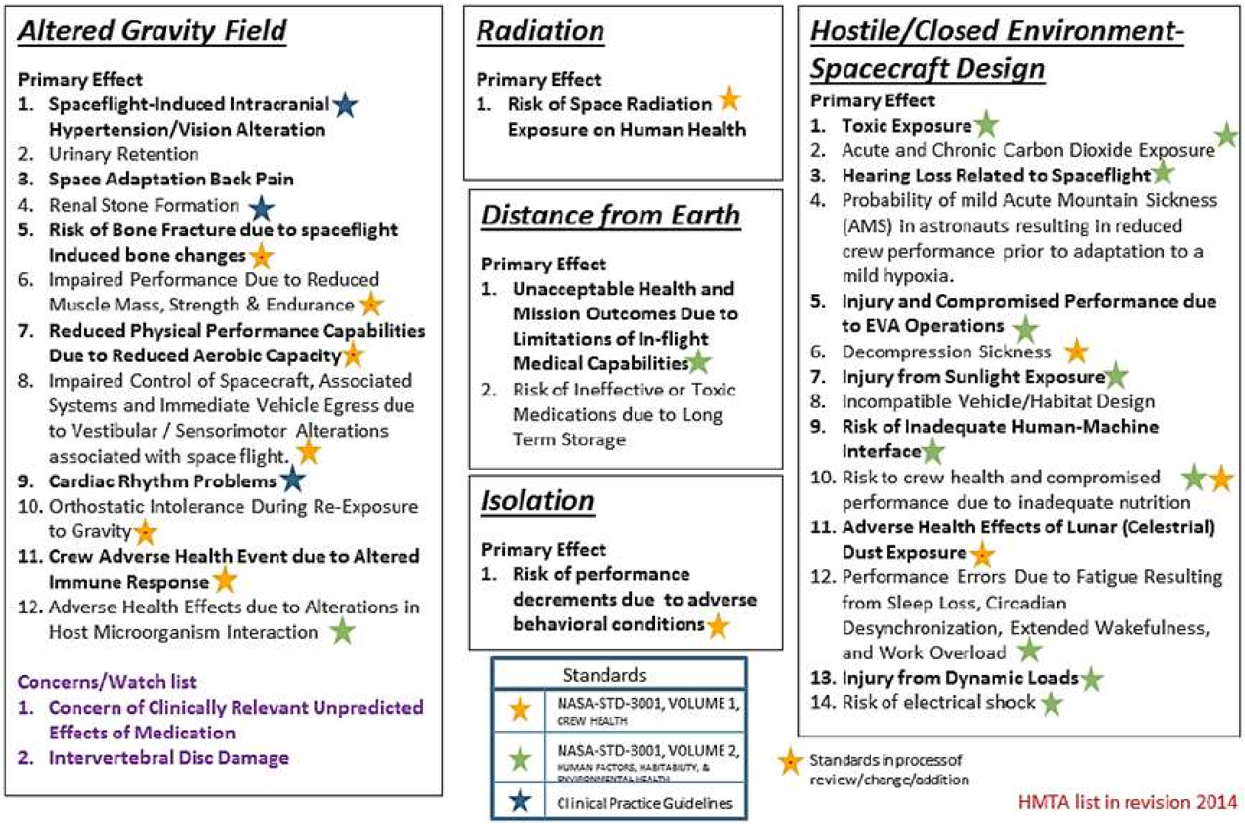
[1] Aerospace Technologist, Engineering Directorate, and AIAA Associate Fellow.
[2] Chief Scientist and AIAA Honorary Fellow.
[3] Aerospace Engineer, Vehicle Analysis Branch, and AIAA Senior Member.
[4] Senior Scientist, Research Directorate, and AIAA Associate Fellow.
[5] Research Engineer, Research Directorate.
[6] Principal Technologist for Propulsion, Space Technology Mission Directorate, and AIAA Associate Fellow.
[7] Chief Executive Officer.
[8] Senior Vice President for Technology Development and AIAA Member.

II. Introduction

National space exploration planning/visioning specifically cites human expeditions to, and human on-site exploration of, Mars (Humans-Mars). In the nearer term, human space exploration beyond LEO (low Earth orbit) is focused upon the Moon, which provides convenient proving grounds for some of the capabilities required for Humans-Mars. The major fundamental metrics for Humans-Mars and indeed any human space exploration or operations are cost and safety/ health/ reliability. The major human crew health issues, as currently identified, are related to reduced gravity and radiation, whose health impacts are much amplified by increasing time in space and can evidently affect nearly every physiological and neurological aspect of human health. Additional mission concerns include EDL (entry, descent and landing), psychological issues and reliability. Current 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.

If the three years could be reduced to the order of a 200-day round trip, via enabling energetics and propulsion, 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. An Alternative major health improvement approach, for the current planned 3-year mission, is serious radiation protection from GCR (Galactic Cosmic Rays), which requires significant cost reductions due to the attendant increase in MLEO (Mass in LEO). Going forward, additional significant health support and improvements will devolve from the ongoing Bio Tech Revolution, including Genomics, Synthetic Biology, CRISPR, Tele- and virtual-med, robotic surgery and Biological Counter Measures for Carcinogenesis from Radiation; but, it is too early to tell how or when these will be ready for implementation for Human-Mars missions.

Human Space flight Health Hazards are categorized by NASA's Human Research Program that identifies and catalogues risks tied to those hazards. [Paloski, 2014; NASA BCMs, 2015; Abadie, 2017; Scott, 2016] There are 5 hazards 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. [NASA Volume 1, 2015; NASA Volume 2, 2015]



Altered Gravity Field

Primary Effect

1. **Spaceflight-Induced Intracranial Hypertension/Vision Alteration** ★
2. Urinary Retention
3. **Space Adaptation Back Pain**
4. Renal Stone Formation ★
5. **Risk of Bone Fracture due to spaceflight Induced bone changes** ★
6. Impaired Performance Due to Reduced Muscle Mass, Strength & Endurance ★
7. **Reduced Physical Performance Capabilities Due to Reduced Aerobic Capacity** ★
8. Impaired Control of Spacecraft, Associated Systems and Immediate Vehicle Egress due to Vestibular / Sensorimotor Alterations associated with space flight. ★
9. **Cardiac Rhythm Problems** ★
10. Orthostatic Intolerance During Re-Exposure to Gravity ★
11. **Crew Adverse Health Event due to Altered Immune Response** ★
12. Adverse Health Effects due to Alterations in Host Microorganism Interaction ★

Concerns/Watch list

1. **Concern of Clinically Relevant Unpredicted Effects of Medication**
2. **Intervertebral Disc Damage**

Radiation

Primary Effect

1. **Risk of Space Radiation Exposure on Human Health** ★

Distance from Earth

Primary Effect

1. **Unacceptable Health and Mission Outcomes Due to Limitations of In-flight Medical Capabilities** ★
2. Risk of Ineffective or Toxic Medications due to Long Term Storage

Isolation

Primary Effect

1. **Risk of performance decrements due to adverse behavioral conditions** ★

Hostile/Closed Environment-Spacecraft Design

Primary Effect

1. **Toxic Exposure** ★
2. Acute and Chronic Carbon Dioxide Exposure ★
3. **Hearing Loss Related to Spaceflight** ★
4. Probability of mild Acute Mountain Sickness (AMS) in astronauts resulting in reduced crew performance prior to adaptation to a mild hypoxia.
5. **Injury and Compromised Performance due to EVA Operations** ★
6. Decompression Sickness ★
7. **Injury from Sunlight Exposure** ★
8. Incompatible Vehicle/Habitat Design
9. **Risk of Inadequate Human-Machine Interface** ★
10. Risk to crew health and compromised performance due to inadequate nutrition ★★
11. **Adverse Health Effects of Lunar (Celestrial) Dust Exposure** ★
12. Performance Errors Due to Fatigue Resulting from Sleep Loss, Circadian Desynchronization, Extended Wakefulness, and Work Overload ★
13. **Injury from Dynamic Loads** ★
14. Risk of electrical shock ★

Standards	
★	NASA-STD-3001, VOLUME 1, CREW HEALTH
★	NASA-STD-3001, VOLUME 2, HUMAN FACTORS, HABITABILITY, & ENVIRONMENTAL HEALTH
★	Clinical Practice Guidelines

★ Standards in process of review/change/addition

HMTA list in revision 2014

Fig. 1 30 Human Risks, 2 Concern/Watch List Items, Which The HRP Aims To Mitigate [from Paloski, 2014]

Some effects are correctable and thus far (6 months on ISS at approximately 45% full GCR) most health issues are recoverable [Davison, 2017]. Our experience with full radiation beyond LEO occurred decades ago during the Apollo program and is limited to a small number of astronauts on roundtrip times to the Moon lasting less than 2 weeks.

The approaches to reduce exposure to GCR and microgravity are to reduce the duration of the mission or to implement mitigation concepts for use during the mission or both. Mission duration, at least the portion in space, can be reduced by fast (< 6 months) interplanetary transits [Wooster, 2006]. There are several trajectories and planetary alignments that provide opportunities for fast transits. They require that the propulsion system be capable of high thrust and preferably high specific impulse [Ilan, 2010; Ilan, 2011; Genta, 2018; Dankanish, 2010]. Exercise [ESA 2010; Davison, 2017], Artificial gravity [Paloski, 2014] and radiation protection concepts [Cucinotta, 2013; Cucinotta, 2015; Singleterry, 2013] aim to stall the health decimation of the space environment.

Using the NASA Space Cancer Risk (NSCR) Model-2012, an acceptable risk for a 55-year-old astronaut is between 277-500 days in deep space, depending on gender and the particular time of the mission in the solar cycle. These rates are not yet based upon full GCR exposure or synergistic effects on health and immune system. Cucinotta [Cucinotta, 2013] suggests that the threshold is more on the order of 150 – 250 days in deep space. A more recent set of results that also includes 2014 models, suggest using 200 days as the number of “safe days in space” based on upper 95% confidence levels [Cucinotta, 2015]. This paper uses a proxy radiation design requirement of 150 millisievers (mSv). This was an established limit in the NASA Constellation Program in 2009 [NASA, 2009] for exposure to Solar Particle Events (SPE) and not GCR. The GCR based limits would be less. This proxy requirement is considered a lifetime limit and would not violate the regulatory risk limit of 3% Radiation Exposure Induced Death (REID) with 95% confidence interval. DNA repair and other advances in medical capabilities may change this over time, but again, it is too early to tell. Although varying slightly with age and sex, this proxy requirement does not bode well for astronauts on a Mars mission lasting as many as 3 years. Also, this proxy requirement has implications for “millions of people living and working in space”, a key vision by one space entrepreneur. [Boyle, 2018; Starkey, 2018]

As Figure 2 illustrates, there are vast differences between our limited experiences in Low Earth Orbit, mainly on the ISS, and the perceived complexity of human missions to Mars that could take as long as 3 years roundtrip. Previous studies have illustrated the benefits of fast or rapid transits to Mars for a variety of propulsion concepts to make the current knowledge base gained through astronaut experiences on ISS more relevant to expectations for Human-Mars missions. [Dankanich, 2010; Mars Architecture Steering Group, 2009; Ilin, 2010; Cassibry, 2016; Burke, 2013; Borowski, 2012; Loeb, 2015; Fiehler, 2003; Oleson, 2010; Thompson, 2018]

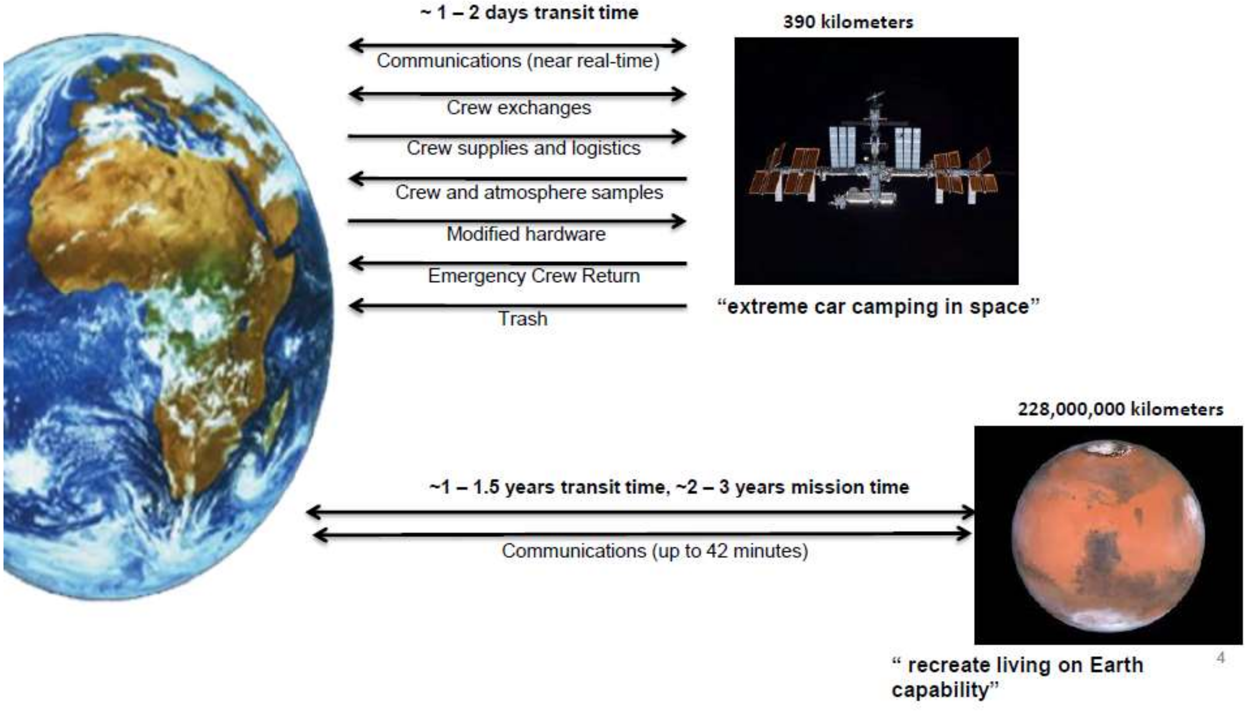


Fig. 2 “Compare Going to Mars to Where We Are Today With ISS” [from Davison, 2017]

Remaining below a proxy requirement minimizes the combinational effects of radiation adding to the effects of reduced gravity. This also implies that if the crew can reach Mars quickly and get down, sufficiently healthy, to the Martian surface, where radiation protection could be available, such as living underground beneath 5 to 7 meters of regolith, or in thick ice Igloos, then crew health might be mainly determined by a smaller set of environmental conditions, including the effects of reduced gravity. And, if training is required at the Moon as a Mars Analog, then the availability of radiation protection on the Lunar surface may also be necessary to remain below the proxy requirement.

This shines new light on the importance of fast transit options. Furthermore, it underscores the need for GCR shielding in mission phases beyond Low Earth Orbit. The purpose of this paper is to illustrate how fast transits and a GCR shielding overcoat in cis-Lunar orbit, on the Lunar surface, and in transit can enable humans on Mars. The paper also suggests that the massive overcoats necessary for GCR shielding during interplanetary transits to and from Mars can be implemented using reusable rockets because of the expected huge cost savings [Richardson, 2018]. Those calculated reductions in effective dose for the 5 mission classes are also presented.

III. Current Health Situation and Near-term Expectations

Our current understanding of long-duration flight effects on human health stems from many years of astronaut experiences on the International Space Station. Flights lasting 6 months began around 2005 and continue to present day [Talik, Spaceflight, 2005]. During this time, a wealth of knowledge as well as advances in technology have contributed to our understanding of the human adaptation to the space environment in Low Earth Orbit and produced suitable countermeasures to mitigate many unwanted side effects to microgravity and space radiation that is 45% of deep space values [Davison, 2017].

Musculoskeletal deconditioning, begin immediately and continue unabated over time, with resultant losses or maintenance dependent on exercise countermeasures and adequate nutrition. Current countermeasures available on the ISS are able to minimize losses of bone density, muscle mass and strength, and aerobic deconditioning to very acceptable levels during the standard 6 month tours. Astronauts maintain muscle and bone strength by exercising for two-and-a-half hours a day, six days a week, guided by strength coaches. [Koren, The Atlantic, 2016] Although the bone rebuilds mass, it may not rebuild in the original places, possibly affecting the overall strength of the rebuilt bone. The exercise devices in zero gravity do not have a neurovestibular component as here on Earth. For instance, when riding a bike on Earth, your body is using multiple muscle groups to stay upright with respect to the horizon. This does not occur when running on a treadmill on orbit with may be on a wall or upside down compared to your colleague.

Not all problems have a solution currently. Some, such as anthropometry, fluid regulation, and red blood cell mass adjustments, adapt completely to space conditions within a week to 10 days and remain about the same throughout the mission. Neurosensory deconditioning accompanies adaptation to weightlessness as the flyer becomes a 3-dimensional operator, but is maladaptive during and after return to a gravity environment; this challenges performance involving motor control and positional sense during the sensitive phases of entry, landing, and postflight. No countermeasures are available at this time, but these are under investigation. Neurosensory re-adaptation does occur after Earth return and leaves no lasting adverse effects, but does take as much as a month to recover. Other changes in humans associated with long duration spaceflight include highly altered but functionally adaptive cardiovascular system regulatory alterations, immune changes, and gastrointestinal function.

There are changes that seem to be less adaptive and more harmful. The recently recognized entity known as Spaceflight Associated Neuro-ophthalmic Syndrome (SANS) involves changes in critical neuroanatomy (optic nerve sheath, optic disk, retinal surfaces, intracranial pressure which results in mild brain edema) that do seem to worsen with cumulative time in weightlessness. This is a function of compliance of the vasculature (ie- stiffness of the vessels and their ability to stretch and change with an increased fluid load). Males have worse compliance than females, and age and other factors (cholesterol, genetics, 1 carbon, etc) can impact a person compliance. The 'attack rate' (how many astronauts will get SANS) is a function of time due to compliance. Right now we see an attack rate close to 30%. But that should be explained as 30% in a six month period. If we left the astronauts up there for 12 months, the attack rate would probably be close to 100% of all males and 70% of all females. At 16-18 months the attack rate would most likely be 100% of all individuals. Some people's vessels can hold the fluid in better than others.

Although crewmembers remain functional in spite of correctable shifts in visual acuity, some of these effects endure for months to years following flight. Neither the mechanism nor the long-term implications of SANS are well understood, but it is reasonable to consider this an adverse consequence of prolonged exposure to weightlessness. As understanding progresses, countermeasures to this entity are likely. This eye issue "could be something that drives us back to artificial gravity," says Barratt [Chang, NYTimes, 2014].

In spite of the nearly global adaptive changes that occur, crew remain in an acceptable operating band for performing missions of 6 months on the ISS, with high levels of functional performance expected throughout this time. Following 6-9 months of deep space cruise in weightlessness, we can have a reasonable expectation of adequate human performance on landing provided ISS-similar countermeasures are available en route and crew activities during entry and landing are scaled appropriately to neurosensory and cardiovascular status. Most all of these weightless-associated adaptations are expected to be significantly mitigated by even a partial gravity field, and the approximate 0.38G of the surface of Mars will certainly maintain humans better than weightlessness.

The major risk for which we have no current viable countermeasures is ionizing radiation, associated with an increased risk of cancers correlated with cumulative dose, acute radiation syndromes in solar particle events, and less well quantified risks of radiation induced vascular disease and central nervous system effects. This is the main limiter to human presence in space, with risk outside of Earth's geomagnetic fields much higher due to full exposure to solar particles and galactic cosmic rays.

Missions lasting far more than 200 days remain unchartered territory. [Kelly, 2017] "A normal mission to the International Space Station lasts five to six months, so scientists have a good deal of data about what happens to the human body in space for that length of time. But very little is known about what occurs after month six.

Bottom line based on ISS experiences: 6-month stays are tied to the Soyuz and represents the vast part of our experience base in Long Duration Flight. Bone / muscle / VO2 can be preserved with current countermeasures. SANS remains an issue, as does radiation. Both of these are gender weighted, albeit in opposite directions. Good countermeasures exist for all but neurosensory decrements, radiation, and SANS. Radiation really remains the long pole in the tent.

For a 200 day round trip Fast Transits, there is little worry about physical performance degradations based on now standard 6-month ISS mission with adequate countermeasures and nutrition and solution sets that do not require artificial gravity. Lower Body Negative Pressure (LBNP) and subject selection may help mitigate SANS but this has not been proven. However, neurosensory considerations will continue to influence crew activities for EDL and post landing.

There are aspects to G thresholds that are generic to any advanced propulsion concept. A learn-as-you-go approach and send a doctor seem an appropriate approach. Since weightlessness for 6 months in microgravity do not seem an issue, then AG not necessary so long as ISS type solution sets are available during transit. On the Mars surface, 1/3 G will be better than weightlessness, radiation possibly reduced, SANS possibly mitigated by low G on surface and by possible future countermeasures in flight.

IV. Health Issues for Humans-Mars

Some Mars mission architects argue that Fast Transits alone will not solve Humans-Mars missions since the hazards expected during surface stays still persist. For thoroughness, those hazards are listed in this section along with suggested ways to deal with them.

The following is a worrisome but incomplete, due to current lack of definitive information [NRC, 2002], list of the human health issues and concerns for a human mission to Mars and return. The basic differences in health related parameters between the ISS in LEO and the missions to and from Mars includes a far longer time frame for the current some 3 year roundtrip duration versus 6 months on ISS, resulting in spacecraft exposed to full GCR vice the some 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. [Scott, 2016] 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 .38g on Mars are also unknown, but partial gravity is expected to relax the issues experienced on ISS during microgravity. The list of issues is followed by a discussion of the many and various mitigation approaches that thus far are mainly directed at trying to establish conditions closer to those on Earth, conditions which resulted in current human physiology. [NASA Evidence; Safe Passage, 2001; McPhee, 2009; National Academies of Science, 2017; National Academies of Science, 2018] For thoroughness, following the discussion of mitigation approaches is a brief section on speculations with respect to physiological adaptation to Martian Conditions, variants of which may be efficacious for Martian Human Colonization.

A. Identified Unmitigated Human Health Issues associated with Humans-Mars

The health and medical challenges expected in a human Mars mission are unlike any prior manned spacecraft experience. [NASA Evidence Report, 2017] Determining the risk of unacceptable health and mission outcomes requires consideration of which medical scenarios are most likely to arise during a mission as well as those presenting the highest risk. There is no analog on Earth that can fully represent conditions on Mars. Hence, there are identified yet unmitigated human health issues associated with Humans-Mars on site exploration that include:

1. Mars Dust which is believed to contain Hexavalent Chromium that causes Cancer, Perchlorates about 10,000 times higher than Earth levels that impact the Thyroid, and small, sharp, and highly oxidative particles that affects respiratory and cardio-pulmonary systems.
2. Pathogens or In space "bugs" that are thought to become more virulent in combination with immune system degradation, resulting in "illnesses" that medications will prove ineffective. [Crucian, 2015; Crucian, 2016] Other immune systems impacts are expected from Weakened T-cell function and immune system due to combination of Radiation, micro gravity, and Psychological 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; DNA Damage such as double strand breaks, chromosome aberrations/mutations, attenuated repair process; down regulation of P53; weakened T-Cells; 1 % per month bone mineral especially calcium loss and early onset osteoporosis plus kidney stone propensity; muscle atrophy, up to some 20% loss in 5-11 days; skin irritation; Cardio-Vascular deconditioning, cardio arrhythmia, and heart degeneration including 30% to 50% decrease in maximal O2 uptake due to blood cell and capillary altered interactions and blood volume loss; Orthostatic Hypotension and low blood pressure; Neurologic, brain, cerebrovascular, neurovestibular changes and 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.
4. Space Radiation present both in space and on planet/body causes: Radiation "sickness"; Degenerative tissue effects, DNA damage, DNA repair process alterations, and 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; Alzheimers (white matter hyperintensities of the brain) reduced length and area of dendrites, performance decrements and memory deficits, loss of awareness, focus, and cognition. A recent study indicates that GCR causes "collateral" tissue damage to adjacent cells (called bystander cell damage from heavy nuclei) and could increase the cancer risk by some factor.
5. Psychiatric effects due to combination of physiological effects already noted plus distance from earth, diet changes, sleep deprivation, proximity to other crew members.
6. Toxic Chemical Exposure from spacecraft components as well as the 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 CO2 which tends to stay near the face and rebreathed.

Then, there are the potential synergistic effects of all of these, which are at this point an early stage work in progress. [Scott, 2016] 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 continue "going south" with time in space, as recently evidenced by Kelly's comments with respect to changes, effects of his nearly one year versus the usual 6 month in space sojourn on ISS. [Kelly, 2017] Some of the effects, to the extent currently known, appear to be permanent. Thus far, engineering system failure have been the major cause of human death in spaceflight. Additional concerns include radiation that causes a mutagen in a pathogen when the immune system is compromised, and the medication on board does not work because the human metabolism has shifted. It is the potential interaction of factors that nobody has considered. "Many of the risks associated with long duration space travel are not fully understood". [NASA Office of Inspector General, 2015]

B. Mitigation Approaches For Human-Mars Health Issues

As stated above, NASA is developing and proving out a robust suite of micro-g countermeasures, including exercise, which thus far mitigate many of these microgravity effects. [NASA Evidence Report, 2017] Some experts have written that many to most of these microgravity effects are simply the body adapting to micro gravity, are mostly reversible, and in the micro gravity environment such changes are not necessarily adverse. However the widely held opinion is "The less time spent in micro gravity the better".

Here is a short list of mitigation approaches being considered for Human-Mars Health Issues:

1. Exercise places loads upon muscles and bones to counteract the micro gravity effects mentioned above. This is proving to be increasingly efficacious per ISS experiences. While mitigating the musculature and skeletal issues,

exercise helps maintain the immune system and cardiovascular fitness. As mentioned above, there are some effects of micro gravity that exercise may not be as effective in mitigating.

2. Nutritional and Dietary supplements plus Pharmaceuticals, Anti-oxidants, and similar regiments are also proving to be efficacious and are a work in progress. "Biological Countermeasure" research is upbeat with respect to several substances, but early days yet. Still too early to determine implementation, there are the long-term possibilities, currently glimmering for the future, of genomics and synthetic biology to solve catastrophic diseases and possibly someday "space Harden Humans".
3. Conventional Space radiation protection shielding using low molecular weight materials, required for high atomic number (Z) radiation, requires a sizable to large amount of additional spacecraft weight and cost. Reduced LEO access costs such as proffered by reusable rockets up to a factor of 14 less cost to LEO [Richardson, 2018] would be enabling. Materials and their arrangements as components of spacecraft architecture are a contributor to radiation protection but additional measures are also required. Potential radiation protection approaches include: Active Approaches that use Magnetics and Electrostatics, including "nano-forest electrostatic concepts to reduce the requisite gap voltages and magnetics moved farther away from the capsule/ in space habitats, and potentially, CNT S-C (Carbon Nanotube Super Conducting) magnetics, and Mini-Magnetosphere and Plasma. An active radiation shielding would not have to deflect all particles. Even a 30% reduction helps to stay within lifetime radiation limits. As indicated herein, a reusable radiation protection overcoat that remains in orbit may be the better approach for minimizing MLEO and dose over time.
4. "Fast Transits" allow for much shorter round trip durations to reduce human exposure time to space conditions that affect human health. NASA has a new "nuclear Battery" approach under study that, in early studies proffers powering VASIMR and resulting in some 200 day Mars round trips vice the usual some 3 years. Such far shorter trip time could largely solve, in the sense of increasing the relevance of 200-day ISS conditions while reducing the requisite MLEO necessary for long-duration missions lasting 3 or more years.
5. Artificial Gravity generally created by rotating portions of the in space habitat is thought to be more efficacious than exercise per se in resolving some health issues associated with micro gravity. AG concepts pose additional requirements on the in-space architecture that are not easily accommodated.
6. Space flight during solar Maximum, during which time period the GCR levels are lower
7. Genomics such as P53 for cancer prevention and EPAS1 for O2 efficiency
8. Supplementing GABA for Neuro-transmission
9. Applying partial vacuum to lower body to pull fluid away from the head, eyes, upper body that mimics somewhat the effects of gravity upon body fluid distribution
10. Hypnosis to induce sleep for alleviating many issues related to sleeplessness
11. Electrical Stimulation and vibrating platforms for bones/ muscles
12. Ever better Virtual and robotic on spacecraft medical care including prevention, diagnosis, treatment, surgery/robotic surgery,

C. Becoming "Martians"

In the nearer term, for travel beyond LEO or even for extended stays in LEO, which along with micro gravity plus some 45% of full in space GCR, the zeroth order approach to reduce, to the extent possible, the adverse effects of space faring on human health is to mimic, to the extent possible, the conditions on the surface of the Earth, via exercise, artificial gravity, and radiation protection.

The suggested major metrics for Humans Mars are Cost and Safety. As suggested by the discussion herein, we are still very much in the problem definition stage with respect to both the problem and solution spaces for maintaining human health in space. In terms of problems, there is a "target rich environment" with more research needed for both problem definition and ideation, triage, development of solution, mitigation spaces. [NRC, 2002] We have some 10 years or so to conduct such research before working the systems developments to go/do humans Mars.

Overall, research is required to further "define" the human health in space problems for longer duration journeys such as humans-Mars. Mars pioneering and colonization at this point could conceivably involve a shift in human physiology to accommodate radiation, partial-g, etc, i.e. humans becoming "Martians". The ongoing research on genomics and synthetic biology could lead someday to human piece parts printing via AI to possibly enable, going forward, such a shift in physiology much faster than normal, "natural" evolution.

V. GCR Shielding Overcoat Opportunities for In-Space and Surface Mission Phases

The major Humans Mars remaining health issue, after the demonstrated efficacy of exercise protocols on ISS for micro-g effects on bones and muscles, is Radiation. The spacecraft is subject to full GCR, up to TeV/nucleon particle radiation [e.g. nickel, iron, and other fully ionized nuclei] in space, beyond the Van Allen belts around Earth, on the long trip to Mars. In LEO, on ISS, the Radiation environment is some 45% of full GCR, and missions are nominally 6 months. Humans-Mars is some 3 years total, much of it spent going to/from beset by full GCR.

The "solution" to Radiation and all its myriad health effects is Radiation protection, as stated previously herein. The most straightforward of the various radiation protection approaches is mass, in particular low Z mass, hydrogen being the most effective. A serious issue with such radiation shielding is the production of secondary radiation, including neutrons, so shielding should minimize neutron production.

Such radiation shielding is currently too expensive in terms of MLEO to be included in the affordable mission planning [Singleterry, 2013]. However, the studies and success thus far of reusable rockets includes up to a factor of 14 less cost to LEO [Richardson, 2018], which would be enabling for the reusable overcoat to and from Mars that remains in orbit, as discussed herein. Such cost reductions will obviously be revolutionary with respect to Space utilization/ commercialization and for Exploration, including Mars Exploration. With such cost reductions a very effective , possibly Polyethylene (PE) with its sizable hydrogen content, Radiation Protection "overcoat" for the spacecraft could be utilized to greatly mitigate the Radiation health issues for the three year chemical fuel planned Mars mission. With the ISS developed exercise regimen for micro-g, the remaining health issues for the three year mission would be the remaining micro-g health impacts writ large and the various "Psychological " issues, along with potential mechanical reliability issues and their resultant impacts upon health.

For the cumulative GCR response evaluation, a preliminary DRM was created that includes 5 phases: 1) cis-Lunar habitat stay; 2) Lunar surfaces stay; 3) Lunar to Mars interplanetary transit; 4) Mars surface stay; and 5) Mars to Earth return transit.

Some initial values for each duration and overcoat material were selected for constructing an evaluation tool that allows total exposure to be summed up for all 5 phases. PE was selected for the in-space phases and surface regolith was selected for the surface stays. Phases and Times, variable is thickness of polyethylene overcoat in RCC (Right Circular Cylinder) and regolith overcoat in hemi-sphere used for the Table are shown as follows, for the five mission legs:

1) Earth to cis-Lunar RCC Habitat
10 g/cm2 poly inside habitat (10cm)
20 g/cm2 Al vehicle (7.4cm)
inside hab radius = 3m, height = 10m
inside overcoat radius and height are the outside radius (3.1m) and height (10.248m) of the habitat

2) Lunar Surface Hemisphere Habitat
10 g/cm2 poly inside hemisphere (10cm)
inside sphere radius = 4m
inside overcoat radius are the outside radius of the sphere (4.1m) adjusted to be on lunar surface

3) Lunar Surface to Mars Surface Transit RCC Habitat
10 g/cm2 poly inside (10cm)
20 g/cm2 Al vehicle (7.4cm)
inside hab radius = 3m, height = 10m
inside overcoat radius and height are the outside radius (3.174m) and height (10.348m) of the habitat

4) Mars Surface Hemisphere Habitat
10 g/cm2 poly inside hemisphere (10cm)
inside sphere radius = 4m
inside overcoat radius are the outside radius of the sphere (4.1m) adjusted to be on Martian surface

5) Mars Surface to Earth Transit RCC Habitat
5 g/cm2 poly inside (5cm)
20 g/cm2 Al vehicle (7.4cm)
inside hab radius = 3m, height = 10m
inside overcoat radius and height are the outside radius (3.124m) and height (10.248m) of the hab

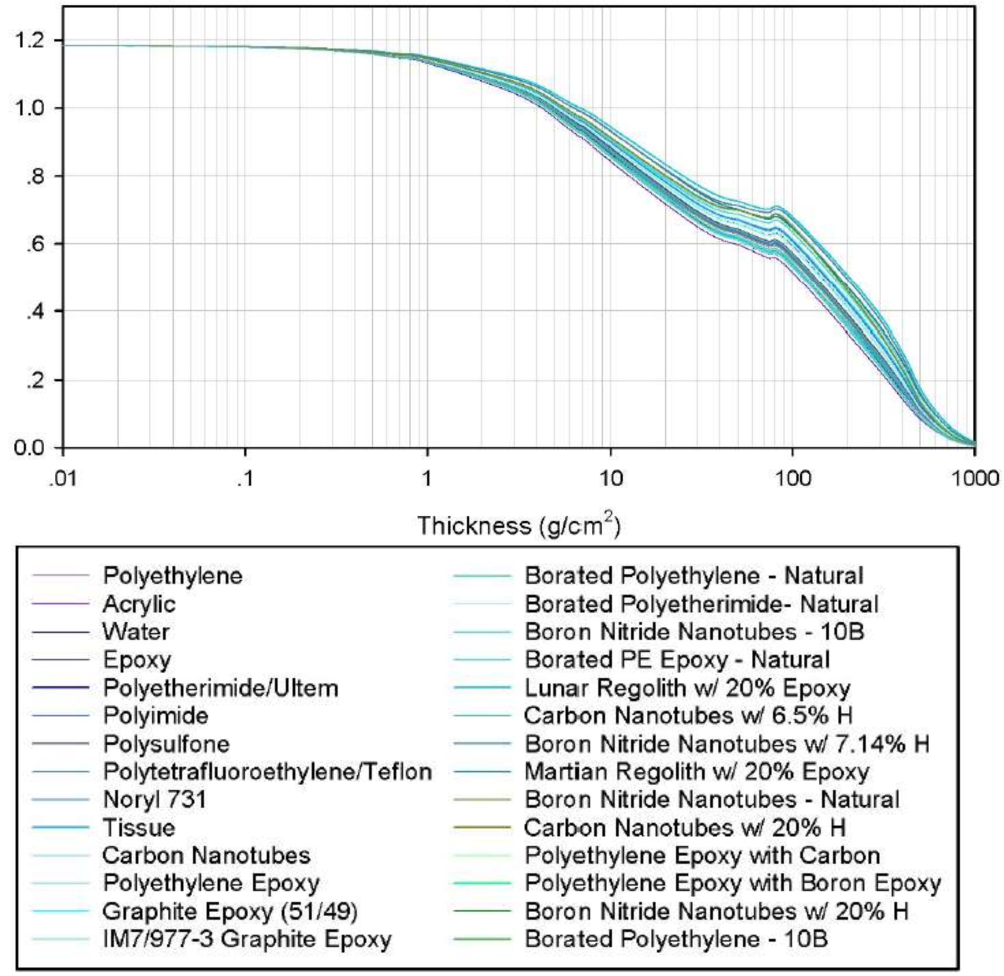


Fig. 3 Polymer and Composite Response to GCR

NASA Langley Research Center has the capability to design, fabricate, and test a variety of shielding materials including new nano-materials and hybrids. Our radiation shielding simulations include the analysis of many materials subjected to GCR (Galactic Cosmic Rays) and SPE (Solar Particle Events) [Thibeault, 2012]. Figure 3 represents the transmission of numerous materials in a GCR environment [Bond, 2017]. Low is better. Hydrogen-rich, low-molecular weight materials, preferably pliable, stable and dense, like Polyethylene (PE) performed best. However, pure PE may not have the engineering stability necessary for some structural and thermal applications.

Shown in Table 1 below, Effective Dose and Overcoat Mass can be estimated for specific mission scenarios. Table 2 offers an enlarged view of portions of Table 1. The mission scenario represented by Tables 1 and 2 includes the 5 mission legs as 180 days cis-lunar, 180 days on the Lunar Surface, 60 days traveling to Mars, 30 days on the Mars surface, and 60 days returning to Earth. These durations are not specific to any particular mission and were selected to illustrate the utility of the tool and tabled results. The results illustrate that for this mission scenario, that a GCR overcoat of 300 g/cm^2 would be needed to remain below the proxy limit of 150 mSv Total Effective Dose. The in-space overcoats would be made of Polyethylene with a mass slightly over 1500 tonnes. The surface overcoats would be made of indigenous regolith and be substantially more massive. This table also allows the analysis of additional mission scenarios having different overcoat thicknesses, as will be illustrated below for the two overcoat cases. In the first case, a GCR overcoat protects crews cis-lunar before making fast transits without a GCR overcoat to and from Mars. The second case includes a reusable GCR overcoat to and from Mars that remains in orbit.

The tables below suggests that 200 g/cm^2 of overcoat thickness is required to reduce full deep space radiation to 45%. That would imply that the ISS benefits from about 200 g/cm^2 of "shielding". The radiation levels on the ISS limit crew member stays to 18 months for females and 24 months for males [Cucinotta, 2014]. Missions to Mars lasting around 3 years at full GCR will be far worse than anything experienced on the ISS.

Table. 1 Daily, Phase, and Total Dose Levels and Overcoat Mass Estimates.

Overcoat Thickness (g/cm^2)	Effective Dose (mSv/day)					Effective Dose per leg (mSv)					Total mSv	Mass (tonnes)					
	E2cisL (poly)	Lsur (regolith)	L2Msur (poly)	Msur (regolith)	Msur2E (poly)	E2cisL (poly)	Lsur (regolith)	L2Msur (poly)	Msur (regolith)	Msur2E (poly)		E2cisL (poly)	Lsur (regolith)	L2Msur (poly)	Msur (regolith)	Msur2E (poly)	Total
0	0.802094	0.513658	0.802094	0.406889	0.853861	144.3770	92.4585	48.1257	12.2067	51.2316	348.3994	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
20	0.749199	0.460369	0.749199	0.396037	0.781685	134.8558	82.8665	44.9519	11.8811	46.9011	321.4564	51.8237	137.1159	51.8237	155.6379	51.8237	448.2249
50	0.694844	0.440639	0.694844	0.379523	0.727577	125.0719	79.3149	41.6906	11.3857	43.6546	301.1178	140.5863	389.5776	140.5863	445.5392	140.5863	1256.876
100	0.587664	0.418256	0.587664	0.343733	0.619364	105.7795	75.2860	35.2598	10.3120	37.1619	263.7992	320.4425	951.5859	320.4425	1100.2178	320.4425	3013.131
150	0.479446	0.383030	0.479446	0.302255	0.507095	86.3004	68.9455	28.7668	9.0676	30.4257	223.5060	544.2809	1716.9080	544.2809	2003.3942	544.2809	5353.145
200	0.382964	0.340173	0.382964	0.260272	0.405919	68.9335	61.2312	22.9778	7.8082	24.3551	185.3059	816.8141	2716.4271	816.8141	3194.4267	816.8141	8361.296
250	0.301771	0.295530	0.301771	0.220653	0.320332	54.3187	53.1954	18.1062	6.6196	19.2199	151.4600	1142.7543	3981.0262	1142.7543	4712.6737	1142.7543	12121.96
300	0.235109	0.252524	0.235109	0.184746	0.249881	42.3196	45.4544	14.1065	5.5424	14.9928	122.4157	1526.8140	5541.5885	1526.8140	6597.4935	1526.8140	16719.52
350	0.181468	0.212982	0.181468	0.153091	0.193057	32.6642	38.3368	10.8881	4.5927	11.5834	98.0652	1973.7056	7428.9970	1973.7056	8888.2444	1973.7056	22238.36
400	0.138920	0.177699	0.138920	0.125730	0.147913	25.0055	31.9858	8.3352	3.7719	8.8748	77.9731	2488.1414	9674.1350	2488.1414	11624.2849	2488.1414	28762.84
450	0.105594	0.146897	0.105594	0.102448	0.112509	19.0068	26.4414	6.3356	3.0734	6.7506	61.6079	3074.8338	12307.8854	3074.8338	14844.9732	3074.8338	36377.36
500	0.079767	0.120463	0.079767	0.082893	0.085042	14.3581	21.6833	4.7860	2.4868	5.1025	48.4168	3738.4953	15361.1314	3738.4953	18589.6677	3738.4953	45166.28
Days	180	180	60	30	60						Density	1	1.6	1	1.7	1	
											RCC inside radius (cm)		300				
Limit	150.000000	mSv									RCC inside height (cm)		1000				
											RCC Inside Volume (cm^3)		282743338.8				

Table. 2 Daily, Phase, and Total Dose Levels (Enlarged View of Portion of Table 1); E2cisL = Earth to Cis-Lunar; Lsur = Lunar Surface; L2Msur= cis-Lunar to Mars surface; Msur = Mars surface; Msur2E = Mars surface to Earth; Poly = Polyethylene.

Overcoat Thickness (g/cm^2)	Effective Dose (mSv/day)					Effective Dose per leg (mSv)					Total mSv
	E2cisL (poly)	Lsur (regolith)	L2Msur (poly)	Msur (regolith)	Msur2E (poly)	E2cisL (poly)	Lsur (regolith)	L2Msur (poly)	Msur (regolith)	Msur2E (poly)	
0	0.802094	0.513658	0.802094	0.406889	0.853861	144.3770	92.4585	48.1257	12.2067	51.2316	348.3994
20	0.749199	0.460369	0.749199	0.396037	0.781685	134.8558	82.8665	44.9519	11.8811	46.9011	321.4564
50	0.694844	0.440639	0.694844	0.379523	0.727577	125.0719	79.3149	41.6906	11.3857	43.6546	301.1178
100	0.587664	0.418256	0.587664	0.343733	0.619364	105.7795	75.2860	35.2598	10.3120	37.1619	263.7992
150	0.479446	0.383030	0.479446	0.302255	0.507095	86.3004	68.9455	28.7668	9.0676	30.4257	223.5060
200	0.382964	0.340173	0.382964	0.260272	0.405919	68.9335	61.2312	22.9778	7.8082	24.3551	185.3059
250	0.301771	0.295530	0.301771	0.220653	0.320332	54.3187	53.1954	18.1062	6.6196	19.2199	151.4600
300	0.235109	0.252524	0.235109	0.184746	0.249881	42.3196	45.4544	14.1065	5.5424	14.9928	122.4157
350	0.181468	0.212982	0.181468	0.153091	0.193057	32.6642	38.3368	10.8881	4.5927	11.5834	98.0652
400	0.138920	0.177699	0.138920	0.125730	0.147913	25.0055	31.9858	8.3352	3.7719	8.8748	77.9731
450	0.105594	0.146897	0.105594	0.102448	0.112509	19.0068	26.4414	6.3356	3.0734	6.7506	61.6079
500	0.079767	0.120463	0.079767	0.082893	0.085042	14.3581	21.6833	4.7860	2.4868	5.1025	48.4168
Days	180	180	60	30	60						
Limit	150.000000	mSv									

Using the estimation tool (Tables 1 & 2), one approach for achieving a proxy limit of 150 mSv total dose level is to use an overcoat for all 5 mission phases that provides just over 250 g/cm^2 for the habitats in-space and on the Lunar and Mars surfaces. As the Table 3 below illustrates, the mass of the PE overcoat in cis-Lunar space would require over 1100 tonnes of mass. As stated previously, the cost reductions of reusable rockets would enable the utilization of reusable radiation protection overcoats, which would be lofted, perhaps in pieces, donned by the spacecraft in orbit, shielding it to and from Mars, and then left in orbit for the next interplanetary transit. Such an overcoat could be utilized for cis-lunar activities.

For shielding on the surface, the mass of the surface overcoats made of regolith do not seem problematic. Moving regolith over top of a crew habitat seems feasible using rovers with the appropriate earth-moving devices. In Situ Construction is already planned for the Lunar and Mars surface. Piling up regolith in bulk over the top of a habitat module seems feasible at this point including regolith overcoats necessary for providing 1000 g/cm^2 of shielding. If the regolith density is around 1.7 g/cm^3, then a depth of about 600 cm or 6 meters would provide 1000 g/cm^2 of shielding.

Shown in Table 2 above, the daily dose level in-space without (0 g/cm^2 case) an overcoat ranges between 0.802094 mSv/day (Lunar to Mars) and 0.853861 mSv/day (Mars to Earth). It can be assumed that an overcoat can be provided on the Lunar and Mars surfaces to mitigate any dose levels necessary. Hence, a dose of 0 mSv/day will be used for surface stays in the forthcoming evaluation of fast transit trajectories in the subsequent sections. Also, cis-Lunar orbit durations will be estimated based on any remaining total dose level allowed after considering the other 3 phases (transit to Mars, Mars surface stay, and return transit from Mars) of the campaign (shown in Table 4).

Table. 3 Total Dose Levels and Overcoat Mass Estimates (Only Shown).

Total mSv	Mass (tonnes)					
	E2cisL (poly)	Lsur (regolith)	L2Msur (poly)	Msur (regolith)	Msur2E (poly)	Total
348.3994	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
321.4564	51.8237	137.1159	51.8237	155.6379	51.8237	448.2249
301.1178	140.5863	389.5776	140.5863	445.5392	140.5863	1256.876
263.7992	320.4425	951.5859	320.4425	1100.2178	320.4425	3013.131
223.5060	544.2809	1716.9080	544.2809	2003.3942	544.2809	5353.145
185.3059	816.8141	2716.4271	816.8141	3194.4267	816.8141	8361.296
151.4600	1142.7543	3981.0262	1142.7543	4712.6737	1142.7543	12121.96
122.4157	1526.8140	5541.5885	1526.8140	6597.4935	1526.8140	16719.52
98.0652	1973.7056	7428.9970	1973.7056	8888.2444	1973.7056	22238.36
77.9731	2488.1414	9674.1350	2488.1414	11624.2849	2488.1414	28762.84
61.6079	3074.8338	12307.8854	3074.8338	14844.9732	3074.8338	36377.36
48.4168	3738.4953	15361.1314	3738.4953	18589.6677	3738.4953	45166.28
Density	1	1.6	1	1.7	1	
RCC inside radius (cm)		300				
RCC inside height (cm)		1000				
RCC Inside Volume (cm^3)		282743338.8				

VI. 5 Trajectory Cases and Their Implications on Altered Gravity and Radiation Countermeasures

Establishing exposure thresholds for microgravity and reduced gravity of Mars surface can be built upon crew affects observed aboard the ISS, primarily for stays between 4-6 months. As mentioned above, exercise devices and proper nutrition are suitable countermeasures used by ISS crew to maintain muscle and bone strength. These countermeasures seem sufficient to mitigate the strength degradations previously anticipated in space and on the Martian surface during crew missions to Mars by Carpenter et. al. [Carpenter, 2010]

Table. 4 Summary of Mission Classes.

Mission Class	Days of Flight to Mars	Days on Mars Surface	Days of Flight to Earth	Total Roundtrip Time	Propulsion Type(s)
Minimium Energy Conjunction	240	420	240	900	Chemical, Nuclear, Solar Electric, Plasma
Faster-Transit Conjunction	120	660	120	900	Chemical with aeroassist; nuclear
Opposition; may involve a Venus Flyby	240	30	180	450	Chemical; nuclear; solar electric
VASIMR 10-20 MW	90	60	150	300	Chemical with aeroassist; Plasma with High Thrust
VASIMR 200 MW	60	60	60	180	Plasma with High Thrust

To illustrate how mission design and technology could be used to address and improve the aforementioned crew health issues related to microgravity and radiation, five different roundtrip mission classes (Table 4) are defined and discussed. It should be noted that the first three cases may involve more MLEO [mass in low earth orbit] and therefore increased launch cost, whereas the last two cases may reduce MLEO due to a major increase in Isp (specific impulse) but require additional technology development cost.

1) Minimum-Energy Conjunction [Mattfeld, 2014]
2) Faster-Transit Conjunction [Griffin, 2004; Wooster, 2006]
3) Opposition [Mattfeld, 2014]
4) One-Year Fast-Transit [Ilin, 2011]
5) Six-Month Fast-Transit [Ilin, 2011]

The minimum-energy conjunction-class mission typically requires a 30-month roundtrip. Chemical , nuclear thermal [Borowski, 2014] and solar electric propulsion [Genta, 2018] are typical propulsive technologies used when designing for this mission class which aims to minimize the energy (propulsive delta-V) required for the trip at the expense of long interplanetary coasts. Typical values are 8 month E-M [Earth to Mars], 14 month Mars stay, 8 month M-E [Mars to Earth], for a roundtrip time of 30 months. As the mass numbers suggest, an overcoat for the interplanetary cruise would be prohibitive, with a mass around 1100 tonnes (Table 3). However, Mars regolith could provide 1000 g/cm^2 of GCR protection using In Situ Construction techniques. For this case, using the total dose estimator, the crew would experience nearly 400 mSv total dose levels during the interplanetary trips to/from Mars. Further reductions in effective dose could be achieved by using a reusable overcoat to and from Mars. A 300 g/cm^2 overcoat made of mostly Polyethylene (PE) would drop the daily dose from 0.802 mSv/day to 0.235 mSv/day which would drop the roundtrip dose from 400 mSv to around 120 mSv total dose. Since PE has a density of around 1 g/cm^3, then a thickness of 300 cm or 3 meters would provide 300 g/cm^2 of shielding. As mentioned above, the length of the interplanetary habitat was selected as 10 meters. The mass values stated in the table above are based on these dimensions.

A faster-transit conjunction-class mission also requires a 30 month roundtrip, but seeks to minimize the interplanetary trip times. In 2016 Space-X unveiled its plans for the Mars Colonial Transport that utilized this mission class. Interplanetary transfer times in the 3-4 month range, both outbound and inbound, were limited by heat flux limits on its thermal protection system. Assuming some form of countermeasures while on the surface of Mars, this class places a priority on mitigating the health risk during interplanetary travel while employing near-term chemical and aeroassist technologies. Architectures utilizing nuclear thermal propulsion could also support this class. Notional mission profile for this class has a 4 month E-M transfer, 22 month Mars stay, and a 4 month M-E transfer for a roundtrip time of 30 months. Trading days on the surface for days spent in space, this 30-month mission scenario, the crew would experience nearly 200 mSv total dose levels during the interplanetary trips to/from Mars. This case offers a drastic reduction in radiation dose while depending only on GCR shielding on the Mars surface using In Situ Construction to provide 1000 g/cm^2 on the Martian surface. Further reductions in effective dose could be achieved by using a reusable overcoat to and from Mars. A 300 g/cm^2 overcoat made of mostly Polyethylene (PE) would drop the daily dose from 0.802 mSv/day to 0.235 mSv/day which would drop the roundtrip dose from 200 mSv to around 60 mSv total dose.

Relative to conjunction-class missions, opposition-class missions cut the overall roundtrip time nearly in half at the expense of increase delta-V. The overall roundtrip time is reduced because the surface stay is short, lasting about a month or so. Chemical, nuclear thermal and electric propulsion technologies could support this class, although the lower specific impulse systems are less mass efficient and increase cost. An opposition case offers 8 month Earth-Mars, 1 month Mars stay, 6 month M-E for a roundtrip time of 15 months. The total GCR dose for this case would be around 350 mSv, while again, just depending on In Situ Construction on the Mars surface. Further reductions in effective dose could be achieved by using a reusable overcoat to and from Mars. A 300 g/cm^2 overcoat made of mostly Polyethylene (PE) would drop the daily dose from 0.802 mSv/day to 0.235 mSv/day which would drop the roundtrip dose from 350 mSv to around 100 mSv total dose.

Reducing the total roundtrip time is possible using some propulsion types. Using a variable specific impulse magnetoplasma rocket (VASIMR) propulsion powered by a 10-20 megawatt nuclear power system (discussed below), a “one year” fast transit mission begins to mitigate the crew health risk by reducing exposure time to less than a year. A notional mission of this class includes a 3 month E-M transfer, 2 month Mars stay, and a 5 month M-E transfer for a roundtrip time of 10 months. Total GCR dose for this case would be around 200 mSv. Further reductions in effective dose could be achieved by using a reusable overcoat to and from Mars. A 300 g/cm^2 overcoat made of mostly

Polyethylene (PE) would drop the daily dose from 0.802 mSv/day to 0.235 mSv/day which would drop the roundtrip dose from 200 mSv to around 60 mSv total dose.

Further reductions in roundtrip time are possible with increased power using VASIMR. A six-month fast-transit mission class made possible with 200-megawatt nuclear power and plasma propulsion appears to reduce crew limit exposure to acceptable levels. A notional mission profile includes a 2 month E-M transfer, a 2 month Mars stay, and a 2 month M-E transfer for a roundtrip time of 6 months. Total GCR dose for this case would be around 100 mSv. Further reductions in effective dose could be achieved by using a reusable overcoat to and from Mars. A 300 g/cm^2 overcoat made of mostly Polyethylene (PE) would drop the daily dose from 0.802 mSv/day to 0.235 mSv/day which would drop the roundtrip dose from 100 mSv to around 30 mSv total dose.

The results above (and summarized in Table 5) illustrate that all mission classes can remain under 150 mSv effective dose total roundtrip when the spacecraft is shielded by 300 g/cm^2 of polyethylene. This is made possible by reusable rockets that reduce costs to LEO by a factor of 14.

Without the reusable overcoat for the interplanetary transit, only the 200 MW VASIMR Fast Transit mission class meets the 150 mSv effective dose total roundtrip. This 200MW VASIMR mission class also creates an opportunity to include cis-Lunar and Lunar Surface training (as a Mars Mission Analog) days since its total dose between Earth and Mars and Return is estimated to be around 100 mSv. Using the GCR estimator, a cis-Lunar overcoat of 300 g/cm^2 would allow a training duration of approximately 215 days, at a mass around 1500 tonnes. A 250 g/cm^2 overcoat thickness would allow a training duration of approximately 168 days, at a mass around 1100 tonnes. A 200 g/cm^2 overcoat thickness would allow a training duration of approximately 132 days, at a mass of around 800 tonnes. A 150 g/cm^2 overcoat thickness would allow a training duration of approximately 106 days, at a mass of 550 tonnes.

The cheap access to LEO would allow for both a reusable overcoat that remains in cis-lunar orbit and a reusable overcoat that shields the spacecraft during transits to and from Mars. Both versions could be built in pieces on Earth and launched to LEO where propellant resupply would allow each to be relocated to their intended orbits and then assembled around the spacecraft there. The only difference between the two versions would be the amount of propellant necessary for TLI versus TMI. These concepts of operations and their analysis are planned for a subsequent paper.

Table. 5 Summary of Total Roundtrip Effective Dose Estimates (mSv) When Using GCR Overcoats

Mission Class	When Using Surface Overcoats, 1000 g/cm^2 Regolith	When Also Using 300 g/cm^2 PE Overcoat to/from Mars
M-E Conjunction	400 mSv	120 mSv
Faster-Conjunction	200 mSv	60 mSv
Opposition	350 mSv	100 mSv
VASIMR 10-20 MW	200 mSv	60 mSv
VASIMR 200 MW	100 mSv	30 mSv

VII. Achieving High Thrust Performance at High Specific Impulse for Fast Transits

As stated in the introduction, “If the three years could be reduced to the order of a 200-day round trip, via enabling energetics and propulsion, 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.”

Less Costly Fast transits would require a much more efficient propulsion system, some 5,000 or more seconds of Isp vs the chemical value which is less than 500 seconds. An order of magnitude improvement. Such propulsive devices have been researched and in some cases applied. What is required is a high thrust, high Isp, low specific mass/Alpha device, which are extant but the options for such are few in number. The leading contenders are all high thrust electrics and include FRC (Field Reversed Configuration) [Pancotti, 2012; Pahl, 2012], Hall Thrusters [Raitses, 1998] and VASIMR [Chang-Diaz, 2013]. Of these VASIMR is perhaps the best possibility based upon a combination of Isp, thrust level, specific mass/alpha and efficiency.

The increased fuel efficiency (6,000 sec. of Isp) of VASIMR reduces the some 80% of the projected 900 tonnes up-mass in LEO that is fuel for the chemical fuel Mission, thereby reducing mission cost. This fuel efficiency also enables propulsive deceleration at Mars, mitigating EDL issues. A 200-day round trip class mission would reduce the human health concerns to those already experienced in the now up to a year stay on ISS, vs, a situation much more worrisome, especially with respect to radiation for the 3-year class mission. The much shorter mission also reduces psychological stress and the upmass required for human maintenance [food, water, breathable atmosphere, etc.] along with improving reliability. Overall, Fast Transits provide a less costly and more “healthy” and safe mission, improving the major mission metrics very significantly.

With all these benefits of fast transits, one can query why we are baselining the three-year chemical mission, which has many open issues with respect to cost, EDL (Entry, Descent, and Landing), health aspects, reliability, and safety. The answer of course is the lack of a suitable, proven, high power level and low weight power source to energize high thrust electrics such as VASIMR. Of the possibilities, solar simply lacks the power level and weight metrics, conventional fission systems are too heavy, and conventional RTGs [radioisotope thermoelectric generator] lack the power level and are also heavy. Fortunately, there are lower TRL (Technology Readiness Level) nuclear power source possibilities for enabling fast transits. One, invented by Sang Choi at NASA Langley Research Center, is the Nuclear Thermionic Avalanche Cell (NTAC). [U.S. Patent, 2016] This device is projected to produce some 10 MWs with a system alpha of order one, more than an order of magnitude lower than state of the art nuclear space power systems. A second alternative, is an advanced fission Brayton cycle utilizing Closed Cycle MHD (CCMHD) energy conversion, as envisioned decades ago by Richard Rosa at AVCO Inc. [Litchford, 2001] Various analyses have shown that a fission CCMHD system is potentially scalable to the 10 MW level with a projected system alpha [Kg/KWe] also of order 1.

An additional contributory technology is advanced structural materials. For example, the work from MIT where nano powder metallurgy, "printing" can provide superb material microstructure with far less issues such as dislocations and grain boundary problems and has resulted in, thus far, some 5X better material properties, with perhaps 10X to 15x possible going forward. In addition, advances in carbon nanotube (CNT) based composites and engineered lattice/cellular materials are enabling serious progress in achieving nanoscale properties at the macroscale needed for vehicle structures. These advances enable serious reductions in dry weight and possibly a doubling or tripling of rocket payload per launch to LEO and beyond. Lower mass reduces cost of space access and enables faster trip time. Added to this is the potential large reductions in LEO access cost from SpaceX reusable stages/technology.

NTAC is a nuclear battery that is quite different from an RTG. The current NASA nuclear RTG utilizes thermal energy generated from the alpha decay process of Pu-238 and has an output, per kg of nuclear material, the order of 10 watts. NTAC, depending upon the final efficiency that is still, in detail, to be determined and the isotopes used to produce high energy gamma photons, is estimated at up to some 20 kWs per kg which is a major improvement in power density. NTAC uses gamma ray photons (100 keV to MeV) to liberate a large number of intra-band (IB), inner shell electrons from atoms for power generation. Experiments conducted for several electron emitter materials using a vacuum UV (VUV, 6 ~ 20 eV deuterium lamp) and a 320 keV X-ray source were successfully carried out to prove the NTAC concept. The use of excited and liberated intraband electrons in addition to just the valence electrons is the major physical mechanism enabling NTAC.

The battery design employs multiple stages, resulting in utilization and consequent reduction in energy level of the applied gamma photons at each stage, increasing battery output and reducing the requisite radiation protection requirements. The device also includes a new approach to thermoelectrics, which again increases the electrical output of the battery while reducing the waste heat issues. The designs and experiments thus far were produced using and are in agreement with theory. The extant theory deals with the primary photon/electron interactions, and is not yet capable of including the secondary/ tertiary etc. interactions. The experimental data indicate these subsequent interactions improve the efficiency of the device further. Depending upon the isotopes employed the battery lifetime is the order of 2 to some 20 years or more.

The NTAC nuclear battery system alpha becomes better even than Fission/ CCMHD energy conversion at lower energy levels, appears to have a low radiation hazard and therefore could obviously, for Mars, also be utilized for on planet and spacecraft power [including power for active radiation protection in space], to power ISRU [in situ resource utilization], and rovers/ habs - the approach scales well. There are many other space related applications, for both NASA Missions and National Security Space. The device is being licensed to process nuclear waste to extract some of the 90% plus of the energy still extant therein and reduce the radioactivity of the waste. Others are interested in powering ships, military bases, manufacturing plants, mining activities and for grid utilization, both distributed generation and central grids. Overall, for many purposes and applications, where the presence of radioactive materials can be tolerated, NTAC can provide "energy Rich" conditions.

The alternative to NTAC to power VASIMR for fast transits is Nuclear Closed Cycle MHD Energy Conversion. System level designs for fission space power systems using CCMHD generators date from the 70's, with initial estimates for alpha from 3.5 to 5 kg/kWe at the 10MW level. Because the system specific mass is dominated by the heat rejection radiator mass, alpha can potentially be driven even lower if the reactor can be operated at increased outlet temperature. Recent design concepts utilizing nonequilibrium Frozen Inert Plasma (FIP) with a reactor temperature between 1800-2000 K yield system alphas of less than 2 kg/kW at power levels exceeding 3MWs.

Fundamental advances in CCMHD have been made in recent decades, but overall TRL remains low. Critical technology development needs include proof-of-principle demonstration of the FIP CCMHD concept, high-temperature superconducting magnetic systems, and high-temperature fission reactors. A key restraining factor on space fission power system investment has been the projected development costs. NASA's current strategy for potentially circumventing this cost restraint is to leverage current development efforts on a high temperature (2850 K) fission reactor for Nuclear Thermal Propulsion (NTP). Preliminary studies indicate that an NTP-derived reduced alpha, high burnup fission reactor is conceivable with an outlet temperature in the desired 1800-200 K range and scalable down to the 5-10 MW power level. Maximizing system architecture commonality for both in-space propulsion and surface power is considered a key to overcoming affordability concerns and enabling a dynamic and vibrant exploration agenda.

Overall, Fast Transit Technologies, both Propulsion and Power appear to be there in terms of viable technology options. The piece parts are at various TRL stages. Such fast transit capabilities would also be enabling for longer distances, the outer planets. However, significant research investments would be required to make this fast transit option real.

VIII. Conclusion

The results above illustrate some environmental factors affecting crew health during human spaceflight, especially for long durations. The results strongly suggest that fast transits and GCR overcoats would enable humans on Mars.

Crew health depends heavily on use of countermeasures and reduced exposure to microgravity and radiation. If muscle and bone degradation countermeasures shown effective on ISS are applicable to human missions to Mars, then "safe days in space" for human spaceflight beyond LEO depends highly on the implementation of GCR shielding overcoats during mission phases. Current mass estimates for an effective GCR shielding overcoat for the interplanetary cruise phase are over 1100 tonnes. The ongoing development of reusable rockets proferring a factor of 14 reductions in LEO access costs enables their utilization, the current best bet for GCR protection. This also has implications on GCR protection for millions of people living and working in space, especially beyond LEO.

One analogy to "safe days in space" is SCUBA Dive Tables used for planning underwater excursions. Dive Tables are based on a limited number of parameters (time, depth, and air type). Crew Deep Space Exposure Tables would need to consider a far greater set of parameters and their combinations, including some symptoms that persist or become permanent following a return to Earth. Minimizing the combinational effects by reducing time in space or increasing use of countermeasures seems to be a reasonable heading to follow. Exercise devices, Artificial Gravity, and perhaps partial gravity on the Lunar and Martian surface may serve as the analogous Decompression Chamber (often required for deep dives) to return crew health (bone and muscle strength primarily, and perhaps other symptoms) to more favorable values necessary for the remainder of the mission. GCR shielding overcoats also play an important role to isolate the crew from the harmful space environment. Digital dosimeters can track crew exposure to harmful radiation.

For various reasons, hedging the bets of the human species for the odd asteroid impact on earth, for National Prestige, Raw Curiosity, because it is there, because the Apollo Program changed the aspirations of a generation many of whom were extremely economically successful, for these and other reasons, Humans are going to Mars. Also in due time, possibly colonizing Mars and possibly turning it into the Walmart for the inner solar system as it is commercially developed using the evolving cheap space LEO access. [Moses, 2016] Mars has truly prodigeous resources including massive amounts of water.

A major impediment to humans-mars writ large is maintaining human health in-space and on planet at conditions different from those on earth, particularly the worrisome, health degrading effects of Radiation and micro-g. Relatively recent successful exercise mitigation approaches for some of the effects of micro-g developed on ISS now needs to be followed up by detailed studies of such mitigation upon the many other observed physiological etc effects of micro g to determine, for beyond 6 months in LEO at 45% full GCR and exercise partially mitigated micro-g (e.g. ISS Conditions), what other micro-g mitigation approaches might be needed. For in space, there is always artificial gravity as a spacecraft design specification.

For Radiation, the two major solution spaces are the combination of cheap space and radiation shielding overcoat as the nearer term approach. For mid-term, the recent invention of two low alpha high power energy sources combined with VASIMR (high thrust, 6,000 sec. of Isp) could provide fast transits, some 200 days there and back, and solving many other mission issues along the way.

In addition, there are the many expected benefits of the ongoing bio revolution which are projected from current research, to "harden" humans for space travel, which would increase the efficacy of other mitigation approaches. Overall, Healthy on Mars (and back) is doable going forward, but health needs to be one of THE MAJOR MISSION METRICS (Cost and Safety, with safety/ health paramount). Thus far, for humans in space, the major operational safety and health issues have been due to engineering, technical systems failures, including acute and chronic exposure. Those issues for Human-Mars missions have not been addressed in this paper.

The paper outlines a way forward for spending days training near the Moon and for completing roundtrip missions to Mars while remaining below the current proxy. In the first case, a GCR overcoat protects crews cis-lunar before making fast transits without GCR overcoats to and from Mars. This case requires continued maturation of low TRL propulsion and power technologies currently around 4 to 5 while depending on continued reductions in launch costs by a factor of 6 expected of current reusable rockets. The second case requires no new technology development except for the expectation that the next near-term generation of reusable rockets will reduce launch costs by a factor of around 14. Five trajectories and GCR overcoat sizes for all mission legs are presented herein to illustrate the opportunities to maintain human health for Humans-Mars missions.

For the fast transit cases mentioned herein, those that use existing technologies such as chemical propulsion combined with a reusable interplanetary GCR overcoats will require far more MLEO than the lower TRL cases like VASIMR combined with NTAC that may not require a reusable interplanetary GCR overcoat to meet the 150 mSv proxy requirement. Both categories of fast transit cases involve either increased launch cost or increased technology development cost or some of both. To understand which case is better, especially in light of cheaper LEO access mentioned herein, will require a benefit-cost analysis. [Arney, 2017] That too is planned for a subsequent paper.

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