Human Health and Performance: Keeping Astronauts Safe & Productive On a Mission to Mars

Introduction

NASA has been sending humans to space for more than 60 years, confronting the essential challenge of human spaceflight: that our bodies and minds evolved to live on Earth. Living and working off our planet, and on another planet, poses unique hazards to the human system. Understanding the effects of spaceflight on human physiology, psychology, and individual and team performance is essential to keep astronauts safe and healthy as exploration moves from low-Earth orbit to deep space destinations on and around the Moon and eventually Mars.

The five main hazards of human spaceflight are space radiation, isolation and confinement, distance from Earth, altered gravity fields, and hostile/closed environments. This paper will highlight how these hazards and the risks they pose to the human system influence NASA's Moon to Mars Architecture. These hazards are not always independent from one another; like human systems, the hazards are frequently coupled and interconnected, potentially causing synergistic effects or combined impacts.

Addressing the hazards and defining solutions will require a combination of human health and performance and engineering solutions. These solutions will be balanced with acceptable risks imposed on the crew and mission parameters such as duration, vehicle designs, operational considerations, and cost.

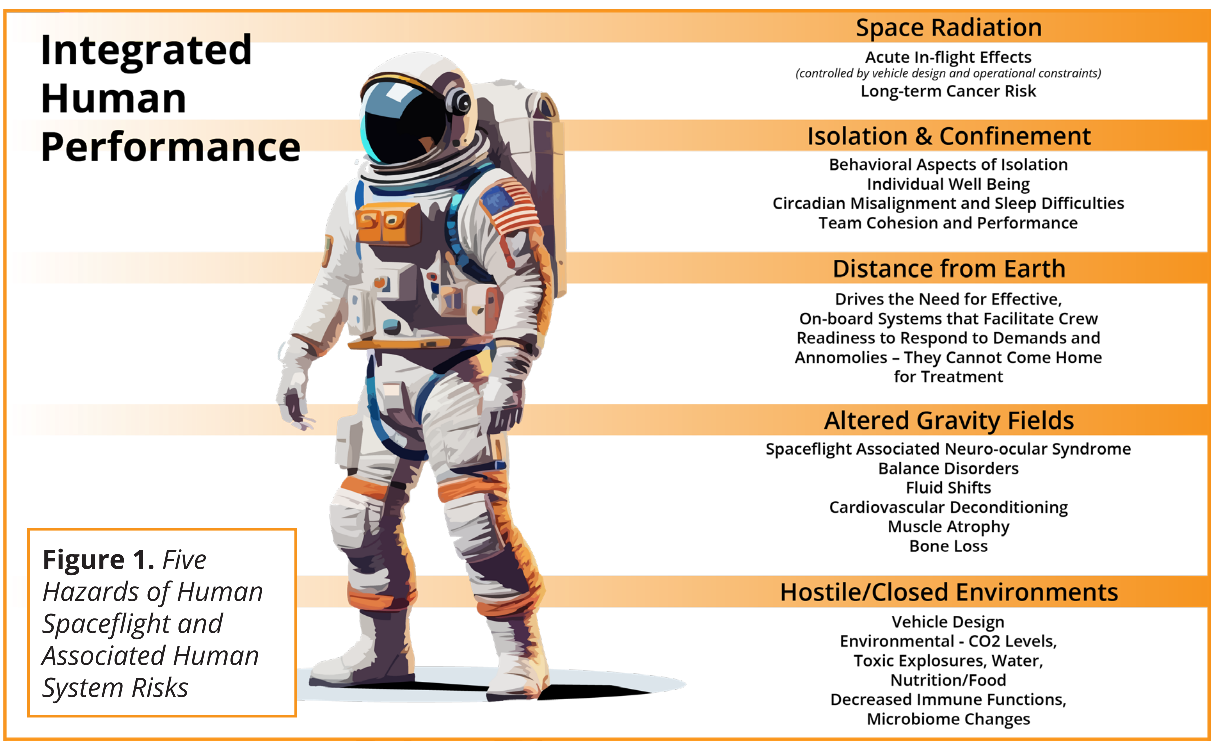

Figure 1. *Five Hazards of Human Spaceflight and Associated Human System Risks*

The following content integrates and summarizes NASA-STD-3001, NASA Spaceflight Human-System Standard Volume 1 and 2, which establishes agency standards that enable human spaceflight missions by minimizing health risks, providing vehicle design parameters, and enabling the performance of flight and ground crew. Applicability and tailoring of standards are determined based on each program's mission profile and procurement strategy.

Space Radiation

On a Mars mission, crew members will experience accumulated ionizing radiation exposure from galactic cosmic radiation and solar particle events. Solar particle events can expose astronauts to sudden increases in radiation, but the probability of a large event that would cause acute syndromes such as nausea and fatigue is extremely low (approximately 1 in 1,000). Shielding of spacecraft and habitats is effective against solar particle events, but only mitigates galactic cosmic radiation exposure by approximately 7–15 percent.

Deep space radiation exposure is a mitigated in-mission risk for acute radiation sickness. The consequences of spaceflight radiation exposure are an increased risk of cancer incidence and death later in life (post-mission), along with increased risk of cardiovascular disease.

The overall increase in cancer mortality for an average weight, non-smoking astronaut would increase from a probability of 15 percent over a lifetime to approximately 20 percent after a 1,000-day Mars trip (which is a 33 percent increase in lifetime mortality risk). Comparatively, an American who is overweight, drinks alcohol, consumes an average diet, and lives a less active lifestyle than a typical astronaut has an approximately 21 percent probability of dying from cancer.

For comparison, occupational controls for terrestrial radiation workers — such as personnel working at nuclear power plants or medical personnel using x-ray equipment — require radiation exposure to incur less than a 0.5 percent increase in mortality risk per year; nominally, exposure is controlled to incur less than a 0.1 percent increase in mortality risk per year.

Transit vehicles and habitat design guidance to minimize radiation exposure should consider the following factors:

- **Transit time and mission timing:** Minimize the total transit time between the planets to reduce the crew's radiation exposure, and plan transits during solar maximum to minimize galactic cosmic radiation exposure.
- **Engineering countermeasures:** Provide shielding from solar particle events using existing/planned vehicle mass. Use of consumables, including environmental control and life support system water/gray water, should be considered for solar particle event protection in lieu of polyethylene.
- **Optimized vehicle design and shielding materials:** Use existing mass to increase global cosmic radiation shielding to approximately 7–15 percent.
- **Monitoring/notification:** Provide onboard capabilities to detect, monitor, and characterize the radiation environment.

Isolation and Confinement

Future exploration missions will involve humans traveling further from Earth for longer mission durations. These missions will likely necessitate prolonged periods of isolation and confinement that pose a greater risk for behavioral health and performance. These hazards could lead to:

1. Adverse cognitive or behavioral conditions affecting crew health and performance during the mission.
2. The development of psychiatric disorders if adverse behavioral health conditions are undetected or inadequately mitigated.
3. Long-term health consequences, including late-emerging cognitive and behavioral changes.

Transit vehicles and habitat design guidance to mitigate various psychological stressors should consider the following factors:

- **Personal/private space:** Provide separate, individual sleeping/personal quarters with auditory isolation and physical separation (if possible) for each crew member. Private spaces separate from common spaces, social areas, and congested movement paths are preferred.
- **Workspace:** Allocate adequate volume and resources to accommodate everyone's work and activities (e.g., science, laboratory equipment, electronic curriculum).
- **Window:** Provide at least one window for direct viewing outside of the vehicle.
- **Cabin environmental controls:** Ensure each crew member can control cabin temperature, ventilation, lighting, humidity, and noise by placing individual controls and distribution vents in crew quarters and at workstations.
- **Communication with home:** Each private quarter should include communication systems that facilitate multiple modes of communication.
- **Crew composition:** Characteristics of expected range of crew composition (including team size, gender makeup, job roles, and cultural backgrounds), which are established before the mission.
- **Team coordination and collaboration:** Provide common areas with enough volume for the team to gather for recreation and dining, including screen access for communal viewing.
- **Human factors and habitation:** Spacecraft designers should use human-centric approaches to create optimal workload, habitable volume, and layout, ensuring adequate movement pathways and volume envelopes and access to rails and harnesses.

Distance from Earth

Mars is, on average, 140 million miles from Earth, with a one-way communication delay of up to 22 minutes. This distance will require astronauts to solve problems and identify solutions as a team, without immediate help from NASA's mission control.

As distance from Earth increases, spaceflight crews will, by necessity, become increasingly independent from mission control, and more dependent on their vehicle and logistics. This elevates the need for effective on-board systems that enable the crew to respond to demands and anomalies that may acutely arise.

This autonomy (or "Earth independence") must enable the astronauts to maintain, debug, and repair the vehicle. It must also allow them to monitor the state of their own health and wellbeing by accessing and using medical information in real-time operations and use decision support tools to reduce cognitive burden. Current plans entail years of training to prepare astronauts for such missions, increasing the risk that not all training will be retained (and/or retrievable).

Transit vehicles, habitats, and operational guidance to enable crew and vehicle autonomy should consider the following factors:

- **Integrated data architecture/decision support tools:** Implement a vehicle-integrated data architecture and decision support tools that enable crew to make decisions independently of immediate ground support.
- **Robust on-board medical capabilities:** Provide advanced prevention, diagnostic, treatment, and rehabilitation modalities.
- **Automation/robotic systems and human interaction:** Human operators need to maintain situational awareness to work effectively with automation.
- **Food and nutrition:** Provide safe, nutritious, and palatable food with sufficient calories, micronutrients, and macronutrients. Consider shelf life if food will be sent ahead of crew.
- **Maintainability:** Design for maintainability, with system-level optimization for parts and ergonomics. Consider tools and information as part of the design to consume minimal crew time.
- **Crew training:** Provide adaptable, in-mission training capabilities for crew.

Altered Gravity Fields

Astronauts will encounter different gravity fields on a Mars mission. On the multi-month trek between the planets, crews will be weightless in microgravity. While living and working on Mars, crews will have to adapt to a partial gravity environment (three-eighths of Earth's gravity), and upon returning home, crews will have to readapt to Earth's gravity. Landing a spacecraft on Mars could be challenging as astronauts adjust to partial gravity.

In addition to sensorimotor disruptions, crew members may have difficulty maintaining their blood pressure while standing, potentially leading to lightheadedness and fainting. Additionally, musculoskeletal unloading in microgravity will lead to decreased aerobic capacity, muscle strength, and bone quality and density (weight-bearing bones are estimated to lose about 1–1.5 percent mineral density per month spent in microgravity, which may lead to long-term changes in bone that increase fracture risk). Fluids in the body also shift upward to the head in microgravity, resulting in structural and functional changes to the eye and increases in the brain ventricular and perivascular volumes that can develop in flight and persist after flight (Spaceflight Associated Neuro-ocular Syndrome [SANS]).

Transit vehicle design, habitat design guidance, and egress/ingress/return considerations to mitigate various physiologic effects should consider the following factors:

- **Exercise:** Provide sufficient volume, mass allocation, and vehicle vibrational damping for physiological countermeasures.
- **Sensorimotor/balance:** Provide for in-flight sensorimotor countermeasures adaptation training to improve astronauts' performance. Operational timelines should reduce the number of critical activities for a defined period after a gravity transition to ensure crew performance, safety, and mission success. Extravehicular activity suit and rover design considerations can also be applied to address sensorimotor functioning.
- **SANS:** Provide sufficient volume and mass allocations for pharmaceutical or mechanical countermeasures.
- **Acceleration and dynamic loads:** Design the vehicle's acceleration/deceleration profiles and dynamic phases of flight for deconditioned crew members with reduced abilities (for both nominal/automated operations and manual crew control).
- **Anthropometrics:** Consider all operational gravity fields and environments, designing habitable volumes that ensure all crewmembers can perform any planned tasks efficiently and effectively.

Hostile/Closed Environments

The ecosystem inside habitats and spacecraft is crucial in everyday astronaut life. In space, enclosed environments (including vehicles and suits) do not have the benefit of natural CO2 removal, relying instead on CO2 removal equipment to help regulate CO2 levels and decrease the risk of negative consequences of elevated CO2 exposure. Additionally, lunar and Martian dust exposure could lead to serious health effects to the crew, such as respiratory, cardiopulmonary, ocular, or dermal harm.

To ensure environmental adequacy, transit vehicles, habitat design, and extravehicular activity planning guidance should consider the following factors:

- **Environmental control and life support system:** Provide clean air and adequate water quantities for consumption and hygiene. Manage air and water quality, waste, atmospheric parameters, and emergency response systems.
- **Countermeasures:** Mitigate the risk of infectious disease (viral and bacterial) and alterations to immunity (due to spaceflight stressors) through implementation of a pre-flight crew health stabilization program.

- **Atmospheric pressures/composition and materials/ flammability:** Consider differences in flammability in different atmospheric pressures and compositions. Vehicle and suit design should also incorporate on-board treatment of decompression sickness.
- **Dust mitigation:** Provide adequate air filtration systems to meet existing standards for dust exposure. Consider an airlock for ingress/egress to separate the vehicle hatch from the habitation area to further prevent contamination. Protect extravehicular activity suit joints and closures functions to prevent breaches.

Key Take-Aways

The human system is being considered early in vehicle design phases and operations for Mars architecture development. The architecture recognizes the five primary hazards of human spaceflight (space radiation, isolation and confinement, distance from earth, altered gravity fields, and hostile/closed environments) and balances risks with cost and design parameters. Missions may be comprised of consecutive segments that occur in different vehicles at different locations in space with varying distances from Earth and that last for different durations. However, the cumulative exposure to the five hazards over the entire mission duration needs to be considered to protect human health and performance. Shorter transit times to Mars would ameliorate many of the human system risks. Mars missions will require crew and vehicle autonomy, which will be a significant paradigm shift from current low-Earth orbit missions.

Additional Reading

1. NASA's Chief Health and Medical Officer, Technical Briefs, National Aeronautics and Space Administration, Washington, D.C. https://www.nasa.gov/ochmo/health-operations-and-oversight/hsa-standards/ochmo-technical-briefs/
2. NASA-STD-3001 VOL 1, NASA Space Flight Human-System Standard Volume 1, Revision A: Crew Health, National Aeronautics and Space Administration, Washington, D.C. (2022).
3. NASA-STD-3001 VOL 2, NASA Space Flight Human System Standard Volume 2: Human Factors, Habitability, and Environmental Health, National Aeronautics and Space Administration, Washington, D.C. (2022).
4. NASA's Human Research Program, The Human Body in Space, National Aeronautics and Space Administration, Washington, D.C. (2021) https://www.nasa.gov/hrp/bodyinspace
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6. NASA's Human Research Program, Human Research Roadmap, National Aeronautics and Space Administration, Washington, D.C. https://humanresearchroadmap.nasa.gov/
7. NASA's Human Research Program, 5 Hazards of Human Spaceflight, National Aeronautics and Space Administration, Washington, D.C. (2021) https://www.nasa.gov/hrp/hazards