Moon 2 Mars
Space Radiation Protection
"Buying Down" Risks to Crew

Lisa C. Simonsen[1]
NASA HQ 1, Washington DC, 20546, USA

Janice A. Zawaski[2] and Jason Weeks[3]
NASA Johnson Space Center 2,3, Houston, Texas 77058, USA

While working on the International Space Station (ISS), astronauts receive orders of magnitude more radiation exposure than any modern terrestrial radiation worker. As NASA develops long-duration mission capabilities beyond LEO, crew radiation exposures levels may exceed our current ISS knowledge base and approach or exceed NASA's new radiation standard of 600 mSv for the longest duration missions to Mars. Within NASA's Moon 2 Mars (M2M) architecture planning, technology solutions to significantly reduce exposures are mass prohibitive. These larger exposures will put crew at increased risk of developing cardiac, vascular, and cerebrovascular diseases in addition to radiogenic cancers. Research is required to quantify these risks and identify countermeasure strategies within mission constraints (mass, power, volume). The integrated solution space to protect crew spans both physical and biological mitigation strategies. Agreement on space radiation health research and test objectives is needed to align biological deliverables with Agency technology roadmaps to develop an integrated protection strategy. Here, we focus on the biological aspects of protection including crew exposure levels for each M2M mission segments and research objectives to "buy down' associated radiogenic health risk.

I. Nomenclature

CNS – Central Nervous System
DOE – Department of Energy
DRM – Design Reference Mission
GCR – Galactic Cosmic Radiation
CRP – International Commission of Radiological Protection
IOM – Institute of Medicine
ISS – International Space Station
LEO – Low Earth Orbit
LSS – Life Span Study
M2M – Moon to Mars
MPS – Million Person Study
NASA – National Aeronautics and Space Administration
REIC – Radiation-Exposure Incidence of Cancer
REID – Risk of Exposure-Induced Death
SPE – Solar Proton Event
STD – Standard

[1] Sr. Research Scientist, Space Operations Mission Directorate.
[2] Space Radiation Element Scientist, Human Research Program.
[3] Space Radiation Element Manager, Human Research Program.

II. Introduction

NASA's Artemis campaign marks a major step in establishing a sustainable human presence on the Moon and preparing for future missions to Mars [1]. Without the protection of Earth's magnetosphere, astronauts will be exposed to significantly higher levels of ionizing radiation. While spacecraft and habitats will incorporate shielding to protect against large solar particle events (SPEs), the persistent and penetrating threat from galactic cosmic radiation (GCR) remains a central concern—especially for the first human missions to Mars.

Radiation exposure poses serious health risks, including increased cancer incidence, neurocognitive and cardiovascular effects, and immune dysfunction. NASA recently adopted a career radiation exposure limit of 600 mSv to cap the mean excess risk of cancer-related death at 3% above baseline [. 2]. Although the new standard extends permissible mission durations by a factor of ~1.5 to >3 compared to the previous limit, it introduces new uncertainties—particularly regarding cardiovascular, cerebrovascular, and cognitive outcomes. Since Mars missions are expected to exceed this threshold, NASA is pursuing a multi-layered protection strategy that includes spacecraft shielding, storm shelters, real-time dosimetry, forecasting systems, and emerging biological countermeasures. Understanding and mitigating radiation risks is essential to protecting astronaut health, ensuring mission success, and supporting the long-term viability of deep space exploration.

III. Comparison of ISS Mission Exposures and Terrestrial Workers

Astronauts represent the most highly exposed occupational group in terms of ionizing radiation. On the International Space Station (ISS), effective doses accumulate at a rate of approximately 0.2 to 0.5 mSv/day, averaging between ~40 and 90 mSv during a typical six-month mission [3]. Cumulative exposures increase with mission frequency and duration, with the highest recorded multi-mission doses for a U.S. astronauts estimated at approximately 240 mSv to 290 mSv. Even for astronauts with extensive flight histories, cumulative exposures remain below NASA's 600 mSv career limit. Russian cosmonauts have historically received slightly higher cumulative exposures, averaging 380–410 mSv, with a maximum of ~470–500 mSv reported after more than 1,110 days in low Earth orbit (LEO) [4].

In contrast, modern terrestrial radiation workers are exposed to significantly lower levels. The U.S. Department of Energy (DOE) occupational limit is 50 mSv per year, but most workers receive far less. DOE employees average under 0.5 mSv annually, with only 25% receiving measurable doses [5]. Navy Nuclear Propulsion Program personnel average 1.13 mSv per year, with lifetime exposures around 10 mSv [6]. Commercial aircrew accumulate roughly 3–6 mSv per year, depending on flight hours and solar activity [7].

For comparison, the general population receives about 3 mSv annually from natural background sources. Typical exposures from common events—such as a roundtrip flight from New York to London or a chest X-ray—are approximately 0.1 mSv.

Overall, astronaut radiation exposures are one to two orders of magnitude higher than those experienced by terrestrial workers or the general public. This underscores the unique and elevated risks astronauts face, particularly as operations move beyond LEO and mission durations lengthen.

IV. Radiation Protection and Exposure estimates for Moon to Mars Missions

Radiation standards have been established for vehicle shield design, real-time and personal monitoring, short-term exposure limits, and career limits [2]. For all Artemis missions, spacecraft designs and operations will ensure individual crew exposures from solar particle events and galactic cosmic radiation remain as low as reasonably achievable while meeting mission objectives. Crew exposures will vary based on solar activity, shielding, and mission duration. Crew will be informed of their overall risks from exposure for each upcoming mission. Post-mission, NASA provides for the long-term care of astronauts from health issues associated with spaceflight per the TREAT act [8].

A. Protection from Solar Particle Events (SPE)

Mitigation strategies for solar particle events (SPEs) are designed to keep crew exposure below NASA's short-term limit of 250 mSv [2]. Vehicles and habitats are being engineered with integrated storm shelters that offer effective protection while minimizing mass. NASA's standards provide specific guidance for shelter shielding design.

Crew safety during SPEs will rely on multiple layers of protection, including solar monitoring, forecasting tools, real-time dosimetry, and established operational protocols to ensure timely sheltering. For cis-lunar missions, NASA is advancing i) onboard and personal active dosimetry systems, and ii) more reliable SPE forecasting

capabilities. Mars missions present additional challenges due to Earth-independent operations. These include the need for compact onboard environmental monitoring systems and new infrastructure to monitor solar activity along the Mars–Sun line. Acute exposure estimates for major SPEs (e.g., the October 1989 event) are included in Table 1. Additional protection may needed for Mars transit trajectories that include a Venus swing-by (0.5 AU) where the intensity of a well-connected SPE an be magnified by a factor of ~2 to >4.

In rare cases of high-dose exposure, terrestrial countermeasures developed for accidental or deliberate radiation events may be repurposed to manage acute radiation syndromes in space.

B. Protection from Galactic Cosmic Radiation (GCR)

Galactic cosmic radiation (GCR) presents a chronic exposure risk due to its high energy and penetrating nature, making it much harder to shield against than SPEs. GCR flux is modulated by the 11-yr solar cycle: intensity is lowest during solar maximum and highest during solar minimum. As a result, estimated crew exposures behind standard spacecraft shielding are reduced by roughly a factor of two during solar maximum [9]. However, this benefit is counterbalanced by an increased likelihood of SPEs during the same period.

Effective GCR shielding is inherently limited by mass constraints. NASA's vehicle designs will be optimized to reduce GCR exposure by approximately 15% for vehicles in free space and 10% on planetary surfaces, as defined in NASA STD 3001 (see Table 1). These reductions can be achieved through optimized vehicle configurations, moderate amounts of shielding, and in some cases, material selection. Further reduction in GCR exposures – by any significant amount (>50%) - remains limited. Additional strategies to address the unique health risks posed by chronic GCR exposure over long-duration missions are under investigation.

Table 1: Estimated SPE exposures using the October 1989 spectrum and design shield thickness recommendations provided in NASA STD [2]; and GCR exposures assuming optimized shield design.

Location	Solar Maximum Conditions (Effective Dose)	Solar Minimum Conditions (Effective dose)	Comparison with ISS exposures
GCR - Free Space -	~0.6 mSv/yr	~1.3 mSv/yr	Dose rate ~two to three times higher than ISS
SPE - Free Space	<150 mSv Orion; ~100 mSv# to <250 mSv (limit)	-	
GCR - Lunar Surface	~0.4 mSv/yr	~0.9 mSv/yr	Protection from lunar surface and optimized shielding
SPE - Lunar Surface	~100 mSv*	-	
GCR - Martian Surface	~0.35 mSv/yr	~0.65 mSv/yr	Protection from Mars surface and thin atmosphere; unclear if moderate shielding provides much additional protection. Dose rate similar to ISS.
SPE Martian Surface	<25 mSv** (shielded) to ~40 mSv (unshielded)	-	

Estimate for October 1989 event with 20 g/cm^2 equivalent water shield as described in Ref. [2] for mission durations of > 6 months beyond LEO.

*Estimate for October 1989 event with 10 g/cm^2 equivalent water shield as described in Ref. [2] for missions to the lunar surface.

**Estimate for October 1989 with 10 g/cm^2 equivalent water shield as described in Ref. [2] for missions to the Martian surface and with no additional shielding provided (only planetary body and atmosphere) for comparison.

C. Mission Exposure Estimates

Mission exposures for NASA's Moon to Mars Exploration Segments [1] are described below. Estimates are based on values provided in Table 1 and assumed mission profiles. Moon-to-Mars mission exposures are described below and summarized in Table 2.

1. Human Lunar Return: Artemis II to III missions will be less than 30 days with estimated exposures between ≤ 20 mSv to ~ 30 mSv [10]. In the unlikely occurrence of a large solar proton event, the Orion spacecraft is designed to limit crew exposures to <150 mSv (more conservative than current standard). These exposures are well below our ISS experience and all crew – including experienced crew - should be eligible to participate and remain below the 600 mSv limit.

2. Foundational Exploration to Sustained Lunar Evolution: As NASA plans for longer crewed missions to the Moon—around the South Pole—operations and technology will be upgraded to support stays ranging from several months to years. The goal is to create a lasting presence and start building a lunar economy. For missions lasting 6 to 12 months, astronauts will be exposed to space radiation ranging from under 100 millisieverts (mSv) during solar maximum to about 350 mSv during solar minimum. These levels are similar to what astronauts experience on the International Space Station (200–300 mSv). A major solar storm could add around 100 mSv to sheltered crew. For longer stays, extra radiation protection may be needed, especially for astronauts with multiple missions or who are more sensitive to radiation, to help reduce long-term health risks including radiogenic cancer morbidity and mortality.

3. Humans to Mars: The Foundational Exploration phase aims to validate the technologies, capabilities, and systems required for the first crewed mission to Mars. Mission duration and surface stay times are primarily governed by orbital mechanics, ranging from *conjunction-class* missions—approximately three years in total with 300–500 sols on the Martian surface—to *opposition-class* missions, lasting approximately two years with 10–50 sols on the surface. A light-footprint, initial mission architecture has been iteratively developed over several design cycles and currently serves as a foundational reference within the broader mission trade space. Current Design Reference Missions (DRMs) emphasize short surface stays of approximately 30 sols, with total mission durations between 870 and 1,250 days.

Estimated radiation exposure for these profiles varies significantly depending on mission duration and solar cycle conditions, ranging from 525 mSv (870-day mission during solar maximum) to 1,625 mSv (1,250-day mission during solar minimum). In the event of a large Solar Particle Event (SPE) during transit, additional doses between 125–250 mSv may be incurred. On the Martian surface, such events may contribute an additional 25 mSv (with shielding) to ~40 mSv (unshielded). Overall, total mission exposures are projected to fall within the range of 1,000 to 1,200 mSv — roughly twice NASA's 600 mSv career exposure limit. These large exposures are expected to:

- Increase the risk of radiogenic cancers, with exposures well beyond current thresholds used to manage acceptable risk levels on ISS.
- Potentially cross dose thresholds associated with cardiovascular disease and late-onset neurocognitive impairments, although human data at these dose levels are limited and uncertainty remains regarding the magnitude of these risks.
- Introduce the possibility of in-mission central nervous system performance impairments, particularly due to chronic large GCR exposure in combination with other spaceflight stressors [11], though the likelihood of such effects is currently unknown.
- Exceed prior spaceflight experience by a factor of 2–3, resulting in significant knowledge gaps in predicting long-term health outcomes.

Solar activity and mission duration are the primary factors driving these large exposures. Further reductions remain challenging. Thick shielding or fast transits are mass prohibitive within current architecture constraints. Thus, it is likely an exception to NASA's radiation health standard would be needed, requiring clear risk communication and informed consent based on an ethical framework [12, 13]. Crew monitoring and development of preventive countermeasures are also deemed necessary to address both acute and long-term health impacts.

Table 2: Radiation Exposure, Health Risks, and Mitigation Strategies for Different Space Exploration Missions

Exploration Class Missions	Description/Duration	Estimated Exposure (Effective Dose, mSv)	Key Risks & Considerations
International Space Station (ISS)	6 – 8 months per flight opportunity	40 to 90 mSv per mission; Cumulative exposures vary between 240-290 mSv	Cumulative crew exposures maintained below 600 mSv limit. All crew are eligible for multiple/long-duration stays.
Human Lunar Return (Artemis II-III)	10 to 30 days total with varying surface stay times. Some crew expected to remain in lunar orbit.	GCR: < 20 to ~30 mSv SPE: 150 mSv transit/orbit SPE: <100 mSv surface	Well below ISS experience; All crew eligible to participate in short duration lunar missions without exceeding limit.
Foundational Exploration to Sustained Lunar Evolution	Months to several years on lunar surface.	GCR: <100 mSv (6 mos., solar max) to ~350 mSv (1yr, solar min) SPE: 150 mSv transit SPE: <100 mSv surface	Approaching/exceeding ISS crew mission exposures; Cumulative exposures increase risk of radiogenic cancers. Additional protection strategies may reduce health risks for most experienced crew and those most sensitive to radiation effects.
Humans to Mars	870 - 1250 days with stay times of 30-50 sols. Some crew may stay in Mars orbit.	~525 mSv (870 days, solar max) to 1650 mSv (1250 days, solar min)	Three to four times > ISS exposures; all reference missions exceed 600 mSv limit; In addition to cancers, increased risks to CNS function, cardiovascular disease, cerebrovascular, and neurocognitive diseases. Effects of the combined stressors of spaceflight unknown. Possibility for unknown unknowns. Risk levels are not well understood. Additional protection strategies required for all crew.

IV Quantifying Radiation Risks

Identifying space radiation–related health risks requires integrating data across a hierarchy of evidence, with human epidemiology, animal studies, and cellular models each playing distinct yet complementary roles. While astronaut data offer the most direct insight into spaceflight health risks, their utility is limited by small cohort sizes and reduced statistical power. Consequently, risk quantification often begins with terrestrial human cohorts exposed to gamma radiation, which provide epidemiological baselines for cancer and, to a lesser extent, cardiovascular and neurodegenerative outcomes. Translating these findings to the spaceflight context necessitates careful extrapolation using animal and cellular models to account for differences in radiation quality, dose rate, and other spaceflight-associated stressors.

A. Risk Model Framework

Figure 1 illustrates NASA's probabilistic cancer risk model, which integrates data across evidence tiers while explicitly quantifying uncertainty. The framework translates data from the acutely exposed 1945 Japanese population to a present-day healthy U.S. astronaut cohort chronically exposed to deep-space radiation. Excess risk estimates for

gamma radiation are adjusted using updated background disease rates for a never-smoking population. To extrapolate to the space environment, animal and cellular studies are incorporated to evaluate biological outcomes from space-relevant high-LET radiation versus gamma rays. Key endpoints—such as tumor incidence and DNA damage—support estimation of radiation quality and uncertainty magnitude. Human, animal, and cellular data collectively inform dose and dose-rate effectiveness factors (DDREF) [14, 15]. These adjusted values are then applied to mission-specific astronaut tissue exposures (Table 2) to calculate radiogenic cancer incidence (REIC) and mortality (REID) as probabilistic outcomes. Radiation quality and dose rate remain the largest contributors to model uncertainty [16].

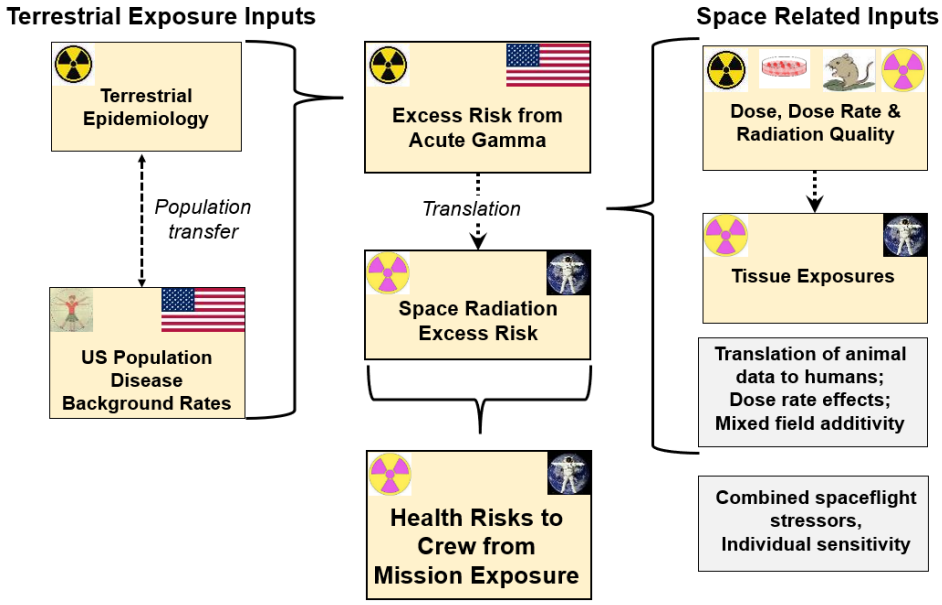

Fig. 1. Notional implementation of the NASA's cancer risk model illustrating the use of epidemiological and radiobiology datasets to scale cancer incidence and mortality in exposed terrestrial populations to space-based risk projections.

Similar frameworks are under consideration for cardiovascular disease (CVD) and late-onset central nervous system (CNS) risk projections [MERA project]. While the translation of terrestrial human radiation risk to space environments is most mature for cancer endpoints, the evidence base for CVD, early CNS impairments, and late-onset neurodegenerative conditions remains limited and continues to evolve. The Life Span Study (LSS) of atomic bomb survivors has produced inconsistent findings for radiation-induced CVD, particularly at the low to moderate doses relevant for spaceflight, with potential confounding from lifestyle uncertainties [17,18]. Direct human data on neurodegeneration due to space radiation effects are currently lacking; however, preliminary findings from the Million Person Study (MPS) suggest a possible link between low-dose occupational radiation and elevated risks for Parkinson's disease [19]. A pooled analysis of additional cohorts within the MPS is on-going to confirm whether a positive correlation holds.

B. Experimental Models

In vivo and *in vitro* studies using simulated space radiation provide mechanistic insights and supporting evidence for space radiation-induced pathologies. Integrating mechanistic insights into epidemiological models can improve risk estimates, especially at low to moderate doses where uncertainties are greatest [18]. Such studies are also vital for determining whether observed health outcomes stem from radiation or are confounded by other factors [19]. These studies are also critical in understanding biological responses to space radiation relative to gamma responses which is used to estimate radiation quality (Q).

Cardiovascular effects observed in rodent models—such as endothelial dysfunction, vascular inflammation, myocardial fibrosis, and accelerated atherosclerosis—mirror human CVD risk factors [20,21]. However, quantifying radiation quality (Q) for CVD remains challenging. The inability to detect consistent differences between gamma and

space-irradiated rodent cohorts underscores the need for higher-order animal models [22]. These studies should be performed in NASA's GCR Simulator to obtain a mixed field quality factor [23].

In the CNS, rodent models have shown changes in neurogenesis, synaptic plasticity, dopaminergic signaling, and heightened neuroinflammation following space radiation exposure [24]. However, correlating these molecular changes to cognitive and executive function deficits in rodents remains elusive. Lack of an established dose-response or other energy-deposition (i.e. fluence) relationship further complicates the ability to quantify the potential risk of early CNS impairments [25]. Translating these responses to humans remains particularly challenging, given species differences in physiology and radiation responses. A framework based on excess risk in irradiated human populations may not be feasible and new approaches may be needed [26 Harrivel] For long-term CNS health, inflammatory responses caused by radiation exposure are suspected in Parkinson's disease progression. However, no specific mechanism has been identified that correlates damage and Parkinson's disease mortality [19]. Collectively, animal studies and human epidemiology suggest potential risks to behavioral performance, cognition, and long-term neurological health for long duration missions.

Although in vitro cellular models occupy a lower tier in the evidence hierarchy, they provide critical mechanistic insights into radiation-induced injury. Studies using high-LET radiation have been shown to induce persistent DNA damage, mitochondrial dysfunction, and epigenetic alterations in vascular endothelial and neural progenitor cells [27,28]. These molecular responses help elucidate pathways leading to tissue and organ dysfunction and support the identification of potential targets for medical countermeasures. In addition to their mechanistic value, cellular data contribute to reducing uncertainties related to radiation quality (Q) and dose-rate effects.

C. Challenges in Risk Projections

While cancer risk models have matured quality factor models (albeit with large uncertainties), models of radiation quality for cardiovascular disease and CNS impairments need to be developed. Lack of CVD responses and a complicated dose-response curve for CNS decrements has hindered model development.

Replicating the chronic, low-dose exposure experienced in deep space remains a central challenge. Most experimental studies use fractionated GCR exposures over a 4- to 6-week period, which cannot fully replicate the continuous low-dose rates in space. While NASA's Space Radiation Laboratory is uniquely equipped for such simulations, dose-rate effects continue to represent a major source of uncertainty [16, 23].

In addition to radiation, astronauts face numerous spaceflight-related stressors—microgravity, isolation, confinement, and sleep disruption—that may compound health risks and impair in-mission performance. The interaction between these stressors and radiation exposure remains poorly understood, particularly for long-duration missions. These combined uncertainties affect projections for not only cancer, but also CNS function, cardiovascular health, degenerative tissue outcomes, and immune regulation. Additional data will be required to inform the development of risk models.

Current risk estimates are based on population models that do not incorporate individual genetic susceptibility, medical history, or emerging risk factors [29]. Integration of known and emerging risk factors aligns with the broader trend toward individualized medicine and can improve the fidelity of risk projections.

Mars mission exposures are expected to exceed NASA's current health standards by upto a factor of ~two. Tools to assess risk for crew informed consent and appropriate acceptance of risk by Agency decision makers are required [12]. Additional biological strategies to further reduce risks are needed as described below.

V Mitigating Risks

A. Medical Countermeasures

Biomedical countermeasures have the potential to reduce the long-term health effects of exposure to space radiation. Cross-risk countermeasures that reduce the risk of multiple late health outcomes (Cardiac and vascular diseases, CNS late neurocognitive impairments, accelerated aging, and cancers.), target common disease pathways (e.g., chronic inflammation, mitochondrial dysfunction, oxidative stress, DNA damage, etc.) and highly susceptible tissues should provide the greatest benefit. Identification and validation of radioprotectants and mitigators – including biological/immunological, pharmaceuticals and nutritional/dietary agents - will require ground-based testing in a space relevant environment and evaluation of efficacy in spaceflight. Time-serial analysis of crew samples and crew tests at pre-flight, in-flight, and several post-mission times can be used to ascertain early biological responses to space

radiation and establish a baseline for longer missions with higher exposures. These data can also be used to determine BCM usage to protect crew most susceptible to radiation effects. Clinical decisions will be required regarding the usage of verified pre-mission and in-flight countermeasures. Coordination with other human systems including provisions for safe pharmaceuticals, nutritious food systems, and exercise is needed.

No medical radiation countermeasures have been identified/validated to protect against long-term health effects. FDA approved countermeasures exist to protect against acute (high dose) terrestrial exposures and are most likely suitable for protection against an unanticipated exposure to a large SPE.

B. Biomarkers and Monitoring

Monitoring approaches using radiation biomarkers and technologies are part of an overall strategy to measure and control health risks to crew from space radiation exposure and other biological stressors during long duration spaceflight. Since individuals may vary in response to the effects of radiation, biomarkers can establish the biological state of an individual and inform a precision medical approach using tailored countermeasures and treatments. This requires development of a suite of validated biomarkers, measurement technologies, and associated decision thresholds that support the identification of susceptible crew preflight and inform clinical decision-making inflight. This capability should focus on the prevention of known adverse clinical outcomes including decrements to the central nervous system, hematopoietic, and immune systems as well as reducing the risk of long-term disease development including radiogenic cancers, cardiovascular, and neurodegenerative diseases. Appropriate biomarkers may include global indicators of radiation damage and response to the body, such as, chronic inflammation, alterations in genomic integrity, fidelity of DNA repair pathways, and other emerging evidence-based biomarkers.

VI Biological Research and Test Objectives

Research and test objectives in support of Artemis moon to Mars missions focus on several key areas to mitigate crew health risks:

- First, it is essential to perform research that quantifies risks from galactic cosmic radiation (GCR). This includes understanding the risk of cardiac and vascular diseases, as well as late neurocognitive impairments. For long duration Mars mission with exposures significantly exceeding 600 mSv, research aims to understand in-mission central nervous system (CNS) performance decrements. Evaluating impact of combined spaceflight hazards on risk and developing computational tools are vital components of this objective.

- Another priority is understanding the biology of individual sensitivity and susceptibility. Leveraging terrestrial radiation research from organizations such as the National Cancer Institute and the International Commission on Radiological Protection will be critical [30]. NASA unique biological research will be required to meet these objectives. This will enable personalized risk assessments and protection plans for all crew members.

- Ensuring *in situ* monitoring of crew health is also crucial to inform timely countermeasure deployment. This requires identifying measurable biomarkers of tissue injury or early disease indicators and validating these markers during space missions longer than six months.

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- Furthermore, the development of biological countermeasures to reduce adverse health outcomes is critical, with a focus on disease prevention. Countermeasures should target disease pathways common across risk areas such as chronic inflammation, mitochondrial dysfunction, oxidative stress, and DNA damage. Validating terrestrial approaches for space applications will enhance these efforts.

- Post-mission strategies involve leveraging advances in early detection and personalized treatments to enable safe return to flight for multiple missions and maintain a high quality of life for astronauts.

Ultimately, this comprehensive approach aims to mitigate health risks posed by space travel while enhancing crew resilience and long-term well-being.

VIII. Concluding Remarks

For NASA's first human mission to Mars, remaining near or below current permissible limits is out-of-reach. Mars missions limited to solar maximum can reduce GCR exposures by roughly a half. However, programmatic constraints and alignment of launch window opportunities may prove insurmountable for mission planning [9]. Breakthrough technologies such as cheap-mass-to-orbit to enable thick shield concepts or propulsion solutions for fast transit could also significantly reduce exposures. However, these concepts are mass prohibitive in the current architecture.

With expected mission exposures greater than career limits, NASA plans to inform and further protect crew from exposure to GCR during long-duration increments and Mars mission as follows:

- Provide tools to assess risk for crew informed consent and appropriate acceptance of risk by Agency decision makers (8900.1B requirement)
- Increase protection for crew which are most susceptible to radiogenic health risks and/or select most resilient crew for the longest durations
- Provide in-flight monitoring and preventative medical countermeasures
- Monitor long-term health of crew member > 5yrs post mission

The research plan presented here is closely aligned with M2M Blueprint objectives, emphasizing the safe return of crew and minimizing health impacts [1]. The plan focuses on investigating and understanding how humans respond and adapt to spaceflight hazards, including monitoring the effects of long-duration radiation exposure in deep space and lunar environments. By addressing these challenges, the plan aims to maintain high levels of human performance, health, and safety while reducing risks for future exploration missions.

IX References

1. NASA, *Moon to Mars Architecture Definition Document*, ESDMD-001, Rev. B, NASA/TP-20240015571, Dec. 2024. URL: https://www.nasa.gov/moontomarsarchitecture-architecturedefinitiondocuments/
2. NASA, *Space Flight Human System Standard*, NASA STD 3001, Vol. I, 2014.
3. Shavers, M. R., Semones, E. J., Tomi, L., Chen, J., Straube, U., Komiyama, T., Shurshakov, V., Li, C., and Rühm, W., "*Space Agency-Specific Standards for Crew Dose and Risk Assessment of Ionising Radiation Exposures for the International Space Station*," *Zeitschrift für Medizinische Physik*, Vol. 34, No. 1, 2024, pp. 14–30. https://doi.org/10.1016/j.zemedi.2023.06.005
4. Kononenko, O., "*Cosmonaut Exposure Profile*," *Wikipedia Entry*, URL: https://en.wikipedia.org/wiki/Oleg_Kononenko
5. U.S. Department of Energy, *Occupational Radiation Exposure Report for Calendar Year 2021*, Office of Environmental Health, Safety and Security, Jan. 2023.
6. Naval Nuclear Propulsion Program, *Occupational Radiation Exposure from U.S. Naval Nuclear Plants and Their Support Facilities*, U.S. Department of the Navy, May 2020.
7. United AFA, "*Cosmic Radiation Exposure*," URL: https://unitedafa.org/safety/cosmic-radiation/
8. NASA, "*Implementation of the TREAT Astronauts Act*," NASA Web Community Manager Robert E. Lewis, 16 Mar. 2023; last updated 11 Mar. 2025; accessed 12 Jun. 2025. URL: https://www.nasa.gov/directorates/esdmd/hhp/treat/implementation-of-the-treat-astronauts-act/
9. Turner, R., "*Impact of Solar Cycle Duration on Astronaut Radiation Exposure during a Human Mars Mission*," *51st International Conference on Environmental Systems (ICES)*, Saint Paul, MN, Jul. 10–14, 2022. URL: https://hdl.handle.net/2346/89570
10. Shavers, M. R., Semones, E. J., Shurshakov, V., Dobynde, M., Sato, T., Komiyama, T., et al., "*Comparison of Dose and Risk Estimates Between ISS Partner Agencies for a 30-Day Lunar Mission*," *Zeitschrift für Medizinische Physik*, Vol. 34, No. 1, 2024, pp. 31–43. https://doi.org/10.1016/j.zemedi.2023.10.005

11. Patel, Z. S., Brunstetter, T. J., Tarver, W. J., et al., "*Red Risks for a Journey to the Red Planet: The Highest Priority Human Health Risks for a Mission to Mars*," *npj Microgravity*, Vol. 6, 2020, Article No. 33. https://doi.org/10.1038/s41526-020-00124-6
12. NASA, *NASA Health and Medical Requirements for Human Spaceflight*, NPR 8900.1B, Appendix F, Mar. 2016. https://nodis3.gsfc.nasa.gov/displayDir.cfm?t=NPR&c=8900&s=1B
13. Institute of Medicine, *Health Standards for Long Duration and Exploration Spaceflight: Ethics Principles, Responsibilities, and Decision Framework*, National Academies Press, Washington, D.C., 2014. https://www.nap.edu/catalog/18576
14. Kocher, D. C., Apostoaei, A. I., Hoffman, F. O., and Trabalka, J. R., "*Probability Distribution of Dose and Dose-Rate Effectiveness Factor for Use in Estimating Risks of Solid Cancers from Exposure to Low-LET Radiation*," *Health Physics*, Vol. 114, No. 6, 2018, pp. 602–622. https://doi.org/10.1097/HP.0000000000000838
15. Cucinotta, F. A., Kim, M. Y., and Chappell, L. J., *Space Radiation Cancer Risk Projections and Uncertainties–2012*, NASA TP-2013–207375, 2013.
16. Simonsen, L. C., and Slaba, T. C., "*Improving Astronaut Cancer Risk Assessment from Space Radiation with an Ensemble Model Framework*," *Life Sciences in Space Research*, Vol. 31, 2021, pp. 14–28. https://doi.org/10.1016/j.lssr.2021.07.002
17. Little, M. P., "*Radiation and Circulatory Disease*," *Mutation Research*, Vol. 770, Part B, 2016, pp. 299–318.
18. Little, M. P., et al., "*Ionising Radiation and Cardiovascular Disease: Systematic Review and Meta-Analysis*," *BMJ*, Vol. 380, 2023, Article e072924. https://doi.org/10.1136/bmj-2022-072924
19. Dauer, L. T., Walsh, L., Mumma, M. T., Cohen, S. S., Golden, A. P., Howard, S. C., et al., "*Moon, Mars and Minds: Evaluating Parkinson's Disease Mortality Among U.S. Radiation Workers and Veterans in the Million Person Study*," *Zeitschrift für Medizinische Physik*, Vol. 34, No. 1, 2024, pp. 100–110. https://doi.org/10.1016/j.zemedi.2023.07.002
20. Tapio, S., Little, M. P., Kaiser, J. C., Impens, N., Hamada, N., Georgakilas, A. G., et al., "*Ionizing Radiation-Induced Circulatory and Metabolic Diseases*," *Environmental International*, Vol. 146, 2021, Article 106235. https://doi.org/10.1016/j.envint.2020.106235
21. Soucy, K. G., Limoli, C. L., and Boerma, M., "*Space Radiation and Cardiovascular Disease: From Low-Dose Research to Risk Prediction*," *npj Microgravity*, Vol. 6, No. 1, 2020, Article 11.
22. Groesser, T., Chen, H., Malanga, G., et al., "*Late Health Effects of Partial Body Irradiation Injury in a Minipig Model Are Associated with Changes in Systemic and Cardiac IGF-1 Signaling*," *Radiation Research*, Vol. 195, No. 4, 2021, pp. 387–396. https://doi.org/10.1667/RADE-20-00138
23. Simonsen, L. C., Slaba, T. C., Guida, P., and Rusek, A., "*NASA's First Ground-Based Galactic Cosmic Ray Simulator: Enabling a New Era in Space Radiobiology Research*," *PLOS Biology*, Vol. 18, No. 5, 2020, Article e3000669. https://doi.org/10.1371/journal.pbio.3000669
24. Britten, R. A., and Limoli, C. L., "*New Radiobiological Principles for the CNS Arising from Space Radiation Research*," *Life (Basel)*, Vol. 13, No. 6, 2023, Article 1293. https://doi.org/10.3390/life13061293
25. Wyrobek, A. J., and Britten, R. A., "*Individual Variations in Dose Response to Spatial Memory Learning Among Outbred Wistar Rats Exposed from 5 to 20 cGy of 56Fe Particles*," *Environmental and Molecular Mutagenesis*, Vol. 57, No. 4, 2016, pp. 331–340. https://doi.org/10.1002/em.22078
26. Harrivel, A., Blattnig, S., Norman, R., and Simonsen, L., "Planned Investigations to Address Acute Central Nervous System Effects of Space Radiation Exposure with Human Performance Data," in Ayaz, H., Asgher, U., and Paletta, L. (eds.), *Advances in Neuroergonomics and Cognitive Engineering*, AHFE 2021, Lecture Notes in Networks and Systems, Vol. 259, Springer, Cham, 2021, pp. 3–12. https://doi.org/10.1007/978-3-030-80285-1_1
27. Verma, R., Passerat de la Chapelle, F., Malkani, A., Juran, C., Boyko, V., Costes, S. V., and Cekanaviciute, E., "*Astrocytes Regulate Vascular Endothelial Responses to Simulated Deep Space Radiation in a Human Organ-on-a-Chip Model*," *Frontiers in Immunology*, Vol. 13, 2022, Article 864923. https://doi.org/10.3389/fimmu.2022.864923
28. Mitchell, A., Pimenta, D., Gill, J., Ahmad, H., and Bogle, R., "*Cardiovascular Effects of Cosmic Radiation and Microgravity: Implications for Future Human Deep Space Exploration*," *European Journal of Preventive Cardiology*, Vol. 26, No. 16, 2019, pp. 1707–1714. https://doi.org/10.1177/2047487319831497
29. Werneth, C. M., Patel, Z. S., Thompson, M. S., Blattnig, S. R., and Huff, J. L., "*Considering Clonal Hematopoiesis of Indeterminate Potential in Space Radiation Risk Analysis for Hematologic Cancers and Cardiovascular Disease*," *Communications Medicine*, Vol. 4, No. 1, 2024, Article 105. https://doi.org/10.1038/s43856-023-00408-4

30. Applegate, K., Dauer, L. T., and Brenner, D. J., "*Individual Response of Humans to Ionising Radiation: Governing Factors and Importance for Radiological Protection*," *Radiation and Environmental Biophysics*, Vol. 59, 2020, pp. 185–209. https://doi.org/10.1007/s00411-020-00846-4