Radiation and Human Exploration of Mars
Briefing to NAC

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Overview of Mars Mission Crew Health Risks

• Mission And Crew Health Risks Are Associated With Any Human Space Mission
  – Briefing is focused on space exploration crew health risks associated with space radiation

• Exploration Health Risks Have Been Identified, And Medical Standards Are In Place To Protect Crew Health And Safety
  – Further investigation and development is required for some areas, but this work will likely be completed well before a Mars mission launches

• There Are No Crew Health Risks At This Time That Are Considered “mission-stoppers” for a Human Mission to Mars
  – The Agency will accept some level of crew health risk for a Mars mission, but that risk will continue to be reduced through research and testing

• The Most Challenging Medical Standard To Meet For A Mars Mission Is That Associated With The Risk Of Radiation-induced Cancer
  – Research and technology development as part of NASA’s integrated radiation protection portfolio will help to minimize this long-term crew health risk
Human System Risk Board (HSRB) Identified 30 Human Spaceflight Health Risks

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

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

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

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

**Hostile/Closed Environment-Spacecraft Design**
1. Toxic Exposure
2. Acute & Chronic Carbon Dioxide Exposure
3. Hearing Loss Related to Spaceflight
4. Risk of reduced crew performance prior to adaptation to mild hypoxia.
5. Injury and Compromised Performance due to EVA Operations
6. Decompression Sickness
7. Injury from Sunlight Exposure
8. Incompatible Vehicle/Habitat Design
9. Inadequate Human-Machine Interface
10. Risk to crew health and compromised performance due to inadequate nutrition
11. Adverse Health Effects of Celestial Dust Exposure
12. Performance Errors Due to Fatigue Resulting from Sleep Loss, Circadian Desynchronization, Extended Wakefulness, and Work Overload
13. Injury from Dynamic Loads
14. Risk of Altered Immune Response
15. Risk of Electrical Shock

Each risk will be controlled by a NASA standard to protect crew health and safety
Mars Mission Human Health Risks

Based On The On-going HSRB Assessment, The Following Risks Are The Most Significant For A Mars Mission:

• Adverse affect on health
  ✧ space radiation exposure (long-term cancer risk)
  ✧ spaceflight-induced vision alterations
  ✧ renal stone formation
  ✧ compromised health due to inadequate nutrition
  ✧ bone fracture due to spaceflight induced bone changes
  ✧ acute and chronic elevated carbon dioxide exposure

• Inability to provide in mission treatment/care
  ✧ lack of medical capabilities
  ✧ ineffective medications due to long term storage

• Adverse impact on performance
  ✧ decrements in performance due to adverse behavioral conditions and training deficiencies
  ✧ impaired performance due to reduced muscle and aerobic capacity, and sensorimotor adaptation
Current Space Flight Health Standards

- NASA Should Be Able To Meet All Fitness for Duty (FFD) And Permissible Outcome Limits (POL) Standards For A Mars Mission
  - Based on long-duration ISS flight experience and mitigation plans

- Meeting The Current Low Earth Orbit (LEO) Space Radiation Permissible Exposure Limit (PEL) Standard Will Be Challenging For A Mars Mission
  - NASA exposure limit is the most conservative of all space agencies

<table>
<thead>
<tr>
<th>Area</th>
<th>Type</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>POL</td>
<td>Maintain bone mass at $\geq -2SD$</td>
</tr>
<tr>
<td>Cardiovascular</td>
<td>FFD</td>
<td>Maintain $\geq 75%$ of baseline VO2 max</td>
</tr>
<tr>
<td>Neurosensory</td>
<td>FFD</td>
<td>General Sensory Motor, Motion Sickness, Perception, Gaze Control</td>
</tr>
<tr>
<td>Behavioral</td>
<td>FFD</td>
<td>Maintain nominal behaviors, cognitive test scores, adequate sleep</td>
</tr>
<tr>
<td>Immunology</td>
<td>POL</td>
<td>WBC $&gt; 5000/\text{ul}; \text{CD4}^+ T &gt; 2000/\text{ul}$</td>
</tr>
<tr>
<td>Nutrition</td>
<td>POL</td>
<td>$90%$ of spaceflight-modified/USDA nutrient requirements</td>
</tr>
<tr>
<td>Muscle</td>
<td>FFD</td>
<td>Maintain $80%$ of baseline muscle strength</td>
</tr>
<tr>
<td>Radiation</td>
<td>PEL</td>
<td>$\leq 3%$ REID (Risk of Exposure Induced Death, 95% C.I.)</td>
</tr>
</tbody>
</table>
Galactic cosmic rays (GCR) – penetrating protons and heavy nuclei

Solar Particle Events (SPE) – low to medium energy protons

What are the levels of radiation in deep space and how does it change with time?

How much radiation is inside the spacecraft, on Mars surface and in the human body?

What are the health risks associated with radiation exposure?

How do we mitigate these health risks?

SMD R&D
Helio- & Astrophysics
Characterize/measure
Modeling/Prediction & Real-time Monitoring

HEOMD R&D
Radiation Transport Code Development
Transport of radiation into body
Tissue/Organ doses

Cancer risks
Acute radiation
Non-cancer risks

NSRL research
Spacecraft Shielding
Bio-Countermeasures
Medical Standards
## Health Risk Areas

### Carcinogenesis
Space radiation exposure may cause increased cancer morbidity or mortality risk in astronauts

- Cancer risk model developed for mission risk assessment
- Model is being refined through research at NASA Space Radiation Laboratory (NSRL)
- Health standard established

### Acute Radiation Syndromes from SPEs
Acute (in-flight) radiation syndromes, which may be clinically severe, may occur due to occupational radiation exposure

- Acute radiation health model has been developed and is mature
- Health standards established
- Operational & shielding mitigations are understood & risk area is controlled

### Degenerative Tissue Effects
Radiation exposure may result in effects to cardiovascular system, as well as cataracts

- Non-cancer risks (Cardiovascular and CNS) are currently being defined
- Research is underway at NSRL and on ISS to address these areas
- May need appropriate animal models to assess clinical significance

### Central Nervous System Risks (CNS)
Acute and late radiation damage to the central CNS may lead to changes in cognition or neurological disorders
Mars Mission Space Radiation Risks

Mars Missions May Expose Crews To Levels Of Radiation Beyond Those Permitted By The Current Standard (≤ 3% REID, 95% C.I.)

- May increase the probability that a crewmember develops a cancer over their lifetime
- May also have undefined health effects to central nervous system and/or cardiovascular system; these areas are currently under study

Mars Missions Cancer Risk Calculations

- Calculations use 900-Day conjunction class (long-stay) trajectory option for Mars mission (500 days or more on Mars surface)
  - Exposure levels are about the same for opposition-class (short-stay) trajectory option

- Based on 2012 NASA Space Radiation Cancer Risk Model as recommended by the National Council on Radiation Protection and National Academies
  - Model calculates risk of exposure induced death (REID) from space radiation-induced cancer with significant uncertainties
  - Mars surface calculations include shielding by the planet, atmosphere, & lander
  - Calculations take into range of solar conditions and shielding configuration
## Post Mission Cancer Risk For A 900-day Mars Mission

<table>
<thead>
<tr>
<th>Mars Mission Timing</th>
<th>Mission Shielding Configuration</th>
<th>Calculated REID, 95% C.I. (Age=45, Male-Female)</th>
<th>Amount Above 3% Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Max</td>
<td>Good shielding like ISS (20 g/cm²) w/no exposure from SPEs</td>
<td>4% - 6%</td>
<td>1% - 3%</td>
</tr>
<tr>
<td>Solar Max</td>
<td>Good shielding like ISS (20 g/cm²) w/large SPE</td>
<td>5% - 7%</td>
<td>2% - 4%</td>
</tr>
<tr>
<td>Solar Min</td>
<td>Good shielding like ISS (20 g/cm²)</td>
<td>7% - 10%</td>
<td>4% - 7%</td>
</tr>
</tbody>
</table>

**NASA Standards Limit The Additional Risk Of Cancer Death By Radiation Exposure, Not The Total Lifetime Risk Of Dying From Cancer**

- Baseline lifetime risk of death from cancer (non-smokers): 16% males, 12% females
- After Mars Mission (solar max), Astronauts lifetime risk of death from cancer ~20%

**Mars Space Radiation Risk For Solar Max Can Be Explained As Follows**

- If 100 astronauts were exposed to the Mars mission space radiation, in a worst case (95% confidence) 5 to 7 would die of cancer, later in life, attributable to their radiation exposure and their life expectancy would be reduced by an average on the order of 15 years
- Challenging to use a population-based risk model to estimate individual risk for the few individuals that would undertake a Mars Mission
Optimize human radiation protection by integrating research, operations and development activities across the agency.
Reducing Mars Mission Radiation Risks

NASA is working across all phases of the Mars mission to minimize the space radiation health risk:

**Pre-Mission**
- **Radiation Factors**
  - Individual Sensitivity – Biomarkers*
  - Selection – age, gender
  - Model Projection of Risk
  - Space Radiation Envir. Model
- *long-term development

**In-Mission**
- **Radiation Factors**
  - Shielding
  - Mission Duration
  - Solar Min vs. Max
  - Ops Planning
  - Dosimetry
  - Countermeasures*
    - Pharmaceutical/Nutritional

**Post-Mission**
- **Radiation Factors**
  - Occupational Health Care for Astronauts**
    - Additional Cancer Screening, Biomarkers
    - Cancer Treatment
- **requires legislative authorization**

**Reduction in Total Risk Posture**
Reducing Radiation Health Risks

Space Radiation Research at NSRL
• Key to reducing the space radiation health effects uncertainties, refinement of cancer risk model, and understanding cardiovascular and CNS risks

Space Radiation Environment Characterization
• LRO-CRaTER measurements of radiation environment
• Solar Energetic Particle real-time monitoring and characterization
• MSL-RAD Measurements of radiation environment during transit and on the surface of Mars

Medical Approaches Applied Pre-/Post-Mission
• Understanding the individual sensitivities and enhancing post mission care are the key areas that can significantly reduce the space radiation risk

Exploration Space Radiation Storm Shelter Design and Real-time Radiation Alert System
• Development of these capabilities for exploration missions can reduce crew exposure risk to SPEs to negligible levels

Mars Mission Design and Deep Space Propulsion
• Reducing deep space transit times can reduce space radiation exposure and mitigate human health risks
Summary

Based on current mitigation plans for Crew Health and Performance Risks, NASA can support a Mars Mission

• Mars Mission Health Risks Have Been Identified And Medical Standards Are In Place To Protect Crew Health And Safety
  – While there is a fair amount of forward work to do, there are no crew health risks at this time that can be considered “mission-stoppers”
  – There will be a level of crew health risk that will need to be accepted by the Agency to undertake a Mars mission, but that risk will continue to be reduced through R&D

• Based on present understanding of risks and standards
  – Some risks (bone, muscle, aerobic, isolation & confinement) current countermeasures require further validation
  – Additional data needed to fully quantify some risks (vision impairment, CO₂ exposure)
  – Renal stone risk also needs additional data to develop treatment/prevention modalities
  – Some risks (nutrition, exercise) require optimization in order to support a Mars Mission
  – Pharmaceutical & food stability/shelf life needs to be improved for a Mars Mission
  – Behavioral health impacts need to be further minimized
  – The radiation standard would not currently be met
Long duration and exploration class space missions beyond low Earth orbit may pose hazards that go beyond current risk limits, where current health/medical standards cannot be met or the level of knowledge doesn’t permit a standard to be developed.

OCHMO requested the Institute of Medicine’s Committee on Aerospace Medicine and Medicine in Extreme Environments to produce a report on policy and ethical issues and principles relevant to crew health standards for long-duration and exploration space missions. Committee was asked to:

- Consider the application of existing health standards and the factors that should be considered in implementing them and the potential development of new health standards.

- Provide a framework of ethical and policy principles that can help guide decision-making associated with implementing health standards for exploration class space missions when existing standards cannot be fully met, or the level of knowledge of a given condition is sufficiently limited that an adequate standard cannot be developed, for the mission.
“Health Standards for Long Duration and Exploration Spaceflight: Ethics Principles, Responsibilities, and Decision Framework” (April, 2014)

The report makes 4 recommendations:

- The first 3 recommendations are directed at how OCHMO develops and implements health and medical standards.

- The fourth recommendation provides a decision-making framework, with 3 levels, based on the ethical principles and responsibilities that can be used when a health/medical standard(s) cannot be met, or when there are health/medical risks that are not fully understood, for a proposed space exploration mission.
Adopt an Ethics-Based Decision Framework

• NASA should apply the relevant ethics principles and fulfill the concomitant responsibilities through a three-level, ethics-based decision framework that examines:
  
  – Level 1: Decisions about allowing risk to astronaut health and safety in excess of that permitted by health standards,
  
  – Level 2: Decisions about undertaking specific missions, and
  
  – Level 3: Decisions concerning individual astronaut participation and crew composition.
Ethics Principles & Responsibilities

Principles

– Avoid Harm
– Beneficence
– Favorable balance of risk and benefit
– Respect for autonomy
– Fairness
– Fidelity

Responsibilities

– informed decision-making process
– continuous learning strategy
– independent advice
– communicate with all relevant stakeholders
– equality of opportunity
– provide preventive long-term health screening and surveillance of astronauts
– protect privacy and confidentiality
If a human spaceflight mission cannot meet NASA’s current health standards, or if inadequate information exists to revise a health standard, the committee identified and examined 3 options:

• Liberalizing existing health standards
  - Current standards based on best available data
  - Modifying outside of established process is arbitrary

• Establishing more permissive health standards for long duration and exploration class missions
  - No clear and compelling justification for why acceptable risks and levels of uncertainty should be greater for long duration/exploration space missions

• Only ethically acceptable option that could allow for increased risk exposures in the context of long duration and exploration spaceflight is granting an exception to existing health standards.
  - Excepting health standards in these situations should be “used under very limited circumstances following the ethics based framework recommended” and that “exceptions increase the responsibilities for NASA and society.”
The selection of the process and criteria to grant exceptions to existing health standards should be evidence-based and should reflect policies that encourage independent advice and transparency of process.

Based on the ethics principles identified, criteria for reviewing exception requests could include requirements that the proposed mission:

- be expected to have exceptionally great social value,
- have great time urgency,
- have expected benefits that would be widely shared,
- be justified over alternate approaches to meeting the mission’s objectives,
- be committed to minimizing harm and continuous learning,
- have a rigorous process to assure that astronauts are fully informed about risks and unknowns,
- their decisions meet standards of informed decision making, and that they are making a voluntary decision, and
- provide health care and health monitoring for astronauts before, during, and after flight and for the astronaut’s lifetime.
OCHMO concurs that excepting health standards (or lack of standards due to limited knowledge) should be “used under very limited circumstances” and would only be excepted at the Agency Level after careful assessment of the risk and benefits with ethical principles guidance.

Would not represent a standard medical waiver

Processes for implementing all 3 levels of decision making developed within the context of the Agency’s overall risk assessment processes:

- health/medical risk analysis
- combined with total mission risk analysis – safety, engineering, health/medical
- individual risk assessment
- balancing of competing ethical principles
- operational justification for standard excepting

Operational exception is under the authority of the Administrator
Summary

• There are a number of formidable human health challenges involved in a Mars mission – radiation is among the foremost of those risks
• Currently, we would exceed career radiation dosage limits for astronauts engaging in a mission to Mars
• There is a collaborative effort underway to fully measure and understand the radiation environments encountered in a Mars mission
• There is a robust research program underway to reduce radiation exposures and to provide radiation countermeasures
• We have developed a process to except the career radiation standard for individual astronauts based on ethical principles and responsibilities, with advice from the Institute of Medicine
• Radiation does not represent an insurmountable barrier to Mars mission planning and execution
BACKUP
Report Implementation

• While the report recommendations relate to health/medical standards, some of the details of the decision making that is needed to implement them involves several Agency stakeholders.

• Implementing report recommendations within the context of existing Agency decision making processes.

• Since the recommendations are related to OCHMO’s development and implementation of health and medical standards and OCHMO executes its responsibilities in this area through its role as the Agency’s Health and Medical Technical Authority (HMTA), the implementation of the recommendations developed in the context of OCHMO as the HMTA.