NASA Strategy to Safely Live and Work in the Space Radiation Environment

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The Space Radiation Problem
What is it and why should we care?

- What is space radiation?
  - High energy particles, including protons, electrons, and the fully ionized, highly charged nuclei of all the elements; neutrons and other products of interactions with materials

- Exposure to radiation in space is unavoidable.
  - Space radiation penetrates all materials -- spacesuits, spacecraft, habitats, devices, equipment, crew bodies and tissues

- Possible health consequences:
  - Tissue damage, cancer, cataracts, functional brain damage, heart and blood vessel damage, inheritable genetic changes
NASA’s Mission: Our Goal

- The Space Radiation Project must assure that NASA can safely live and work in the space radiation environment, anywhere, any time.
  - “Safely” means that acceptable risks are not exceeded during crew members’ lifetime
  - “Acceptable risks” include limits on mission, post-mission and multi-mission consequences (e.g., excess lifetime fatal cancer risk)
  - The Space Radiation Project strategy must understand the risks and determine methods to mitigate the risks by optimizing the vehicle environment, crew selection criteria and mission length to ensure the consequences of exposure to space radiation are kept as low as reasonably achievable
Where are we now?

- We can’t predict all the significant risks and there is substantial uncertainty in the risks that can be predicted. Insufficient biological knowledge is the largest contributor to the uncertainty
- Prior to 2003, few ground-based accelerators were capable of producing the ions and energies important to NASA
- Risk projection models are based largely on epidemiological data from a population vastly different than the Astronaut population
- Although radiation protection is an important factor in spaceflight, it is not well integrated into the vehicle design process
What are we doing about it?

- Using a peer-reviewed research program to increase our mechanistic knowledge and genetic capabilities to develop tools for individual risk projection, thereby reducing our dependency on epidemiological data and population-based risk assessment.

- The NASA Space Radiation Laboratory now provides a ground-based facility to study the understanding of health effects/mechanisms of damage from space radiation exposure and the development and validation of biological models of risk, as well as methods for extrapolation to human risk.

- Developing a risk modeling tool that integrates the results from research efforts into models of human risk to reduce uncertainties in predicting risk of carcinogenesis, central nervous system damage, degenerative tissue disease, and acute radiation effects.

- Developing computer codes to predict radiation transport properties, evaluate integrated shielding technologies and provide design optimization recommendations for the design of human space systems.
Integrated Risk Projection

Mitigation:
- Shielding materials
- Radioprotectants
- Pharmaceuticals

Risk Assessment:
- Dosimetry
- Biomarkers
- Uncertainties
- Space Validation

Risk: $R_{ij}$ (age, sex, mission)

Space Radiation Environment

Radiation Shielding

Initial Cellular and Tissue Damage

DNA breaks, tissue microlesions

DNA repair, Recombination,
Cell cycle checkpoint, Apoptosis, Mutation,
Persistent oxidative damage, & Genomic Instability

Tissue and Immune Responses

Risks:
Chronic: Cancer, Cataracts, CNS, Heart Disease
Acute: Lethality, Sickness, Performance

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Uncertainty in Predicting Risk

Radiation Environment (10-15%)
Physical Interactions (50%)
Dose and Dose Rate Effectiveness (200-300%)
Radiation Quality (300-500%)

The uncertainties in risk must be reduced to assure radiation safety in space.
Population-Based to Individual-based Risk Projection

Reduce size of uncertainty by changing the components (knowledge-based).
Confidence Levels for Career Risks on ISS
EXAMPLE: 45-yr-Old Males; GCR and trapped proton exposures

Reducing uncertainty leads to increased “safe” days in space (curves move to the right).

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Using a peer-reviewed research program to increase our mechanistic knowledge and genetic capabilities to develop tools for individual risk projection, thereby reducing our dependency on epidemiological data and population-based risk assessment.
Peer-Reviewed Research Program to Understand the Space Radiation Problem

- Unique damage to biomolecules, cells, and tissues occurs from HZE ions
- Few human data to estimate risk from HZE
- The mechanisms by which radiation damage to biomolecules and cells develops into health risks are poorly understood
- Animal models must be applied or developed to estimate cancer, CNS or other risks
- Effective shielding can reduce, but not eliminate, the space radiation problem.
Titanium – 2 Gy

Primary human skin cells irradiated with 2 Gray $\gamma$-rays (left) or Titanium ions (right) at NSRL. DNA damage is clearly visible at sites marked by new fluorescent technology. DNA damage is diffuse for $\gamma$-rays and localized along the Ti ion tracks through the cells. This pattern of energy deposition accounts for most of the increased risk of space radiation. (Cucinotta et al. 2004)
Ground-based Research Portfolio

NASA Specialized Center of Research (NSCOR)
- The Space Radiation Project has 5 NSCORs to focus efforts and attract the best researchers and institutions
- NSCORs are solicited for specific critical research areas
  - Leukemogenesis, DNA Damage and Repair, Lung Cancer, Solid Cancer, Progressive Alterations in CNS
- Awards are approximately $2M per year for 5 years
- Results from these “project” like awards provide the scientific basis for improved risk assessment

Individual Research Grants
- The Space Radiation Project has 44 individual research grants, with expectations for selection of 10 new awards per year
- Individual research is solicited in more general research areas
  - Mechanisms of carcinogenesis, CNS effects, Degenerative tissue disease, dietary countermeasures to radiation effects
- Awards are approximately $300K per year for 3 years
- Results from these awards provide the scientific basis for improved risk assessment and help identify additional critical research areas
The NASA Space Radiation Laboratory now provides a ground-based facility to study the effects/mechanisms of damage from space radiation exposure.
The NASA Space Radiation Laboratory (NSRL), a $34-million facility, is located at DOE’s Brookhaven National Laboratory on Long Island and is managed by NASA’s Johnson Space Center. The NSRL construction was completed on schedule and within budget. It is one of the few places in the world that can simulate the harsh cosmic and solar radiation environment found in space. The facility, opened in 2003, employs beams of heavy ions extracted from Brookhaven’s Booster accelerator, and has supported 90 investigators from the US and Europe utilizing 2100 hours of beam time (through NSRL-6) to perform experiments with Iron, Titanium, Silicon, Carbon, and protons.
Developing a **risk modeling tool** that integrates the results from research efforts into models of human risk to reduce uncertainties in predicting risk of carcinogenesis, central nervous system damage, degenerative tissue disease, and acute radiation effects.
Cancer Risk Assessment Model

- Tissue specific risk transfer, $\nu$
  - 3rd largest uncertainty
  - Estimates of coefficients

- Dose & Dose-Rate Effectiveness factor, DDREF
  - 2nd largest uncertainty
  - Dose-dependent changes

- Human epidemiology data (age/gender)
  - Excess Relative or Additive Risk (ERR/EAR)
  - Radiation Quality (Q/RBE)
  - Space particle spectra, $F(L=LET)$
  - Double Detriment Life Table (US Population – age/gender)

- Tissue Specific Cancer Rate (Mortality/Incidence)
  - $n(E,a_{v},a) = \left[\nu ERRg_{E}(a) + (1-\nu) EARg_{E}(a)\right] Q_{DDREF}^{(L)} F^{(L)}$

- Mission/Astronaut Specific Cancer Risk (R + Uncertainties)

- Assumption: Heavy ion effects can be scaled to Gamma-rays?
  - Tests basic assumptions
  - Largest uncertainty
  - Molecular basis for tumor latency

- Assumption: Risk is linear & additive over mixed high- & low-LET env.?

- Application to mixed radiation fields

- Assumption: Astronauts genetic/epigenetic background identical to Ave. US Population?

- Studies of Individual Radiation Sensitivity

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Open Questions for Non-Cancer Risks

- Risk model cannot be developed without answers to basic questions
- Is there a dose-threshold for non-cancer risks?
- Is multiplicative transfer of cardiac risk the appropriate way to use epidemiology data?
- Will heavy ion CNS risk lead to mission performance impacts?

Experimental studies are needed to establish mechanistic basis in support of risk projection
Developing computer codes to predict radiation transport properties, evaluate integrated shielding technologies and provide design optimization recommendations for the design of human space systems.
Experimental measurements of physical interactions provide the missing database on nuclear interactions ("cross sections").

Experimental measurements also validate the computational tools and radiation shielding materials effectiveness ("yields").

Models are used to calculate the changes in radiation as it penetrates and traverses materials ("transport calculations").
Web-based Design Tool

- User creates CAD model of shielding and defines shield materials consistent with those provided by the Design Tool.
- User has the option of loading the CAD object that incorporates the CAM & CAF target points into their model and placing it in an appropriate location and orientation.
- User executes ray traces using the ray distribution and material definitions downloaded from the Design Tool web site. The target points are either defined by the user or taken from the CAM/CAF target point sets.
Prototype Use Case for Web-based Design Tool Familiarization & First Use

User goes to web site and has access to procedure descriptions, documentation, technical references, and contact lists.

The user can also download a CAD object in either IGES or STEP format that incorporates the CAM & CAF target points with point numbers and labels required by the Design Tool.

In this Use Case, the user is responsible for their own CAD modeling and Ray Tracing processes. All other steps of the analysis, including incorporation of the CAM and CAF, are provided by the Design Tool.

User downloads ray distribution files, file format descriptions, material definitions, example subroutines that can generate the files in the correct format, and scripts that can convert from popular known formats to the Thickness Metafile format required by the Design Tool.
CONCLUSION

- Understanding the risks and determining methods to mitigate the risks are keys to a successful radiation protection strategy.

**Uncertainties**
- Environment
- Shielding

**Basic Knowledge**
- ROBOTIC PRECURSOR MISSIONS
- ACCELERATOR EXPOSURE FACILITIES
- protons
- HZE

**Vehicle Design Assessment**
- operational shielding
- biomedical
- Validate
- Loma Linda
- Brookhaven

**Ground Research:**
- Simulate Space Radiation
- Determine Biological Factors of Risk