Reducing Human Radiation Risks on Deep Space Missions

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Abstract— **This paper uses systems engineering approaches to address radiation exposure risks for humans on early missions to Mars. Alternatives are reviewed in the areas of current Mars mission architectures, contemporary shielding technologies, and medical treatment options to mitigate the risks of radiation doses received. The over-arching goal of this study is to determine whether any alternatives will reduce astronaut radiation exposure on a mission to Mars to meet the NASA space worker limits, while concurrently minimizing launch weight, costs, and other risks.**

Alternatives are compared via a combination of existing trade studies and *swing matrices*. Using these tools, it is determined that Boronated Nitride Nanotubes (BNNTs) are the highest potential composite for vehicle shielding, and it is recommended that Martian regolith should be used in parallel for any long stay by crews on the Martian surface. Two medical countermeasures, already FDA-approved, (*Amifostine* and *Neupogen*) have the highest potential for use. Further, no single shielding alternative will reduce crew exposure below existing limits, but further research may determine that a combination of composite shielding and regolith barriers could improve this outlook.

Notably, the systems engineering techniques utilized herein to analyze a human mission to Mars are easily extensible to other deep space mission, such as a lunar outpost.

This paper is summarized from the first author's master's thesis [1]**and readers should refer there for detail beyond this paper.**

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1. INTRODUCTION

Sending astronauts to space has many inherent risks. One significant risk is radiation exposure; this risk drove the Occupational Safety and Health Administration (OSHA) to classify all astronauts as radiation workers in 1982 [2]. Because OSHA's Earth-based limits were deemed too restrictive for effective space exploration, NASA was granted a waiver to establish its own set of radiation limits for ionizing exposure to astronauts in low Earth orbit (LEO). While these overall limits allow higher career doses than currently permitted for Earth-based radiation workers, they are still governed by the overarching principal of maintaining space worker exposure "as low as reasonably achievable," or ALARA.

However, radiation exposure in *deep space* is significantly higher than in LEO, where the planet's magnetosphere provides shielding from both Galactic Cosmic Rays (GCR) and Solar Particle Events (SPE). Studies have predicted that a human on a typical mission to Mars may receive levels of exposure that nearly double or triple the existing OSHA limits for astronauts working on the International Space Station (ISS) [3]. These same studies reveal that for astronauts returning home, this may result in significant loss of lifespan and quality of life due to increased risk of cancer, cardiovascular abnormalities, and other organ abnormalities.

This study aims to address the following question: **How can systems engineering techniques be applied to suggest optimal combinations of mission architectures, shielding designs, and medical counter-measures; with the goal of helping to ensure that human radiation health criteria are met on missions to Mars?**

In Part 2 of this paper, the types of radiation encountered in deep space—primarily GCRs and SPEs -- are reviewed, along with the hazards they present to humans.

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Part 3 summarizes the anticipated doses that would be received by astronauts in various Mars mission models. Radiation types are reviewed, and the concept of Quality Factor (QF) is introduced, which equates to the level of biological damage that each radiation particle type is capable of doing for a given energy level. Summaries for anticipated astronaut doses on Mars mission models conclude that astronauts will vastly exceed the current limit for a career-based 3% increase in Risk of Exposure Induced Death (REID) over the course of a typical mission, that these impacts are worse for women given the higher risks to reproductive organs and lungs [4], and that a large degree of uncertainty for anticipated exposures still exists.

In Part 4, mission architecture options are reviewed and compared from a stand-point of human health risks. Short stay or Opposition Class missions are those which comprise overall shorter mission durations, with a very short (roughly 30-day) stay on the Martian surface, and overall longer transit times between Earth and Mars. Long Stay or Conjunction Class missions involve shorter transit times, but with a very long Martian surface stay (~540 days) to permit time for optimal orbital alignment on the return trip. The longer transit times, combined with trajectories that will require passage within the orbit of Venus (or closer) to the Sun, equate to overall higher radiation concerns for Short Stay missions due to the risk of Solar Particle Events. Conversely, Short Stay missions do also yield slightly less mission duration risk due to their overall shorter length, and significantly lower risks for the uncertainty of the conditions that will be encountered during their relatively short periods on the Martian surface.

Shielding alternatives are discussed in Part 5. Existing shielding designs are reviewed, including the use of aluminum structure and water walls for the design reference Mars Transit Vehicle designs. Shielding considerations on the Mars surface suggest the need to consider novel shielding materials and the use of Martian Regolith in order to gain substantial shielding benefits verses the effects of secondary radiation interactions with aluminum shielding materials on the surface. Multiple novel shielding studies are discussed, highlighting the potential of hydrogen or methane rich materials, and in particular, Hydrogenated BNNT technologies to provide shielding improvements or at least equivalent shielding when compared to pure hydrogen or polyethylene materials (which are too impractical and too heavy to use on their own, respectively). The nanotube technologies are particularly promising in part because of their potential cross-application for structural materials as well.

In Part 6, the ethical principles that serve as the basis for NASA exposure limits and policy are reviewed. These principles create a complex decision process where the balance must be maintained between providing autonomy to crew members who knowingly assume the very high risks associated with space exploration, and the obligation of NASA to protect them against long term harm. Medical countermeasures for radiation exposure are also reviewed, with a highlight on several drugs currently in the early stages of use or development.

Part 7 conducts the analysis of all alternatives. Simplifying assumptions are made based on existing trade studies in the Drake publications [5] [6] which conclude that long stay missions are preferable to short stay missions and that pre-deploy mission configurations are superior to all-up configurations. The concept of swing weight matrices is reviewed as a powerful tool to calculate measures of effectiveness (MOEs) for various alternatives. Crew mission objectives are defined in the context of priorities for NASA missions in general; and using NASA risk roadmaps [7] that are pertinent to human radiation concerns on deep space/planetary missions. Using objective rating scales, the findings articulated in the abstract are obtained and summarized in Part 8.

Readers should note that this paper is summarized from the first authors master's thesis [1], and should refer there for detail beyond this publication.

2. Radiation in Outer Space

Astronauts and spacecraft will encounter various sources and types of radiation depending on spacecraft location relative to planetary orbit, and solar cycles. Two key types[1] of radiation that will be encountered on any interplanetary/deep space mission are discussed as follows.

Galactic Cosmic Radiation

Galactic cosmic radiation (GCR) is a primary concern for any mission that will take astronauts beyond the range of the earth's protective magnetic field. There, spacecraft are exposed to a small, isotropically distributed, high-energy flux that originates from outside the solar system, in the form of ionized charged atomic nuclei. This ion flux is comprised of largely hydrogen nuclei (a.k.a. protons, approximately 85%), and helium nuclei (a.k.a. alpha particles, approximately 14%), with some traces of other heavy nuclei [8]. These High (H) charge (Z), high energy (E) nuclei consist of any elements

[1] A third source of radiation that we did not include here is trapped radiation, which occurs when the earth's magnetic field traps protons and electrons. While not one of the two dominant radiation types encountered by spacecraft in deep space, astronauts on deep space missions will still receive exposure to it while in earth orbit, and while conducting maneuvers to leave Earth orbit for deep space.
Mars has no magnetic field, so unlike Earth, it is not able to trap charged particles. Thus, trapped radiation will have a minimal impact on Mars missions when compared to the scale of exposure received from GCRs and SPEs over hundreds of days in deep space. As such, it is not specifically included in our calculations.
It should also be noted that Mars has an atmosphere that is significantly less thick/dense than that of Earth, which also affects the assumptions made for Mars surface exposure levels later in this paper.

heavier than helium and are also given the shorthand name of HZE [3].

GCR particles move at extremely high speeds (in some cases nearly the speed of light), and thus they have the potential to impart high kinetic energy on the surfaces they collide with. Depending on the type of particle and its mass, these particles are capable of either directly damaging human cells or DNA structures if they are not attenuated by shielding prior to entering the body; or alternately they may cause further damage through a process called secondary interaction, in which heavier GCR particles that are attenuated by shielding in turn release other particles (often neutrons and other ions) which are still energetic enough to cause biological damage. These mechanisms and other amplifying studies that adjust exposure assumptions beyond the basic LET (linear energy transfer) models are discussed in greater detail in Section 3.

GCR flux varies with each 11-year solar cycle, as discussed by the NASA Space Radiation Analysis Group [9]. At solar maximum, the sun's magnetic field (solar wind) provides some measure of protection by attenuating a large portion of the lower energy particles in the GCR flux. Measurements have shown that particles with energies <2000 MeV/u (where 'u' is atomic mass unit) are most significantly reduced [10]. GCR dose rate is notably higher at solar minimum [9].

The typical unshielded dose to internal organs that would be encountered by astronauts on a deep space mission occurs at an annual rate of 60 Rem/year, where Rem are units of equivalent radiation dose [9]. Equivalent radiation dose is a measure of the biological damage that a radiation dose is capable of delivering (see Part 3). Shielding can help to reduce this amount, but only to a limited extent as compared to different shielding thicknesses. Shield thickness is a unit that is discussed repeatedly throughout this paper – it indicates the mass of shielding that is placed between an object to be protected and the source of radiation, per unit area. Thus, where aluminum has a density of 2.7g/cm^3 as shown in the figure, an aluminum shield thickness of 5g/cm^2 would correlate to an actual shield that is just under 2cm thick, and so forth.

Secondary interactions account for the plateau in shielding effectiveness seen in Figure 1. Secondary interactions occur when the primary source of radiation (in this case, GCR particles) interacts with another material (people, clothing, spacecraft shielding, etc.), which in turn causes scattering where other particles (neutrons, etc.) are freed and in turn become a part of the radiation flux themselves. The figure shows how thicker shields eventually cause an increase in the resulting secondary particle flux, which then causes the level of dose that can be prevented to level [9].

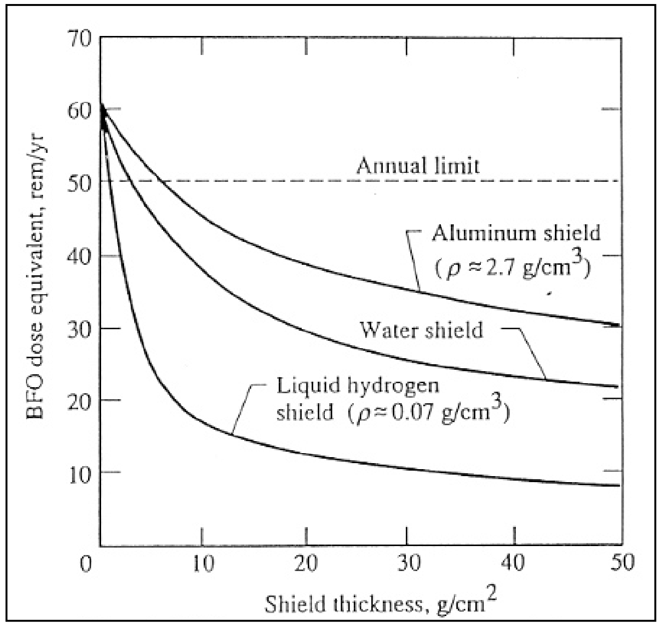

Figure 1: Shielding effectiveness of GCR at solar minimum. Source: [9]
***Note*: BFO (blood forming organs) consist of the lymph nodes, bone marrow, spleen, and liver.**

Biological mechanisms of the radiation interaction with living tissue are detailed further in the next Part. Overall, GCR is considered to be one of the most limiting factors in near term human missions to deep space.

Solar Particle Events

Solar particle events (SPE) are short-term expulsions of protons, alpha particles, and other heavier nuclei from our own sun, which are seen during flares, solar storms, and coronal mass ejections (CME) that may occur at any time, but also more frequently during periods of elevated solar activity [9]. Due to their short-term nature (minute to day durations) and often isolated trajectories, there is a high degree of uncertainty associated with their prediction for mission risk assessment. For SPEs, the quantity of higher energy particles seen during these events is relatively small, but the fluence observed for lower energy particles is relatively high. Figure 2 provides sample curves for what the effective dose to BFO would be when compared with varying levels of aluminum shielding. When one considers the 'nominal' shielding values for spacecraft, which range from 5–20g/cm^2, one can see the risk of receiving a significant dose (20 to over 100 Rem) in the course of a worst-case event would be almost certain. The effects of such a dose are reviewed further in Part 3.

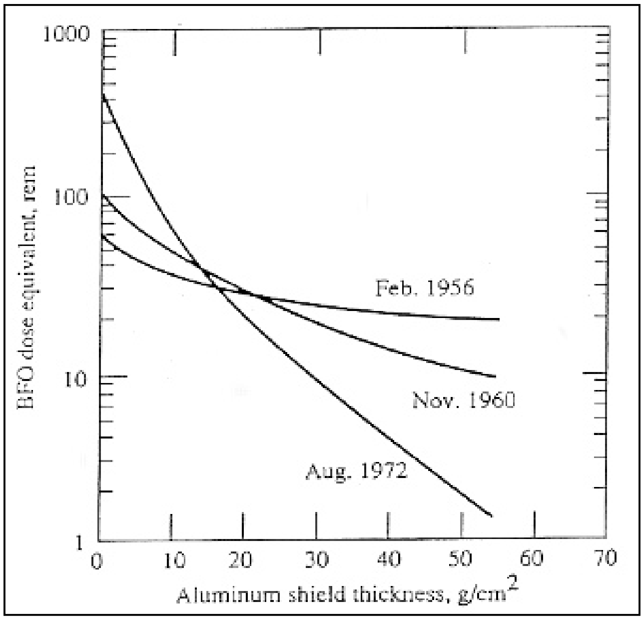

Figure 2: Shielding Effectiveness for Three Significant SPEs. Source: [9]**.**

SPEs also differ from GCR in that while the particles generated during solar events overall have lower energy levels, their fluence is much higher within the directional trajectory of the given event [8]. Higher fluence is more damaging in many cases due to the fact that more particles moving through a unit area integrated over time increases the likelihood of those particles causing more interactions (and therefore potential cell or tissue damage) in that time.

Due to the uncertain nature of SPEs, historical observations of frequency of occurrence versus all solar maxima are relevant for probability analysis. Such research has been well documented both through direct observations within the last century, and through polar ice measurements which enabled scientists to document SPEs going back as far as the 15th century [10]. Cucinotta's study reviews data that show that in the last five solar cycles, 13 events have occurred in which the measured omnidirectional proton fluence exceeded 30 MeV at a density greater than 10^9 protons/cm^2. Going back through polar ice history, 71 SPEs with the same energy levels at a fluence of greater than $2*10^9$ protons/cm^2 were measured from the years 1561 to 1950. SPEs with a fluence of less than 30 MeV and less than 10^8 protons/cm^2 are typically ignored for shielding studies because such levels will not yield a significant dose to spacecraft crew with nominal (5g/cm^2) shielding present.

SPEs are also notoriously difficult to predict due to the fact that while some have occurred during peak activity or sunspots during solar maximum, many others have occurred at different times during the cycle and in particular at random intervals during the ascent/descent from the maximum cycle [9]. According to the same research paper by Cucinotta et al., while resources have been dedicated to conduct probability analyses in an effort to determine whether consistent event size distributions can be mapped for the last five solar cycles, no definitive pattern has been identified. However, in spite of this random behavior, the short duration of one to two days for SPEs does make them easier to design into mission structure. In cases such as these, deep space crews could easily shelter in a small-volume with heavier shielding to ride out the worst of such an event [9][2].

Improvements to Measurements of Space Radiation

One significant gap in the GCR and SPE data is that all of the measurements summarized are based around Earth. The analysis of comparable radiation "weather" conditions in interplanetary space and on Mars was only recently undertaken with the incorporation of a state-of-the-art Radiation Assessment Detector (RAD) on the Curiosity Rover mission. This detector has already provided data on the GCR flux levels within the transit vehicle that brought the rover to Mars, and continues to provide radiation measurements from the Martian Surface [11]. Further, the mission team's decision to leave the detector powered on for the transit from Earth to Mars was validated when the spacecraft was exposed to a significant solar event in early 2012. This event provided valuable data because the combined solar flare and CME hit not only the spacecraft while it was between planets, but also both Earth and Mars due to their planetary alignment at the time. As such, simultaneous measurements were recorded by multiple instruments at several locations, including: the RAD on the Curiosity mission, multiple satellites including the Advanced Composition Explorer (ACE) around Earth, and the Solar Heliospheric Observatory (SOHO) operating at L1, the first Lagrangian Point[3] [11].

Mars Science Lab Space Measurements--The measurements observed by RAD have been summarized recently. Köhler et al. reviewed the measurements observed in space, including the Solar Particle Events of 2012 [12]. This article reviews the placement of the detector on the MSL spacecraft which

[2] The need to shelter from severe SPEs on a Mars mission highlights another technical challenge for the mission – to improve space weather prediction technologies. The current warning system around Earth provides limited notice when a solar event is impending. This notice is provided because satellites and observatories are able to observe the brightening (photons) from the Sun almost immediately when a significant flare or larger event occurs. These photons lead the more dangerous particle flux by anywhere from 20 minutes to several hours before they also arrive at Earth. This provides limited time to shelter electronics on Earth, and is certainly not enough notice to allow astronauts to return to shelter if they are on a longer duration exploratory mission on Mars. Algorithms are under development that may enable sensors to predict a storm by as large a margin as three days, and then to relay the warnings to the satellites in orbit at either planet, or to spacecraft in transit.

[3] This L1 point is a location four times closer to the sun than the distance between the Earth and the Moon, where the gravitational forces on the satellite from the Earth and the Sun balance such that the satellite is able to maintain an orbit in lockstep with the Earth around the Sun.

transported the rover to Mars, which resulted in a mixed shielding environment with densities that vary from <10g/cm^2 to over 80g/cm^2. This is similar to the varied shielding found on the ISS, but likely different from a transit module for Mars where the shield design would be more uniform throughout to better protect the crew. This shielding also means that the RAD instruments are measuring a mix of primary and secondary particle radiation. The measurements are taken with two types of detectors: a silicone detector and a plastic scintillator. The latter was chosen because it closely mimics the composition of human tissue. The calculated average for dose rate was roughly 481±80μGy/day using the silicone detector, which is consistent with the 461±92μGy/day measured with the plastic scintillator.

The authors were able to calculate the Linear Energy Transfer (LET)[4] in water (shielding) of the GCR based on the silicone detector measurements recorded during the final month of the cruise (June-July 2012), during which no solar events occurred. The result of these LET calculations was an average GCR Quality Factor of 3.82±0.25, which resulted in an estimated dose equivalent of 1.84±0.33mSv/day [12]. For comparison, 2mSv is a dose equivalent roughly equivalent to that received from a single CT scan of the head.

The SPE event measured in March 2012 is notable for the high dosage received which would amount to roughly 10 CT scans of the head in just three days' time. A comparison of the dose rates measured by the RAD plastic scintillator and the GOES-11 space weather satellite in orbit around Earth was also made and shown to be consistent given their relative positions from the sun.

Köhler et al. were able to use the data collected in their study to estimate GCR dose predictions for crew on a Mars mission assuming a 180-day transit in each direction. For the cruise phases alone there and back, this dose estimate came to 662±108mSv in total, not accounting for the variable spikes in dose rate that could also occur for a SPE. Comparing this data to the exposure limits reviewed in Part 3 – we can see that just the cruise phases of the model predicted here would have a high chance of exceeding the 0.6sV (600mSv) career limit set forth for 30-year-old never-smoking females, and would utilize a majority percentage of the career dose limits set forth for males and females of any age. Finally, it is important to note that the data observed by RAD occurred during a weaker than average solar maximum cycle. Unfortunately, this also means that crew on a Mars journey could also encounter SPEs with higher event exposures than those described here [12].

Curiosity Rover Surface Measurements--Hassler et al. also published the surface measurements collected by the RAD instruments on the Martian surface from 2012-2013 [13]. During this time, the team was also fortunate to observe one 'hard' SPE, albeit a weaker one. They also observed several 'soft' events, meaning they were not energetic enough to penetrate the Martian atmosphere. During these soft events a decrease in surface dose rate was observed because the lower-energy CMEs from the sun actually helped to attenuate some of the incoming GCR instead. This phenomenon is known as a "Forbush decrease".

The study also found a correlation between Martian atmospheric pressure (which would impact atmospheric density over the rover), and dose rate. The data reveals that measured dose rates at the rover were lower when atmospheric pressure was higher which in turn caused the denser atmosphere over the rover to attenuate more radiation [13].

The solar particle event observed in April of 2013 also provided a unique comparison to measurements of the same event that were collected at the STEREO observatory in orbit around the sun (which was magnetically aligned with Mars at the time, a.k.a. located at approximately the same Heliospheric longitude), and the GOES-13 satellite in Earth orbit (which was 180 degrees from Mars in Heliospheric longitude at the time). First, the SPE caused an increase in dose rate on the Martian surface of roughly 30% as observed by RAD. It is important to consider that it takes a proton energy of roughly 150MeV to actually reach the surface at Gale Crater where the lander was located. The STEREO-B telescope which was slightly leading Mars orbit saw an increase of nearly four orders of magnitude for this flare, though again one must consider that much of this flux was not energetic enough to reach the Martian surface. The GOES-13 satellite only saw an increase of two orders of magnitude of proton flux, which is consistent with the fact that it was essentially on the opposite side of the sun from this flare at the time.

Finally, Hassler's team was able to calculate some helpful/improved comparisons in dose rates and total doses received. Figure 3 shows a quick reference in total equivalent doses that would have been received based on RAD calculations for both a Mars transit, and 500-day surface stay as compared to other Earth and ISS based bench-marks in dose levels.

[4] LET is a measure of energy deposited by a particle radiation flux per unit of distance. It is commonly used to calculate quality factors (a measure of the damage that a particle type/energy is capable of doing) and dose equivalents (a measure of the biological impact of the dose received in tissue), discussed in the following section. Quality Factor is further discussed in Part 3.

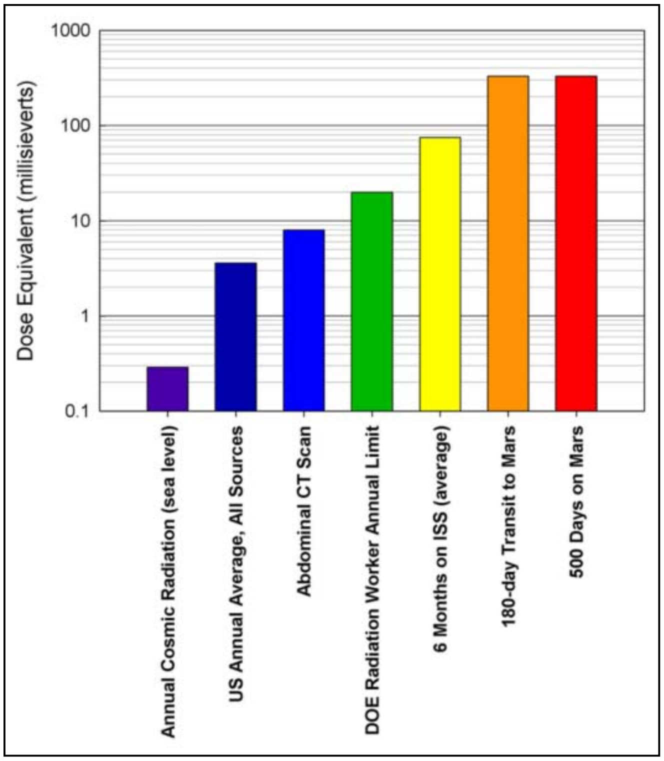

Figure 3: Comparison of radiation dose equivalents. Source: [13].
***Note*: Dose equivalent is providing using a log scale on the vertical axis of this plot. Dose equivalent is the dose rate multiplied by the quality factor for the particle type.**

Perhaps most interesting, Figure 4 shows how the study team was able to approximate anticipated GCR dose rates as a function of depth below the surface, based on the RAD measurements on the Martian surface and a transfer model to estimate the results of shielding beneath Martian regolith. This model makes a strong case for the benefits of using the Martian surface to help reduce overall dose equivalent rate – especially if the regolith can be built up around habitats (or caves can be located) at depths of 2-3m or more.

Depth below Surface	Effective Shielding mass (g/cm^2)	GCR Dose Rate (mGy/yr)	GCR Dose Equiv. Rate (mSv/yr)
Mars Surface (RAD)	0	76	232
-10 cm	28	96	295
-1 m	280	36.4	81
-2 m	560	8.7	15
-3 m	840	1.8	2.9

Figure 4: Radiation Environment measured by MSL/Rover for GCR Only. Source: [13]

In summary for Part 2, anticipated astronaut doses on Mars mission models conclude that astronauts will vastly exceed the current limit for a career-based 3% increase in Risk of Exposure Induced Death (REID) over the course of a typical mission, that these impacts are worse for women given the higher risks to reproductive organs and lungs [4], and that a large degree of uncertainty for anticipated exposures still exists. All of these improvements in Mars transit and surface exposure data are used in conjunction with the shielding discussion in order to conduct analytical calculations in Part 7 of this paper.

3. Biological Effects of Space Radiation

Particulate Radiation

Particulate radiation consists of various atomic particle types that are generated either as a primary source (example: Galactic Cosmic radiation), or via secondary interaction which is the result of radiation interaction with nearby shielding or biological matter. Examples of particulate radiation include alpha particles, beta particles (released electrons, encountered mostly in planetary magnetic fields), protons, and neutrons. As described in Part 2, the chief particulate radiation encountered in deep space comes from GCR, in a mixture of protons, alpha particles, and a small percentage of other heavy ions. Significant neutron flux is also generated as a result of the secondary interaction of GCR with spacecraft materials, which causes them to release neutrons and other particles which are themselves energetic enough to damage biological tissue.

Expansion on Solar Particle Events

Beyond the background particulate radiation flux for GCR, two types of ionization radiation are encountered in succession during significant SPEs. During large flares or coronal mass ejections, photons from the event travel eight times faster than any particulate radiation released—thus the photon radiation would be encountered by a deep space spacecraft in minutes. This wave of electromagnetic radiation can also signify the strength of the particulate radiation that is yet to come. In worst case scenarios—this particulate increase has yielded increased flux levels on the order of three to five orders of magnitude higher. These rare scenarios could lead to lethal doses of radiation for deep space crew with only nominal shielding in a matter of hours [14]. Fortunately, due to scattering processes as the particulate radiation moves away from the sun, this typically spreads the exposure increase out over one to two days' timeframe—and allows us to treat that radiation as isotropic versus directional in nature for shielding or shelter designs.

Measurement of Radiation

Radiation exposure is measured in units known as Gray (Gy), where one Gray is defined as the absorption and ionization/excitation of one joule of energy per kilogram of tissue [14]. Grays are next converted to Sieverts[5] once a

[5] Sieverts are an international standard for equivalent dose, but in many US-based dosimetry programs units of Rem (which distinguish equivalent dose or Roentgen Equivalent Man dose) are used. For ease of reference in this document, one Sievert is equivalent to 100 Rem; and one mSv is equivalent to 100mrem.

"quality factor" of the radiation dose received is considered, resulting in a net "equivalent dose." These factors are dictated by the level of biological damage or impact that can occur once a radiation or particulate type is absorbed within biological tissue. This distinction is important because certain types of radiation (alpha particles for example) are large enough that the particles are easily stopped by barriers such as skin or clothing—but concurrently due to their size they have the potential to cause damage if absorbed into the tissue via other means (ingestion, inhalation).

Biological Impact Mechanisms

Biological impact mechanisms of radiation exposure may be described in two categories—those that can lead to cancer and those that cause a variety of acute and long-term non-cancerous biological effects.

Epelman and Hamilton's article [14] summarizes the most common mechanisms by which radiation can impact tissue. First, it can break double strands of DNA and impact cell proliferation, which is especially apparent in tissues such as bone marrow and the lining of the gastro-intestinal organs where cells normally need to see a higher rate of turnover for effective function. Radiation exposure can cause lasting chromosomal alterations in the types of white blood cells that support the human immune system (a.k.a. lymphocytes)—an effect that has already been validated through its use to verify radiation absorption on long-duration space missions. Finally, radiation can interact with water molecules throughout the tissues of the body, which may result in the generation of free radicals of oxygen (free radicals being atoms that have unpaired valence electrons and are therefore highly reactive). These free radicals may in turn cause subsequent damage to surrounding tissues, and cell death through prolonged exposure.

The article "Concepts and challenges in cancer risk prediction for the space radiation environment" reviews many of the challenges in modeling human carcinogenesis predictions in deep space, starting with a discussion of the short-comings of studies in rodents which are helpful but ultimately not infallible due to the fact that rodent tumors are not human tumors [15].

A further challenge in modeling these mechanisms arises because even current cell-culture research underway to model GCR ion impacts on biological tissue is reliant on means to condense such a study to reproduce the possible effects of a three-year mission in a much shorter time period. Thus, higher fluxes are used to simulate prolonged exposure totals. Unfortunately, due to the stages by which cells undergo changes during carcinogenesis (which themselves are not perfectly understood)—such simulations may not be accurate [15]. The article goes on to review some of the details that have recently been discovered in this progression whereby cell structures are neo-plastically altered, or DNA is damaged.

NASA uses the National Council on Radiation Protection & Measurements (NCRP) publications as a basis for its radiation protocols and exposure limits for space workers. The most recent publication (NCRP Commentary #23) reviews the non-cancer basis for NASA organ-based exposure limits, which include central nervous system (CNS) dysfunction, cardiovascular disease and cataracts [16].

Basis of Existing Exposure Limits

Astronauts are classified as Radiation Workers and are required by Presidential Executive Order to comply with OSHA regulations concerning radiation exposure. However, given OSHA has no space-specific limits for exposure, and terrestrial limits have been deemed to be too restrictive for reasonable mission scopes and durations; alternate limits have been adopted per 29 CFR 1960.18 based on the following six requirements:

(1) that its use applies to a limited population, (2) maintenance of detailed flight crew exposure records, (3) pre-flight hazard assessment/appraisal, (4) planned exposures be kept As Low As Reasonably Achievable (ALARA), (5) maintenance of operational procedures and flight rules to minimize the chance of excessive exposure and (6) man-made onboard radiation exposure complies with 29 CFR 1910.96 except where the NASA mission/objectives cannot be accomplished otherwise [9].

These alternate limits were calculated based on the study of terrestrial radiation exposure risks, and with a goal to limit the change in space worker life-time cancer likelihood to only an additional 3% REID (a.k.a. Risk of Exposure Induced Death), within a confidence of 95%. The study data used to calculate these limits were based on research conducted by the National Council of Radiation Protection and Measurements (NCRP), and the resulting limits were vetted by the Nuclear Regulatory Commission (NRC) for approval [17].

The most recent calculation of the career space worker permissible exposure limits (PELs) is published in the 2015 NASA Space Flight Human-System Standard – Volume 1A; and is shown in Table 1 here [18]. These limits are calculated assuming one-year mission length, and most importantly assume that the space worker has no prior radiation exposure (otherwise, prior exposure must be considered with limits for that astronaut adjusted which may impact mission crew selection or designation for activities that will increase exposure like extravehicular activities or EVAs).

Table 1: Career Effective Dose Limits

	Females		Males	
Age (yr)	Avg. US Adult Population	Never-Smokers	Avg. US Adult Population	Never-Smokers
30	0.44 Sv	0.6 Sv	0.63 Sv	0.78 Sv
40	0.48	0.70	0.70	0.88
50	0.54	0.82	0.77	1.00
60	0.64	0.98	0.90	1.17

The NASA standards also define organ-specific exposure limits with the purpose of mitigating a combination of short term acute effects, and other long term non-cancer impacts [18].

Reference [1] contains a review of dosimetry measurement and recent improvements to the technologies, for the interested reader.

Exposure Forecasts

It is helpful to provide some background data from low earth orbit missions for context in comparison to what crew will receive in deep space. Even the time spent on the ISS at solar maximum where the shielding of the solar wind provides maximum deflection of GCR, the dose received in just 6 months on board averages 80mSv, and at solar minimum, the six-month exposure is 160mSv [2]. These quantities are a significant fraction of the career dose limits and again this is within the protection of the Earth's magnetic field!

The following sub-sections further demonstrate how severe the exposure forecasts are both for general predictive models in deep space, and for specific Mars mission models. This data is the justification for all other alternatives being reviewed in this paper to mitigate exposure so a human mission to Mars can be feasible from the perspective of radiation exposure.

An increase in shielding (and thus spacecraft weight) will yield substantial impact in the reduction of SPE dose received. However, the same change in shielding has only minimal effect in the reduction of GCR dose due to the higher energy of these particles. This point helps to support the assumption that is made in this paper that any Mars mission architecture will incorporate heavier shielding into a small shelter area to be used in the event of a significant SPE.

The results also highlight the challenges that exist in modeling overall effective dose for SPEs because the skin, thyroid, breast, and gonad effective doses from such events are disproportionately higher than the dose for other organs. This distorts weighting factors and yields overall effective doses that seem un-realistic as measures of whole-body lethality.

Numerous models have been derived from the dose estimates above to attempt to predict the Risk of Exposure Induced Cancers (REICs), and the risk of mortality from said occurrence (Risk of Exposure Induced Death, or REID). Much of this same research identifies the need to further adjust mission dose estimates for exposure received at low dose rates, because the epidemiology data used to derive all REIC/REID models is based on acute gamma ray doses which are expected to be more damaging as opposed to the relatively low GCR dose rates that would typically be encountered day-to-day in deep space (~.05Gy/hr). This adjustment is accomplished by reducing the REIC/REID by a Dose and Dose Rate Effectiveness Factor (DDREF). DDREFs of ~2.0 are typical values that have been used in most cancer predictions before further modification [10].

"Space Radiation Cancer Risks Prediction and Uncertainties—2010" shows comparisons between different REIC/REID models as compared to 2005 U.S. Census data for various tissue type cancer incidences and ratios [10]. A DDREF of 1.75 for solid (tumor) cancer estimates and for the linear component of leukemia mortality models is assumed. The key take-away from this study is that REIC for the same unit exposure of radiation is higher using all models at younger ages – which impacts medical screening and selection as a method to mitigate crew radiation risk.

Mission Specific Models

The article "How Safe Is Safe Enough? Radiation Risk for a Human Mission to Mars" provides a detailed review of anticipated total REIC risks from GCR flux and confidence levels for both 45-year old non-smoking males and females on a typical Mars mission [3]. Both mission timeframe (solar minimum versus maximum) and mission architecture are considered. For the purposes of this study, a 940-day mission timeframe was used, and mission timing was assumed to fall at solar minimum where GCR flux would be at its strongest.

The unfortunate reality revealed by these studies is that if present nominal shielding capabilities are used on missions of this duration, that astronauts will more than double or triple their risk of cancer incidence versus the current 3% limit. For women, the risk is even higher than men. Incidences of cancer from such missions may yield at least a 15-year loss of lifespan—as compared to a typical loss of lifespan of 40 years if a mission results in Loss of Crew (LOC). The studies also demonstrate that efforts to reduce the large uncertainty seen in some of the 95% confidence intervals may at least yield better predictions for these missions in the future. The need for further research is also highlighted in order to better understand phenomena such as impacts to cognitive function and memory that may be caused by GCR within the time-span of some of the longer-duration missions proposed [3].

Based on the predicted exposure levels and impacts reviewed in this chapter, a mission to Mars may seem untenable for human beings at this time. However, research is also currently in progress on methods to reduce this exposure, or to mitigate the impacts of any exposure received.

4. Reducing Exposure Through Mission Architecture

Drake et al. published a consolidated comparison of the radiological advantages and disadvantages of different Mars mission types [6]. The mission types are necessitated because in cases where a more energy efficient outbound orbit is used, orbital alignment (phase angle) upon arrival at Mars is not favorable for an energy efficient return trajectory until a longer timeframe has passed. In cases where less efficient trajectories are used, the conditions at Mars align for an energy efficient return fairly soon after arrival on the surface. Thus, Mars missions fall into two distinct classes: Opposition Class or 'short stay' Missions with longer deep space transit times (~600 days total) and limited surface stays (30–90 days); and Conjunction Class or 'long stay' missions with shorter deep space transit times (~400 days total), and longer surface stays (~500 days).

Opposition Class Mission Architecture

This mission class has higher propulsive requirements versus the Conjunction Class, and must use additional deep space propulsion maneuvers or orbital swing-by maneuvers with other planets (Venus) to both reduce total mission energy and fuel weight required, and to help constrain Mars and Earth re-entry speeds. The most significant feature of this mission class is the requirement for either the outbound or the inbound orbit to pass relatively close to the sun during the longer leg of the transit – typically 0.7 Astronomical Units or less (where one AU is 149.6 million kilometers, the mean distance from the center of the earth to the center of the sun). From a thermal standpoint, this will require transit vehicle designs to incorporate additional thermal shields, and potentially deployable radiators, cooling loops, and sun-shades to mitigate the heating effects of the perihelion (closest to the sun) passage. Positioning of shields, sun-shades, and solar arrays on the vehicle relative to the sun will also have to be precisely controlled in order to prevent over-heating of critical components [6].

From a radiation standpoint, the most significant impact of the perihelion passage necessitated by the short stay model is the fact that proximity to the sun will yield significantly larger radiation exposures during SPEs and even throughout longer-duration solar storms. The strength of the radiation dose is proportional to the square of the distance from the sun ($1/R^2$)—so these mission models will likely necessitate a transit vehicle design that has both additional module shielding to protect the crew and components during perihelion passage; and also, a heavier shelter to protect the crew from the higher flux that could be encountered during a worst-case SPE [6].

Conjunction Class Mission Architecture

The Conjunction Class or Long Stay Mission Class utilizes the most energy-efficient trajectories to transit between Earth and Mars when the orbital alignment of the two planets is relatively close. A longer stay on the Martian surface allows the crew to wait for a return of optimal orbital alignment to use a minimum energy trajectory for the return trip as well. Drake et al. also make a distinction between two basic categories of long stay missions. First, there are those that use minimal energy trajectories for optimum fuel efficiency. The second is referred to as a "fast transit" Mars mission, where trajectories have been chosen to minimize the time spent in deep space between the two planets. The comparison of these Long Stay mission types, along with a typical short stay mission, is shown in comparison to the first European nautical journey to India by Vasco de Gama in Figure 5 below:

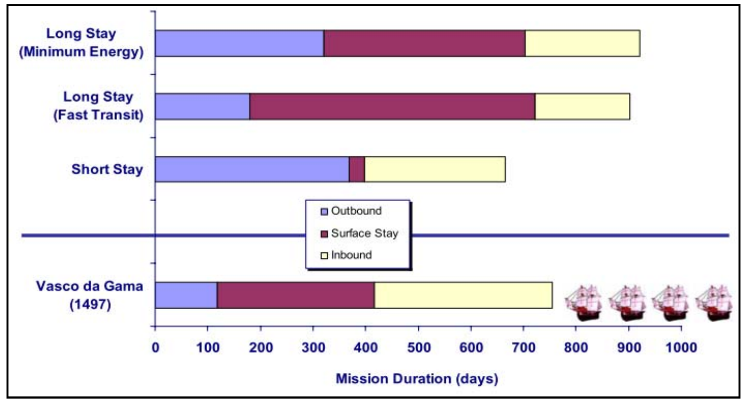

Figure 5: Comparison of Mission Class Transit Times, Stay Times, and Total Durations. Source: [6]

In general, for Long Stay missions, the trade-off of shorter transit times for a longer Martian surface stay time may actually have several advantages [6], including:

- Reduced risk due to shorter deep space transit times, thus minimizing isotropic GCR exposure times and chance of a significant SPE occurring while in transit.
- More time on the Martian Surface, which permits more time for crew acclimatization to the planet's conditions after a long zero-G transit, and more exploration time beyond that.
- Greater shielding while on the Martian Surface for 70% of the long stay mission duration, where a significant portion of the GCR flux is blocked by both the mass of the planet and its thin atmosphere. Specifically, the mass of the planet under the crew and its atmosphere may be estimated to provide 10–20 g/cm^2 Al-equivalent, depending on habitat latitude and the season.
- Adequate surface stay time to implement further shielding methods including regolith applications for habitat shielding, and potential habitat assembly in caves.

Overall, the research reviewed here indicates that Long Stay mission models may be more favorable from a radiation exposure standpoint. However, this is balanced by the higher mission risk that is inherent in more time spent away from

Earth, and by the fact that there are still uncertainties on how the exposure environment on the Mars surface will impact the crew.

5. Reducing Exposure Through Mission Shielding Technologies

Existing shielding designs are reviewed in reference [1], including the use of aluminum structure and water walls for the design reference Mars Transit Vehicle designs. Shielding considerations on the Mars surface are discussed in a series of studies that suggest the need to consider novel shielding materials and the use of Martian Regolith in order to gain substantial shielding benefits verses the effects of secondary radiation interactions with aluminum shielding materials on the surface. Finally, multiple novel shielding studies are discussed, highlighting the potential of hydrogen or methane rich materials, and in particular, Hydrogenated BNNT technologies to provide shielding improvements or at least equivalent shielding when compared to pure hydrogen or polyethylene materials (which are too impractical and too heavy to use on their own, respectively). The nanotube technologies are particularly promising in part because of their potential cross-application as structural materials as well.

A summary of the shielding options considered is provided here for further use in the analysis in Part 7 of this paper:

- In situ resource usage (primarily regolith) for shielding on the Martian surface
- Hydrogenated boron nitride nanotubes (BNNTs). Specific "best case" example under comparison: BNNT + 20% by weight H_2
- Hydrogen-loaded metal organic frameworks (MOFs). Specific "best case" example under comparison: $C_{432}H_{1120}Be_{48}O_{144}$
- Nanoporous carbon composites (CNTs). Specific "best case" example under comparison: $(C_2H_4)39.13\%(CH_3)60.87\%$
- metal hydrides (MHs). Specific "best case" example under comparison: 91% $Li_{2.35}Si$ and 9% H
- Field-based shielding concepts

6. Reducing Impacts of Exposure Through Medical Countermeasures

In Part 6, the ethical principles that serve as the basis for NASA exposure limits and policy are reviewed. These principles create a complex decision process where the balance must be maintained between providing autonomy to crew members who knowingly assume the very high risks associated with space exploration, and the obligation of NASA to protect them against long term harm. Medical countermeasures for radiation exposure are also reviewed, with a highlight on several drugs currently in the early stages of use or development. These drugs work by either preventing radiation damage, or mitigating radiation sickness symptoms after acute exposure. While the potential benefits and cost savings provided by these drugs are high in the sense that medicine takes up relatively little cargo space/launch mass, the use of such countermeasures must be weighed against several concerns. These include the schedule risk incurred by the lengthy testing and approval process mandated by the FDA, the risks of side effects, and the limitations of shelf lives for drugs on lengthy deep space missions. Exciting potential technology does exist however, which may mitigate some of these concerns by permitting remote synthesis of new or existing drugs through the use of computer systems and basic substrate chemicals while a mission is underway.

The Worden thesis reviews the following drugs which have potential for use as medical counter measures on future deep space missions [1]:

- **Amifostine**: A protectant which reduces radiation damage to tissue if taken even minutes before radiation exposure. FDA approved for use.
- **Neupogen**: A mitigator taken after exposure which stimulates the bone marrow to more rapidly replenish white blood cells. FDA approved for use.
- **Entolimod**: can be given before or after exposure and shown to protect primates from damaging effects for up to 48 hours after exposure. Currently in Phase II clinical trials.
- **Recilisib**: tested in mice and shown to mitigate damaging effects if administered either before or up to 24 hours after exposure. Currently in Phase I clinical trials.
- **Romyelocel-L**: improves white blood cell regeneration and has the potential to mitigate damage even if administered 3-5 days after exposure. Developmental studies have been completed but no formal clinical trials.

7. Determination of Optimal Solutions

Part 7 presents the analysis of all alternatives. The Worden thesis [1] reduces the scope of this analysis by leveraging existing trade studies in the Drake publications [5] [6], which conclude that long stay missions are preferable to short stay missions and that pre-deploy mission configurations are superior to all-up configurations. The concept of swing weight matrices is reviewed as a powerful tool to calculate measures of effectiveness (MOEs) for various alternatives.

In this method, mission objectives are assigned values within a table that compares objective importance and potential variance based on differences in performance. Each "weight" assigned to this table is rated such that more important or higher variance objectives are always given higher values. The table is then "normalized" by dividing each objective's weight by the total of all weights assigned in the table. This provides weighted objective values which can be used to assess the overall Measure of Effectiveness (MOE) for a given alternative [1]. Normalized weights and assignments for all mission objectives are summarized in the section below.

Definition of Objectives

Crew mission objectives are defined in the context of priorities for NASA missions in general, and using NASA risk roadmaps that are pertinent to human radiation concerns on deep space/planetary missions. These objectives are detailed in [1], and summarized in the hierarchy Figure 6 here:

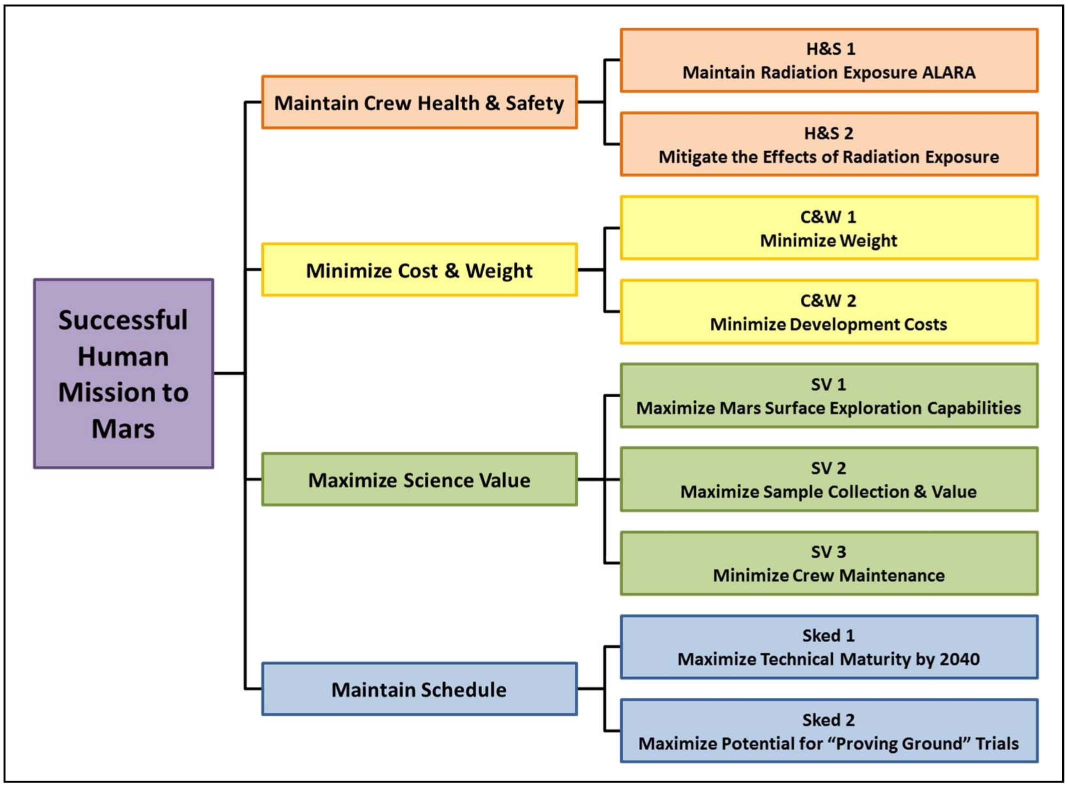

Figure 6: Mission Objective Hierarchy

Based on these objectives, a swing weight table is developed which provides the desired relative weightings between the different objective categories. Tables 2 and 3 provide a summary of the weights assigned and their normalized values, and an assignment of objectives to different weights with the relative comparison between them. The initial goal for this analysis was to weight Health & Safety objectives with 40% of the total values assigned, followed by Cost & Weight at 30%, Science Value at 20%, and Schedule at 10%. These weights could easily be adjusted to provide more or less weight to a given category by increasing or decreasing the weights assigned in the initial table. Refer to the thesis document for more detail on how the initial tables are set up [1].

Table 2: Assigned Swing Weight Matrix and Normalized Values

Swing Weight Matrix (assign numbers 1-100 for each block)						
Importance (Right)	Low	Medium	High			
Variance (Down)						
High	8	13	37			
Moderate	6	11	18			
Low	4	9	14		**Total Weights:**	120
Normalized Weight Matrix (divide each block by the sum of all)						
Importance (Right)	Low	Medium	High			
Variance (Down)						
High	0.067	0.108	0.308			
Moderate	0.050	0.092	0.150			
Low	0.033	0.075	0.117			

Table 3: Normalized Weights by Objective and Objective Category Weighting

Objective	**Importance, Variance**	**Weight**	**Subtotals**	**Total assigned weights*:**	1.000
H&S 1	High, High	0.308		Human safety %	40.0%
H&S 2	Medium, Moderate	0.092	0.400	Cost weight %	30.0%
C&W 1	High, Moderate	0.150		Science %	19.2%
C&W 2	High, Moderate	0.150	0.300	Schedule %	10.8%
SV 1	Low, Moderate	0.050		**% calculated based on this total*	
SV 2	Medium, Moderate	0.092			
SV 3	Low, Moderate	0.050	0.192		
Sked 1	Low, Low	0.033			
Sked 2	Medium, Low	0.075	0.108		

Each objective assigned to these tables is then assigned a rating scale from 1.0 to 0.0. Depending on the objective, these ratings may correlate to either “highest” performance, to “greatest” reduction, to neutral values as in cases where certain alternatives under consideration may have no impact on certain objectives, and so forth. Detailed explanation of each rating scale is shown Table 4 below.

These ratings are used to assess the relative performance of each alternative for each mission objective relative to other alternatives of the same type (i.e. shielding alternatives or medical alternatives are each compared as a group).

Table 4: Definition of Objective Rating Scales and Assumptions

Objective	Description of Rationale & Assumptions	Rating Scale
H&S 1	Based on the fact that some shielding data is only measured up to a thickness of $30g/cm^2$, this thickness is used to calculate the effectiveness various materials against each other. In cases where exposure against GCRs could be impacted in all phases of a human Mars mission, exposure for a total duration of 1000 days is estimated for each alternative relative to a baseline of comparable Aluminum shielding. Table 1 reviews the NASA exposure limits. Any alternative that lowers exposure levels less than the existing exposure limits for all ages/genders receive a rating of 1.0. Remaining alternatives are assigned ratings based on their relative effectiveness. Alternatives that do not have numerical data available receive a best estimate of their potential for effectiveness. Alternatives that have no effectiveness on radiation exposure receive a rating of 0.	• 1.0 = Exposure limits met • 0.75 = High effectiveness • 0.5 = Moderate effectiveness • 0.25 = Low effectiveness • 0.0 = No impact on exposure
H&S 2	Any alternative under study that has the potential to mitigate 100% of any exposure effects (either by cellular damage prevention or healing) receives a rating of 1.0. Any alternative that has no impact on exposure mitigation has a rating of 0.0. All alternatives with a moderate level of radiation mitigation receive ratings from 0.1 through 0.9 based on the relative potential for mitigation. For alternatives with the potential for medical side effects, it is assumed that all side effects are acceptable if these drugs are ultimately FDA approved for human use.	• 1.0 = 100% mitigation • 0.0 = No impact on mitigation
C&W 1	Alternatives that have zero/negligible impact on mission weight receive a neutral rating of 0.5. Alternatives that have the potential to increase mission weight (including that of Pre-Deployed cargo) receive ratings from 0.4 to 0.0 based on estimated impact, with 0.0 being the most weight/cost intensive. Alternatives that have the potential to reduce mission weight receive ratings from 0.6 to 1.0.	• 1.0 = Highest potential to reduce weight • 0.5 = Weight neutral • 0.0 = Highest potential to increase weight
C&W 2	Alternatives that carry the highest potential development costs receive a rating of 0.0. Alternatives with no additional development receive a rating of 1.0. All other new technology alternatives are scaled for potential development cost between these two values.	• 1.0 = No additional cost • 0.8 = Low cost • 0.5 = Moderate cost • 0.2 = High cost • 0.0 = Highest potential cost
SV 1	Alternatives that provide the highest potential for mission tasks that provide science value receive a rating of 1.0. Alternatives that have no impact on the potential for science value receive a rating of 0.0.	• 1.0 = Highest potential • 0.5 = Moderate potential • 0.0 = No impact on science gain potential
SV 2	Alternatives that support in-depth local analysis of samples with the potential to re-sample as needed receive a rating of 1.0. Alternatives that support sample return with minimal analysis receive a rating of 0.5. Any alternative that prevents sample return receives a rating of 0.0.	• 1.0 = In-depth analyzed sample return • 0.5 = Basic sample return • 0.0 = Prevents sample return
SV 3	Alternatives that have no impact on the potential need for "crew time" (maintenance) receive a rating of 0.5. Alternatives that simplify or lessen the need for crew maintenance receive ratings of 0.6 to 1.0 on a relative scale. Alternatives that increase the need for crew maintenance receive ratings of 0.5 to 0.0 where 0.0 is the most time-intensive.	• 1.0 = Least time-intensive • 0.5 = Neutral impact on crew time • 0.0 = Most time-intensive
Sked 1	Alternatives receive confidence ratings based on their potential to have technical maturity to support a human mission to the Martian surface by 2040. The alternatives with the highest confidence or least schedule risk receive a 1.0 rating. Alternatives with the lowest confidence or highest schedule risk receive a 0.0 rating. Alternatives that have no impact on schedule also receive a 1.0 rating.	• 1.0 = High confidence of readiness by 2040 • 0.0 = Zero confidence of readiness by 2040.
Sked 2	Alternatives with the highest potential for "proving ground" trials in the 2020 timeframe receive a 1.0 rating. Alternatives with the no potential for proving ground trials receive a 0.0 rating. All other alternatives receive a rating based on an estimate of how soon they may be ready for in-space trials, with alternatives that may be ready sooner receiving higher ratings. Alternatives with no need for proving ground trials also receive a rating of 1.0.	• 1.0 = Capable of supporting trials by 2020. • 0.0 = No potential for trials.

Ref. [1] conducted a series of calculations to determine approximate relative performance for shielding alternative, as shown in Table 5 here. Ratings are then assigned for each shielding alternative relative to the others, and for each medical countermeasure alternative relative to a 0-1.0 performance scale. A sample rating assignment is shown here in Table 6, while all other alternatives are detailed in [1]. In Tables 7 and 8, the MOE for each given alternative is calculated by finding the sum-product of each rating by the normalized weight for each objective.

Table 5: Calculation of Approximate Shielding Performance

Alternative	Shielding Calculation Density & Thickness Calculation
Martian regolith shield	Comparable to aluminum in effectiveness–extrapolating the Aluminum Curve from Figure 40 in [1] yields a dose rate of .043cGy/day at an effective thickness of 100g/cm^2, and a slope of approximate -.01cGy/day per increase of 40g/cm^2. It stands to reason that increasing shield thickness to 300g/cm^2 (calculated at a thickness of ~2m of regolith) will reduce absorbed dose rate to negligible levels. Of note, this shielding will only be available for the surface portion of any mission so this is not a full solution.
	Density ~1.52g/cm^3, ~2m required to be effective against GCR
BNNT + 20% by weight H_2	Figure 46 in [1] shows an equivalent dose comparison of Al verses this composite at a difference of 1.7mSv/day verses 0.9mSv/day: 1.7mSv/day×1000days×1Sv/1000mSv**=1.7Sv equivalent dose with Al shielding** 0.9mSv/day×1000days×1Sv/1000mSv**=0.9Sv equivalent dose with BNNT shielding** **Mission improvement verses aluminum = 0.8Sv**
	BNNT Density = 1.4g/cm^3 30g/cm^2 shield thickness required×1cm^3/1.4g=**21cm thickness required to achieve the calculated shielding density**
MOF: $C_{432}H_{1120}Be_{48}O_{144}$	Figure 40 in [1] shows an absorbed dose comparison of Al verses this composite at a difference of .061cGy/day verses .053cGy/day: .061cGy/day×1000days×10mSv/cGy×1Sv/1000mSv**=.61Sv absorbed* with Al shielding** .053cGy/day×1000days×10mSv/cGy×1Sv/1000mSv**=.53Sv absorbed* with MOF shielding** *We can use the fact that effective dose is equal to absorbed dose multiplied by a Quality Factor (QF) to estimate the equivalent dose of the data for this composite and others below. **1.7Sv equivalent dose with 30g/cm^2 Aluminum shielding÷** 0.61Sv absorbed dose with the same shielding **=an average Quality Factor of ~2.8.** Converting the MOF data calculated above by Quality Factor: 0.53Sv×2.8QF = **1.5Sv equivalent dose with MOF shielding** **Mission improvement verses aluminum = 0.2Sv**
	MOF Density = 0.46g/cm^3 30g/cm^2 shield thickness required×1cm^3/0.46g=**65cm thickness required to achieve the calculated shielding density**
CNT: (C_2H_4)39.13%(CH_3)60.87%	Figure 41 in [1] shows an absorbed dose comparison of Al verses this composite at a difference of .061cGy/day verses .052cGy/day: .061cGy/day×1000days×10mSv/cGy×1Sv/1000mSv×2.8QF **=1.7Sv equivalent dose with Al shielding** .052cGy/day×1000days×10mSv/cGy×1Sv/1000mSv×2.8QF **=1.4Sv equivalent dose with CNT shielding** **Mission improvement verses aluminum = 0.3Sv**
	CNT Density = 1.17g/cm^3 30g/cm^2 shield thickness required×1cm^3/1.17g=**26cm thickness required to achieve the calculated shielding density**

Alternative	Shielding Calculation Density & Thickness Calculation
MH: 91% $Li_{2.35}Si$ and 9% H	Figure 42 in [1] shows an absorbed dose comparison of Al serves this composite at a difference of .061cGy/day verses .048cGy/day: .061cGy/day×1000days×10mSv/cGy×1Sv/1000mSv×2.8QF **=1.7Sv equivalent dose with Al shielding** .048cGy/day×1000days×10mSv/cGy×1Sv/1000mSv×2.8QF **=1.3Sv equivalent dose with MH shielding** **Mission improvement verses aluminum = 0.4Sv**
	MH Density = $0.84g/cm^3$ $30g/cm^2$ shield thickness required×$1cm^3$/0.84g=**36cm thickness required to achieve the calculated shielding density**
Field based shield	No shield performance data available–effectiveness is estimated to be high.
	Density is N/A although it is noted that the weight of cargo needed to generate the power for such technology may be quite high.

Table 6: Sample Rating Assignment for BNNT Shielding

Objective	Discussion	Rating
H&S 1	BNNTs are by far the most effective of the potential vehicle shielding technologies under consideration, with an estimated 1000-day equivalent of 0.9Sv. However, this still exceeds the career does limit for all but the oldest male and female never-smoker categories. As such we assign it a rating of 0.8.	0.8
H&S 2	No impact on exposure mitigation	0.0
C&W 1	BNNTs require a shield thickness of 21cm to match the shielding density of 11cm of aluminum–that said their performance is much higher. It is assumed that a thicker composite shield will require more structural material to help encase and support it however. As such this material receives a rating of 0.4 for its likelihood to cause a minor increase in vehicle weight.	0.4
C&W 2	BNNTs are a very new composite technology and it is assumed that their complexity is higher than MOHs, CNTs, and MFs based on the fact that nanotube production is involved. As such, their development costs are assumed to be somewhat high. A rating of 0.3 is assigned.	0.3
SV 1	Composite shielding technology yields science gains in the sense that composites not only enable greater potential for space exploration, but also potential for cross-application on Earth. BNNTs arguably have higher potential than the other composites due to the strength of nanotube technology. A rating of 0.6 is assigned.	0.6
SV 2	All composite shielding technologies are assumed to improve performance over aluminum alone, but none of them reduce exposure levels below the existing limits. That said, a chief goal of human missions to Mars is to enable improved basic sample return, so it is assumed that these technologies support that goal. A rating of 0.5 is assumed.	0.5
SV 3	All composite shielding technologies require some level of increased crew maintenance to inspect and ensure that the composites are not degrading over time. It is assumed that BNNTs may be more stable than the other composites under consideration due to the nanotube technology, but hydrogen off-gassing will still be a significant concern. A rating of 0.4 is assigned.	0.4
Sked 1	Because BNNTs are an extremely new technology, they are assumed to have further technological development to complete in order to be ready for fielding. In the absence of discrete schedule data, they are given a moderate rating of 0.5 which is slightly lower than the other composites under research will receive.	0.5
Sked 2	Based on the same reasoning as Sked 1, BNNTs are assigned a rating of 0.5 for their likelihood to be ready for proving ground trials on cis-Lunar missions in the 2020s.	0.5
MOE		**0.502**

Table 7: Summary of MOE Calculations for Shielding

SHIELDING TRADE STUDY								
Objective	**Importance, Variance**	**Weight**	**Regolith Ratings**	**BNNT Ratings**	**MOF Ratings**	**CNT Ratings**	**MH Ratings**	**Field based Ratings**
H&S 1	High, High	0.308	0.5	0.8	0.2	0.3	0.4	0.9
H&S 2	Medium, Moderate	0.092	0.0	0.0	0.0	0.0	0.0	0.0
C&W 1	High, Moderate	0.150	0.1	0.4	0.2	0.4	0.3	0.0
C&W 2	High, Moderate	0.150	0.5	0.3	0.4	0.4	0.4	0.1
SV 1	Medium, High	0.050	0.9	0.6	0.5	0.5	0.5	0.8
SV 2	Medium, Moderate	0.092	1.0	0.5	0.5	0.5	0.5	1.0
SV 3	Low, Moderate	0.050	0.6	0.4	0.3	0.3	0.3	0.1
Sked 1	Low, Low	0.033	0.9	0.5	0.6	0.6	0.6	0.1
Sked 2	Medium, Low	0.075	0.2	0.5	0.6	0.6	0.6	0.0
		MOE:	0.456	**0.502**	0.303	0.363	0.379	0.433

Table 8: Summary of MOE Calculations for Medical Countermeasures

MEDICAL TRADE STUDY							
Objective	**Importance, Variance**	**Weight**	**Amifostine Ratings**	**Neupogen Ratings**	**Entolimod Ratings**	**Recilisib Ratings**	**Romyelocel-L Ratings**
H&S 1	High, High	0.308	0.0	0.0	0.0	0.0	0.0
H&S 2	Medium, Moderate	0.092	0.8	0.5	0.7	0.6	0.8
C&W 1	High, Moderate	0.150	0.5	0.5	0.5	0.5	0.5
C&W 2	High, Moderate	0.150	1.0	1.0	0.8	0.7	0.6
SV 1	Medium, High	0.050	0.5	0.5	0.5	0.5	0.5
SV 2	Medium, Moderate	0.092	0.5	0.5	0.5	0.5	0.5
SV 3	Low, Moderate	0.050	0.5	0.5	0.5	0.5	0.5
Sked 1	Low, Low	0.033	1.0	1.0	0.7	0.6	0.5
Sked 2	Medium, Low	0.075	1.0	1.0	0.5	0.4	0.3
		MOE:	**0.503**	**0.475**	0.416	0.381	0.373

The calculations in Table 7 reveal that overall; BNNT composites have the highest MOE and are therefore the most promising of the vehicle-based alternatives for shielding. Regolith receives relatively high score in spite of the fact that it can only be used for the surface-based phases of a mission, which indicates it should be considered as a parallel solution to any vehicle-based shields. It is worth noting that field-based shields also received a relatively high MOE, indicating it is well worth studying them as a promising alternative in the longer term.

The results from Table 8 are not surprising in that the two medical alternatives (Amifostine and Neupogen) that already have FDA approval are the most favored for use. That said, given how little weight medical countermeasures take up, it will likely be beneficial to include any medication that has FDA approval on future missions in order to optimize the variety of treatment available to the crew. As these medications are actually used in space, some may reveal themselves as more effective in the future.

8. Conclusions

The systems engineering technique of swing weight analyses is found to produce meaningful results in a problem of this scale and complexity that poses high risk in combination with multiple technologies that can each address the risk in limited measure. Notably, this technique is readily extensible to other deep space mission analyses, such as a Lunar Outpost mission.

Based on trade studies conducted in the Drake Mars Mission Design Reference Architecture documents, we determine that a long stay mission in which the astronauts spend approximately 500 days each in transit and on the Martian surface (1000 days total) is a preferable model to maximize mission Science Value while also using orbital trajectories that minimize the crew's time in space and in closer proximity to the Sun where the risk of acute exposure from solar storms is potentially higher. Other Drake trade studies [5] [6] are used to determine that a pre-deploy mission model is preferable - in which all necessary surface habitat, return vehicle, and other heavy cargo are sent to the Martian surface in advance of the crewed vehicle. This preference stems largely from the capability of this model to both minimize the weight of separate vehicles sent for the transit which is logistically simpler and less costly than sending an extremely large vehicle with all cargo; and from the fact that advance arrival of the surface habitat and other cargo provides a safety margin for the crew because they would not begin their journey to Mars until they have confirmation that all the necessary equipment arrived safely and is in working order.

Shielding alternatives for human missions to Mars present the greatest challenge for analysis because at present, the crew is predicted to exceed all existing career exposure limits on such a mission by a factor of 200-300%. Several assumptions are made to simplify this analysis for the purposes of this paper. The first is that all transit and habitat vehicles will include the design of a crew sleeping area/emergency shelter with water wall shielding to sufficiently mitigate acute exposure from any SPEs. Second and related to this, it is assumed that adequate sensors and space weather forecast technology will be implemented as needed in space around the inner solar system such that crews can receive reliable advance warning to take shelter if such an event occurs.

In the attempt to drastically reduce crew radiation exposure from GCR over a 1000 day long stay mission, aluminum shielding alone is not sufficient - but there are a number of promising composite material and in situ resource options that may help to improve performance. A detailed swing weight analysis reveals that out of all composite alternatives, BNNTs are the most promising option, due to the fact that they have potential for use both as part of vehicle/habitat structures and in yarns for clothing; and because they are extremely lightweight for the level of shielding provided. Regolith shielding is also found to have high promise for the surface portion of long-stay missions, providing that resources are invested to design the tools and equipment needed to facilitate its use (ideally Martian excavation equipment or even advance robotics that could generate bricks from the material). Manual "sand bag" labor by crew is also an option, though it will incur significant use of astronauts' time to pile up meters of regolith around their habitat. In the long run, field based shielding has been shown to have high potential, and should be given a high priority for development by the 2040 timeframe, in parallel with the development of composite shields which would still be needed as a "backup" for shielding in the event of a field-based system maintenance shutdown or failure.

A swing weight analysis is also conducted to compare different options for medical countermeasures which may help to prevent damage from crew radiation exposure, or to help heal damage in the aftermath. Of all options, the two that are already FDA-approved (Amifostine and Neupogen) are shown to be preferable; though three other options currently in various stages of developmental or clinical trials also show high potential. With medications, it is important to remember that these are designed to be used as a failsafe in the event that something goes wrong (for example, crew receiving an acute radiation dose due to unexpected conditions on the Martian surface or being unable to get to shelter before an SPE). Further, due to the minimal weight involved, it may be logical to bring "any and all" options that are FDA approved as part of cargo, at least until practical application in space determines whether certain options are superior for human use or not.

We also find that no single shielding option exists at present to reduce crew exposure to GCRs below existing limits during the transit periods in space. It is possible that a combination of 2m+ regolith shielding for the surface stay portion of a mission in addition to the use of composites on transit vehicles and habitats may help to improve this outlook – but it is hard to quantify these numbers especially when the very first missions to Mars will likely involve either humans in orbit or a very short surface stay which negates the value of regolith shielding entirely while still incurring at least 500 days or more in transit in deep space.

These conclusions indicate two high-priority paths for further research that should be conducted on shields. First, detailed studies about the combination of composite vehicle and regolith shielding should be conducted to determine whether it is possible to reduce potential exposure levels below the limits for all gender and age groups on long stay mission models. Second, field based shields should be shifted to higher priority for funding and implementation within the next twenty years. Another area that likely merits further research is the question of whether crew dosage with any medical countermeasure (for example, Amifostine) could serve to safely mitigate a large portion of the risk of GCR exposure, provided the dosing is given at a regular interval during the deep space transit periods of the mission. This is another question that may be hard to analyze given the ethical limitations of studying the effectiveness of these medicines with humans on Earth.

Finally, in terms of the existing crew exposure limits one must also ask the most challenging question of all – given NASA's Space Worker Regulations include a section on the concept of autonomy, is it worth it to relax exposure limits for the earliest Mars missions provided the astronauts involved are willing to accept this risk for the potential of being the first explorers on another planet? Much like the "leap" that human kind made on the first lunar missions, these increased risks may be far outweighed by the potential returns.

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