Space Radiation Issues for Manned Spaceflight

AMS-02 Workshop October 23, 2015

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

**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?

SMD R&D
Helio- & Astrophysics Characterization/ measurement
Modeling/Prediction & Measurements

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

What are the health risks associated with radiation exposure?

Cancer risks
Acute radiation
Non-cancer risks

How do we mitigate these health risks?

NSRL research
Spacecraft Shielding
Bio-Countermeasures
Medical Standards
### Space Radiation Health Risks

#### Health Risk Areas

<table>
<thead>
<tr>
<th>Carcinogenesis</th>
<th>Status</th>
</tr>
</thead>
</table>
| 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 |

<table>
<thead>
<tr>
<th>Acute Radiation Syndromes from SPEs</th>
<th>Status</th>
</tr>
</thead>
</table>
| 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 |

<table>
<thead>
<tr>
<th>Degenerative Tissue Effects</th>
<th>Status</th>
</tr>
</thead>
</table>
| 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 |

<table>
<thead>
<tr>
<th>Central Nervous System Risks (CNS)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acute and late radiation damage to the central CNS may lead to changes in cognition or neurological disorders</td>
<td>-</td>
</tr>
</tbody>
</table>
Major Sources of Uncertainty in Estimating Risks from Space Radiation for Exploration Missions

- Radiation quality effects on biological damage
  - Qualitative and quantitative differences between space radiation compared with x-rays or gamma rays

- Dependence of risk on dose rates in space
  - Biology of repair, cell, and tissue regulation

- Extrapolation from experimental animal data to humans

- Individual radiation sensitivity
  - Genetic, dietary and healthy worker effects

- Predicting galactic cosmic ray solar min/max conditions at future time points

- Predicting solar events
  - Temporal and size predictions
NASA Permissible Exposure Limits (PELs)

Cancer

- NASA Standard is 95% Confidence level for Risk of Exposure Induced Death (REID) less than 3%.
  - Less than 1 in 33 chance of early death
  - Best estimate is multi year life loss for space radiation attributable cancer

- Limit of 3% fatal cancer risk based on 1989 comparison of risks in “less-safe” industries

- NCRP-132 carried this forward with comparison to ground based standards.
  - Current PELs are set to limit Central Nervous System (CNS) and circulatory disease risks from space radiation
  - Protection further provided by cancer REID PEL

95% confidence is conservative and is intended to account for uncertainties inherent in risk projection model – vary from 50% - <300%

Epidemiology data (statistics, bias, transfer to US population)
Dose-rate reduction factors
Biological response to space radiation, Q
Organ dose equivalent assessment measurement dosimetry, space environment, radiation transport models
The NASA Space Cancer Risk (NSCR)* model was reviewed by the National Research Council in 2012 (last NASA model update was 2005).

- Basis for estimating crew risks for ISS missions and trade studies of future Exploration Class missions
- Only considers the risk of carcinogenesis
- Includes up to date GCR environment (Badhwar-O’Neill 2011/2014), AP8/E8 trapped radiation environment, and radiation transport (HZETRN), for comprehensive dosimetry evaluation
- Provides estimate of cancer incidence and mortality
  - Age and Gender Specific Risks
- Slope for age modification 1.3:1 from age 35 to 55
- Risk model utilizes astronaut healthy population characteristics (lifetime never-smokers), lowers space radiation risk compared to U.S. Avg. population of about 20%
- New Quality Factors and improved Uncertainty estimates

Model utilizes data/information from:

Astronaut Cancer Risk Analyses
Risk Assessment Flow

NASA NSCR Cancer Risk Assessments and Projections

Environment Models
- GCR (BON-2011)
- Trapped Proton (AP-8)
- Environment Model Normalization

Shielding Models
- Phantom (CAM/CAF)
- ISS Vehicle (CAD)

Radiation Transport
- HZE, n, EM, π/µ
- BRYNTRN (trapped protons)
- HZETRN lookup tables (GCR)

NSCR-2012 Cancer Risk Model
- NASA REID pt estimate
- NASA Mixture
- ERR Baseline (SEER,)

ISS Passive Area Dosimeters
Passive Monitoring Locations - Example
Original ISS Operational Instruments Provide Real-time Dosimetry and Alarming

EV/IV detailed radiation survey information
ISS Dosimetry – low dose/dose rates

- Current estimate of NASA Effective Dose Rate in 2017: 0.6 mSv/day
## NSCR-2012 Model Inputs

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Example Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Crewmember Parameter</strong></td>
<td></td>
</tr>
<tr>
<td>Sex</td>
<td>Sex-based risk parameters</td>
</tr>
<tr>
<td>Smoking status</td>
<td>organ-risk dependence</td>
</tr>
<tr>
<td>Birthdate</td>
<td>Age at exposure</td>
</tr>
<tr>
<td><strong>Mission Parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Launch date</td>
<td>Calculate mid-mission date</td>
</tr>
<tr>
<td>Land date</td>
<td>Calculate mid-mission date</td>
</tr>
<tr>
<td>Altitude &amp; orbit inclination</td>
<td>Trapped proton env.</td>
</tr>
<tr>
<td><strong>Space Weather</strong></td>
<td></td>
</tr>
<tr>
<td>Avg sunspot number</td>
<td>GCR modulation</td>
</tr>
<tr>
<td>Avg F10.7 radio flux</td>
<td>Trapped proton env.</td>
</tr>
<tr>
<td>Avg GCR - Phi</td>
<td>Modulation parameter</td>
</tr>
<tr>
<td><strong>Shield Models</strong></td>
<td></td>
</tr>
<tr>
<td>Vehicle CAD</td>
<td>Shielding</td>
</tr>
<tr>
<td>Phantom (male/female)</td>
<td>Self-shielding</td>
</tr>
<tr>
<td><strong>ISS Area Dosimeters</strong></td>
<td></td>
</tr>
<tr>
<td>RAMs (x4)</td>
<td>Normalize trapped protons</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Example Results for ISS Mission

**Solar Minimum Activity, altitude 400 km, Male, age 57, never-smoker**

### Crewmember Parameter
- **Sex**: Sex-based risk parameters
- **Smoking status**: organ-risk dependence
- **Birthdate**: Age at exposure

### Mission Parameters
- **Launch date**: Calculate mid-mission date
- **Land date**: Calculate mid-mission date
- **Altitude & orbit inclination**: Trapped proton env.

### Space Weather
- **Avg sunspot number**: GCR modulation
- **Avg F10.7 radio flux**: Trapped proton env.
- **Avg GCR - Phi**: Modulation parameter

### Shield Models
- **Vehicle CAD**: Shielding
- **Phantom (male/female)**: Self-shielding

### ISS Area Dosimeters
- **RAMs (x4)**: Normalize trapped protons

<table>
<thead>
<tr>
<th>Organ</th>
<th>D(mGy)</th>
<th>H(mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stomach</td>
<td>88.77</td>
<td>210.15</td>
</tr>
<tr>
<td>Colon</td>
<td>101.98</td>
<td>237.98</td>
</tr>
<tr>
<td>Liver</td>
<td>93.02</td>
<td>219.11</td>
</tr>
<tr>
<td>Lung</td>
<td>98.47</td>
<td>230.77</td>
</tr>
<tr>
<td>Breast</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Prostate</td>
<td>109.08</td>
<td>252.14</td>
</tr>
<tr>
<td>Uterus</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Ovary</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Bladder</td>
<td>87.09</td>
<td>206.55</td>
</tr>
<tr>
<td>Esophagus</td>
<td>96.98</td>
<td>227.67</td>
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<tr>
<td>Brain-CNS</td>
<td>118.11</td>
<td>272.04</td>
</tr>
<tr>
<td>Thyroid</td>
<td>107.78</td>
<td>250.35</td>
</tr>
<tr>
<td>OralCavity</td>
<td>107.78</td>
<td>250.35</td>
</tr>
<tr>
<td>Remainder</td>
<td>103.57</td>
<td>241.40</td>
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<tr>
<td>EffectiveSolid</td>
<td>97.72</td>
<td>229.03</td>
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<tr>
<td>BoneMarrow</td>
<td>103.57</td>
<td>137.53</td>
</tr>
<tr>
<td>NASA_Eff_Dose</td>
<td>97.72</td>
<td>229.03</td>
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<tr>
<td>Heart</td>
<td>108.61</td>
<td>266.79</td>
</tr>
<tr>
<td>Skin</td>
<td>142.90</td>
<td>320.97</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Organ</th>
<th>REIC [%]</th>
<th>REID [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leukemia</td>
<td>0.13594</td>
<td>0.07175</td>
</tr>
<tr>
<td>Stomach</td>
<td>0.11448</td>
<td>0.06597</td>
</tr>
<tr>
<td>Colon</td>
<td>0.14064</td>
<td>0.0659</td>
</tr>
<tr>
<td>Liver</td>
<td>0.05378</td>
<td>0.04606</td>
</tr>
<tr>
<td>Bladder</td>
<td>0.27221</td>
<td>0.06726</td>
</tr>
<tr>
<td>Lung</td>
<td>0.16625</td>
<td>0.14858</td>
</tr>
<tr>
<td>Esophagus</td>
<td>0.01618</td>
<td>0.01523</td>
</tr>
<tr>
<td>OralCav</td>
<td>0.02057</td>
<td>0.00624</td>
</tr>
<tr>
<td>Brain-CNS</td>
<td>0.01243</td>
<td>0.01078</td>
</tr>
<tr>
<td>Thyroid</td>
<td>0.00073</td>
<td>0.00011</td>
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<tr>
<td>Skin</td>
<td>0.0011</td>
<td>0.00087</td>
</tr>
<tr>
<td>Remainder</td>
<td>0.05429</td>
<td>0.02514</td>
</tr>
<tr>
<td>Prostate</td>
<td>0.17103</td>
<td>0.03627</td>
</tr>
<tr>
<td>TotalSolid</td>
<td>1.0237</td>
<td>0.48843</td>
</tr>
<tr>
<td>Total(sol+leuk)</td>
<td>1.16944</td>
<td>0.56017</td>
</tr>
</tbody>
</table>

Heff = 290 mSv
GCR Dose Rates in Free Space

- NASA Effective Dose are 
  ~500 mSv/year in Solar min
  - 1.36 mSv/day
- Influence of body shielding
- # Safe Days are based on these calculated doses

NASA Radiation Risk Prediction Model

**Solar Minimum Safe Days**

in Deep Space Maximum Days in Deep Space to have 95% Confidence Level to be below the NASA Limit of 3%. Calculations are for average solar minimum with 20g/cm² of aluminum shielding. Values in parenthesis is deep solar minimum of 2009.

<table>
<thead>
<tr>
<th>aₜ, y</th>
<th>NASA 2012 Never-smokers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males</td>
</tr>
<tr>
<td>35</td>
<td>271 (256)</td>
</tr>
<tr>
<td>45</td>
<td>308 (291)</td>
</tr>
<tr>
<td>55</td>
<td>351 (335)</td>
</tr>
<tr>
<td></td>
<td>Females</td>
</tr>
<tr>
<td>35</td>
<td>187 (180)</td>
</tr>
<tr>
<td>45</td>
<td>227 (212)</td>
</tr>
<tr>
<td>55</td>
<td>277 (246)</td>
</tr>
</tbody>
</table>

**Solar Maximum Safe Days**

in Deep Space to have 95% Confidence Level to be below the NASA Limit of 3%. Calculations are for average solar maximum assuming large August of 1972 SPE with 20g/cm² aluminum shielding. Values in parenthesis without the 1972 SPE event and ideal storm shelters/monitoring which would reduce SPE doses to negligible amounts.

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<tr>
<td></td>
<td>Males</td>
</tr>
<tr>
<td>35</td>
<td>395 (458)</td>
</tr>
<tr>
<td>45</td>
<td>456 (526)</td>
</tr>
<tr>
<td>55</td>
<td>500 (615)</td>
</tr>
<tr>
<td></td>
<td>Females</td>
</tr>
<tr>
<td>35</td>
<td>276 (325)</td>
</tr>
<tr>
<td>45</td>
<td>319 (394)</td>
</tr>
<tr>
<td>55</td>
<td>383 (472)</td>
</tr>
</tbody>
</table>

Higher GCR
Lower SPE

Lower GCR
Higher SPE
### 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
Mitigation Approaches

• Crew Selection
  - Age, gender, lifestyle factors, etc.
  - Individual Sensitivity (genetic factors

• Mission date-time in the Solar Cycle

• Ability to minimize exposure to SPE’s
  - Real time spectral measurements
  - Radiation Shielding
    - Amounts and material types
    - Design Optimization

• Biological Countermeasures (BCMs)
  - Radioprotectors / Mitigators

• Biomarkers predictive of radiation induced diseases
  - Future individualized risk assessment
  - Early detection and prognostic monitoring

Variation of Solar Activity

Individual Susceptibility

(NCRP 2011)
Active Radiation Area Monitoring:
REM: Radiation Event Monitor
limited particle + dose
HERA: Hybrid Electronic Radiation Assessor
limited particle + dose; will be tech-demoed on ISS
IV-TEPC: Intra-Vehicle Tissue Equivalent Proportional Counter
broad sensitivity dosimeter
Charged Particle Spectrometer (CPS):
Current technology is ISS-Radiation Assessment Detector (RAD)
Neutron Spectrometers:
ISS-RAD, Fast Neutron Spectrometer (FNS)

Passive Radiation Area Monitoring:
RAM: Radiation Area Monitor
CPD: Crew Passive Dosimeter
Uses same technology as RAM; may be replaced with PRD (right)

Active Radiation Area Monitoring:
HERA: Hybrid Electronic Radiation Assessor
limited particle + dose; planned for EM-1, EM-2
Charged Particle Spectrometer (CPS): TBD
Neutron Spectrometers: TBD

Active Personal Radiation Dosimeter (PRD):
Currently looking at options; market survey, dose only, not real time; planned for EM-2 and potentially ISS

Passive Radiation Area Monitoring:
RAM: Radiation Area Monitor
planned for EM-1; will not fly EM-2
Crew Passive Dosimeter (CPD):
If PRD (above) is successful, will not be required
Acute Radiation Effects from a Solar Particle Event

- 30-day and yearly limits to the blood forming organs (BFO) and skin are intended to protect astronauts from acute radiation syndromes (ARS) including the prodromal risks (i.e., nausea, vomiting, anorexia, and fatigue), alterations to the hematopoietic system, and skin injury resulting from exposure to a large solar particle event (SPE)
  - Symptoms appear 4 to 48 hours post-exposure for sub-lethal doses with a latency time inversely correlated with dose
  - Clinical course of ARS are well defined in human populations accidently exposed to acute, high doses of gamma- and X-rays
  - Uncertainty exists about the magnitude of acute health effects from whole-body exposures to protons from an SPE, which are characterized by a high degree of variability in dose distribution in the body as well as by dynamic changes in dose-rates and energy spectra

- Majority of SPE’s are harmless; however, prodromal effects could occur during the occurrence of an historically large event if crew fails to seek shelter in a timely manner
  - Radiation sickness possible if unprotected >2 hours
  - Occurrence and magnitude of SPE’s are difficult to predict
  - Optimized event alert, dosimetry, and operational responses must be assured
  - Adequate shielding must be provided

- Minimizing cancer risk is a priority for both EVA and IVA even if ARS are avoided
Protecting ISS Crew: Solar Particle Event (SPE) Action Summary

• Radiation flight controller returns to console during contingency operations such as SPEs
  – Alert/Warning messages to management and flight control team
  – Ensure radiation monitoring system availability

• If SPE dose projection is determined to be negligible, then no action will be taken

• If energetic solar particle event has increased above threshold or radiation detector alarm activation is confirmed, inform crew to remain in higher shielded areas during intervals of high risk orbital alignments (geomagnetic cut-offs).

• ISS higher shielded locations used to protect crew
  – Service module aft of treadmill (panel 339), Node 2 crew quarters, and U.S. Lab
MPCV SPE Operational Response

Similar to locating to higher shielded locations on ISS to protect crew, relocating and reconfiguring MPCV stowage can provide SPE protection for crew.

Nominal Seated Position

SPE Contingency Position
Solar Particle Event Storm Shelter
Technology Maturation (AES)

Goal: Minimal Mass Shield Concepts
Approach:
• Design concepts utilizing onboard mass (water, equipment, consumables, waste, etc.)
• Evaluate radiation protection
• Fabricate of prototypes
• Perform operational evaluations

Concepts developed:
• Water walls and pantries in the crew quarters
• Reconfigurable logistics concepts
• Wearable vests and augmented sleep restraints

Radiation Protection Analyses

Multiple versions analyzed in realistic vehicle architecture to identify options requiring least parasitic mass.

Reconfigurable Logistics

Water Walls

Operational Testing
Mitigation of Galactic Cosmic Rays: STMD GCR Thick Shield Project

Problem being Addressed:
- Cost/mass effective radiation shield solutions against galactic cosmic radiation to enable NASA’s exploration DRMs beyond LEO do not exist.

Project:
- Establish first shield thickness requirements for exploration taking passive shielding out of design trade space.
-Validate multi-purpose GCR thick shielding material systems and technologies that offset the mass and volume penalties of parasitic shielding by performing other mission essential functions.

Why now?
- New analytical evidence of minimum in dose equivalent at depths important to shield design allowing for optimization.
- NASA radiation facility upgrades allows experimental validation of thick shield approaches.
Integrated Radiation Protection Strategy Enables Human Mars Exploration

Integration across Research and Technology Required...

Mission and Architecture Systems Analysis
- Near Earth Asteroid Systems
- Mars NTV
- In-situ Resource Utilization
- Active Shielding Concepts

Environmental Modeling, Monitoring, and Prediction
- Predictive Models
- Precursor Data — MSL RAD
- On-board Dosimetry — ISS TEPC

Crew Selection and Operations
- Individualized Risk Assessment

Radiobiology and Biological Countermeasures
- NASA Space Radiation Lab at Brookhaven National Laboratory
- X-ray vs. Heavy Ion Track Damage to DNA
- Leukemia induction with GCR — Mouse Model

Innovative Multi-Purpose Shield Solutions
- Heavy Ion Testing of Inflatable Shield Prototype
- Water Filled Composite Shield Sections
- Reconfigurable Personal Shielding
- Hydrogen Storage BNNT

Integrated Radiation Protection System Design and Analysis
- Design and Optimization Tools
- Crew Exploration Vehicle Shield Analysis
- High Energy Nuclear Physics and Transport