# Space Radiation and Exploration -Information for the Augustine Committee Review

**Space and Life Sciences Directorate**
**Lyndon B. Johnson Space Center**

**July 14, 2009**

# Executive Summary

- Space radiation presents significant health risks including mortality for Exploration missions
  - Galactic cosmic ray (GCR) heavy ions are distinct from radiation that occurs on Earth leading to different biological impacts
  - Large uncertainties in GCR risk projections impact ability to design and assess mitigation approaches and select crew
  - Solar Proton Events (SPEs) require new operational and shielding approaches and new biological data on risks
- Risk estimates are changing as new scientific knowledge is gained:
  - Research on biological effects of space radiation show qualitative and quantitative differences with X- or gamma-rays
  - Expert recommendations and regulatory policy are changing
  - New knowledge leads to changes in estimates for the number of days in space to stay below Permissible Exposure Limits (PELs)

# Executive Summary- continued

- NASA limits acceptable levels of risks of astronauts to a 3% Risk of Exposure Induced Death (REID) from cancer
  - PEL requirement to be below 95% Confidence Interval (C.I.) for cancer risk protects against uncertainties in risk projection models
  - Estimates of number of days to be within a 95% C.I. are used to assess:
    - Safe mission lengths
    - Crew selection criteria such as Age, Gender and Prior Exposure
    - Mitigations such as Shielding or Biological Countermeasure Requirements
- New scientific findings may modify NASA's Risk Projection Models:
  - New research results and findings from NASA, DoE and NIH scientists
  - Findings of international bodies such as the National Academy of Sciences and the United Nations, or regulatory bodies (NCRP or ICRP)
  - Potential for late Non-cancer mortality risks (Heart and Brain) on long-term exploration missions confounds assessments of Acceptable Risk, which includes only cancer at this time

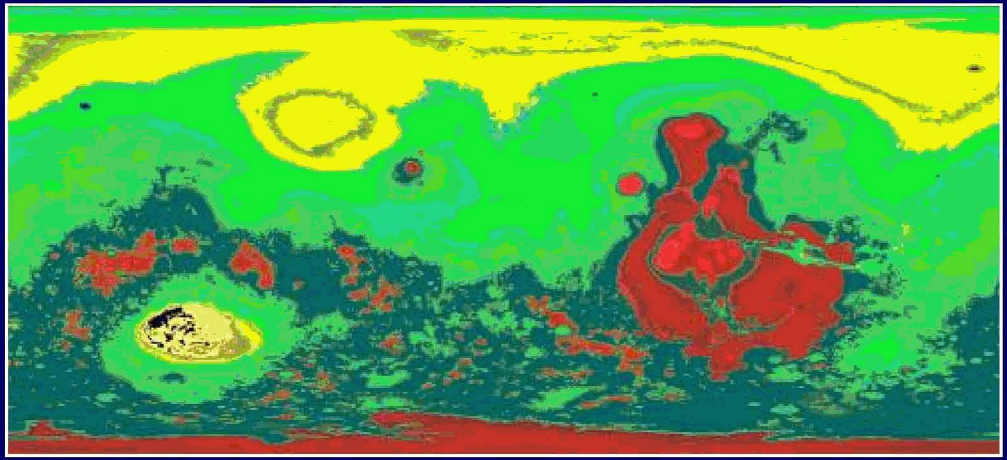
# Space Radiation Environments

**Galactic cosmic rays (GCR) penetrating protons and heavy nuclei-**
*a biological science challenge*

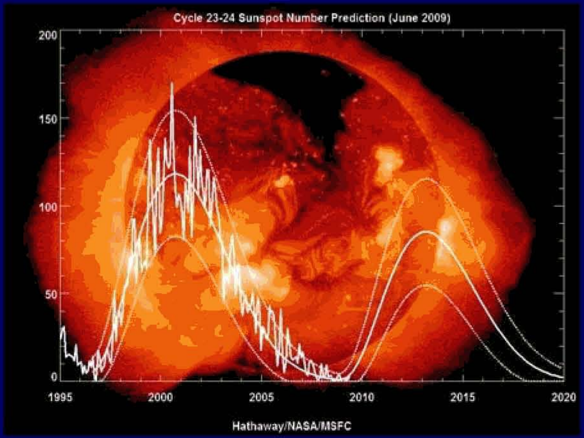
- shielding is not effective
- large biological uncertainties limits ability to evaluate risks and effectiveness of mitigations

**Solar Particle Events (SPE) largely medium energy protons–**
*a shielding, operational, and risk assessment challenge*

- shielding is effective; optimization needed to reduce weight
- improved understanding of radiobiology needed to perform optimization
- accurate event alert and responses is essential for crew safety



*GCR doses on Mars*




*Solar particle events and the 11-yr solar cycle*

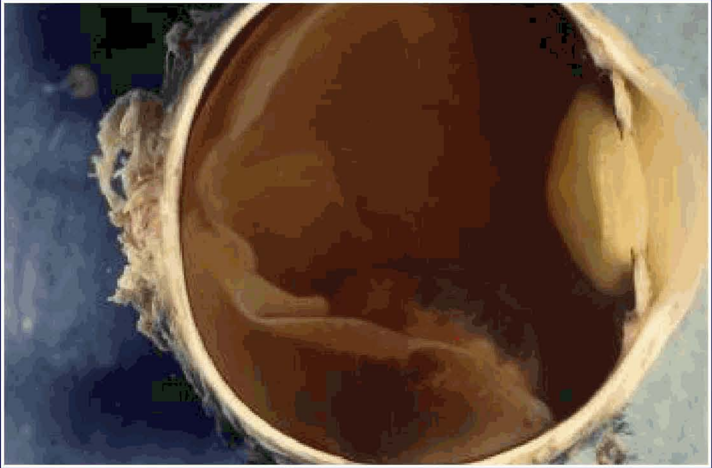
# Categories of Radiation Risk

**Four categories of risk of concern to NASA:**

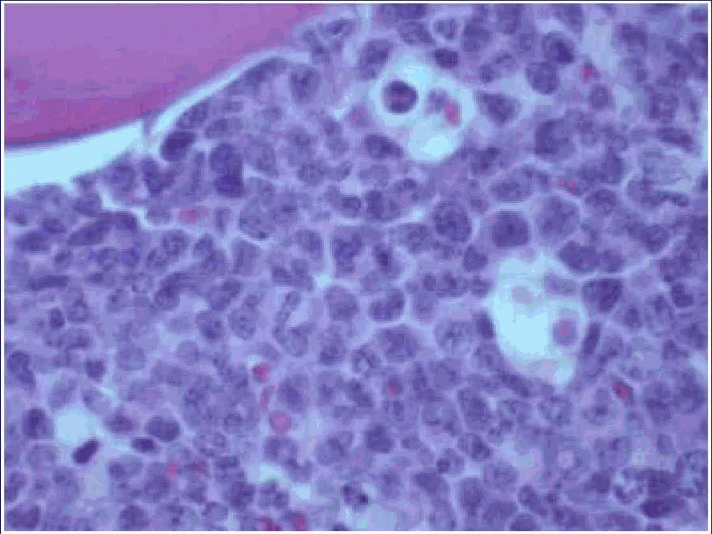
- ***Carcinogenesis (morbidity and mortality risk)***
- ***Acute and Late Central Nervous System (CNS) risks to the Brain***
- ***Chronic & Degenerative Tissue Risks***
  - ✓ cataracts, heart-disease, etc.
- ***Acute Radiation Risks***

**Differences in biological damage of heavy nuclei in space with x-rays, limits Earth-based data on health effects for space applications**

- **New knowledge on risks must be obtained**



*Lens changes in cataracts*



*1st experiments for leukemia induction with GCR*

# Roles of Select Committees and Radiation Projection Councils

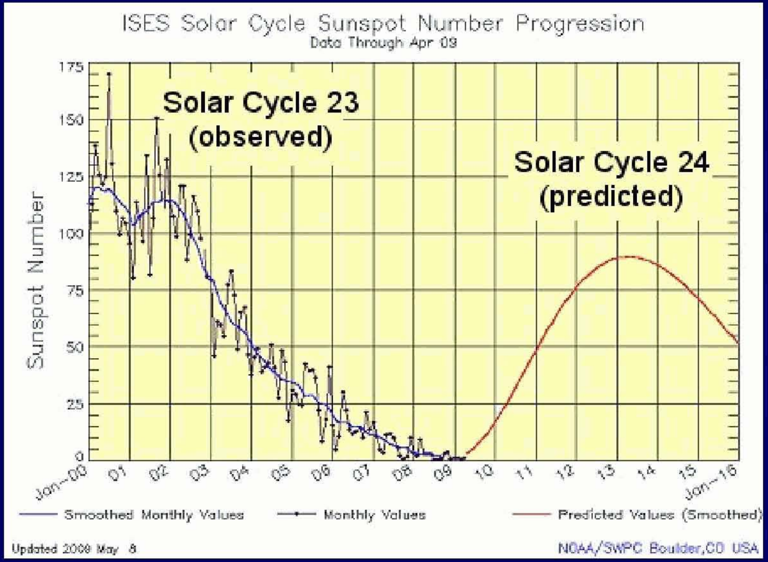
- Select expert panels from the National Academy of Sciences (NAS) and United Nations (UN) update human radio-epidemiology based estimates of radiation cancer risks each decade
- These reports form the basis for revised radiation protection standards and policy as recommended by the US National Council on Radiation Protection and Measurements (NCRP) and International Commission on Radiological Protection (ICRP)
- The most recent reports from NAS (BEIR VII) and the UN (UNSCEAR 2006) make important changes to the description of the age dependence of cancer risks, and cancer risks at low dose-rates
- These changes will increase risk projections if accepted by NCRP and ultimately by NASA

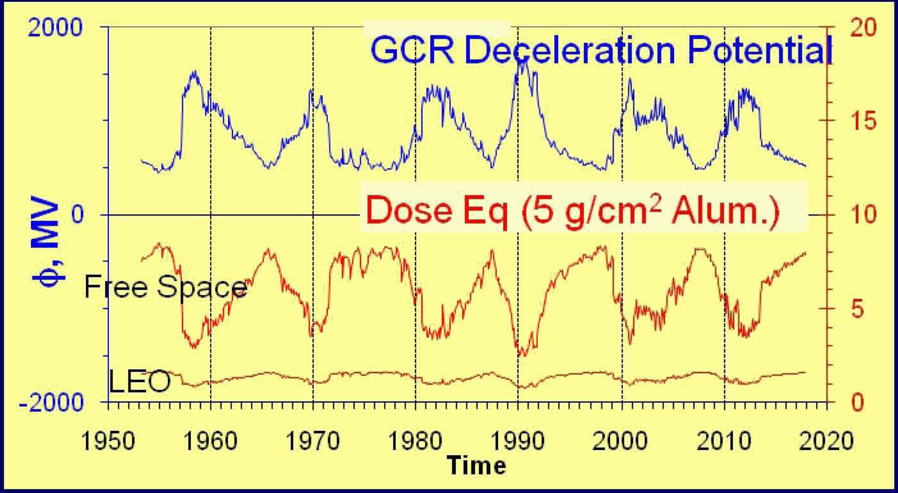
# Changes to NASA Cancer Projection Model

- Revised Risk model scheduled to be reviewed by National Academy of Sciences (NAS) in Summer of 2010
- Changes to current NASA projection model :
  - Revise Dose and Dose-rate Reduction Factor (DDREF) used to extrapolate high dose-rates data to the low dose-rates in space
  - New NASA Quality Factor (NASA-QF) from Research Findings
    - Distinct QF for leukemias (lower) and solid cancers (higher than current)
    - New physical description for high-energy GCR ions replacing current description based on outdated neutron and alpha emitter studies
  - Modify age at exposure dependence of cancer risk based on recent NAS and United Nations (UN) Reports
  - Re-define Tissue weighting factors to reflect astronaut ages and expected cancer types above age 30-y
  - Update Human Risk Coefficients from Japanese survivor and other exposed cohort analysis by NAS and UN
  - Update US population life-tables and cancer rates used in models

# Solar Cycle Effects and Risks

- The solar cycle is approximately 11-years in length, however variations in length of ±2 y can occur
  - Doses from SPEs are highest at solar maximum when solar activity is highest
  - Doses from GCR are highest at solar minimum when the solar wind is strongest
- Each cycle will have varying modulation conditions and number and sizes of SPE
- The prediction of solar conditions temporal patterns are uncertain for future solar cycles




JSC/SRP Model

# Projections for Exploration Missions

- Estimates of %-REID with uncertainty estimates, and Maximum Days with 95% Confidence Levels consider:
  - New BEIR and UNSCEAR estimates of cancer risk coefficients for low LET radiation including dose-rate modifiers
  - Preliminary updates of the revised NASA Model-2011
  - NASA Transport , Nuclear interaction and Space environment models including estimates of lunar and Mars Albedo dose
  - Constellation Architecture Team (CAT III) Shielding designs based on Aluminum structure with addition of 10 cm Water shield
- Estimates do not consider:
  - Prior Crew exposures on ISS or other missions
  - Heart or other late mortality risks from space radiation
  - Impacts of new Non-Targeted Effects Biology on Risk models
    - **Possible Non-linear relationships between exposure and risk**
    - **Distinct age dependence of risk**

# Maximum Mission Lengths with a 95% CI on Lunar Surface at Solar Min for Lunar Min-Hab

| | Current NASA Model* | NAS-BEIRVII | UNSCEAR | Preliminary NASA update |
|---|---|---|---|---|
| | Males | | | |
| 35 | 207 | 215 | **167** | 234 |
| 45 | 274 | 223 | 220 | 265 |
| 55 | 400 | 243 | 305 | 315 |
| | Females | | | |
| 35 | **169** | **152** | **123** | **156** |
| 45 | 227 | **159** | **169** | 183 |
| 55 | 342 | **176** | 254 | 226 |

*Based on NCRP 132 Report (2000)

# Maximum Mission Lengths with a 95% CI on Lunar Surface at Solar Max (GCR and Median SPE Exposure)

| | Current NASA Model* | NAS-BEIRVII | UNSCEAR | Preliminary NASA update |
|---|---|---|---|---|
| | Males | | | |
| 35 | 455 | 496 | 372 | 493 |
| 45 | 606 | 511 | 481 | 580 |
| 55 | 885 | 545 | 682 | 689 |
| | Females | | | |
| 35 | 374 | 337 | 272 | 328 |
| 45 | 503 | 352 | 375 | 394 |
| 55 | 758 | 388 | 493 | 459 |

*Based on NCRP 132 Report (2000)

# Maximum Mission Lengths with a 95% CI in Deep Space at Solar Min

| | Current NASA Model* | NAS-BEIRVII | UNSCEAR | Preliminary NASA update |
|---|---|---|---|---|
| | Males | | | |
| 35 | 158 | 168 | 129 | 173 |
| 45 | 207 | 174 | 168 | 203 |
| 55 | 302 | 187 | 232 | 240 |
| | Females | | | |
| 35 | 129 | 116 | 103 | 116 |
| 45 | 173 | 121 | 122 | 140 |
| 55 | 259 | 133 | 152 | 172 |

*Based on NCRP 132 Report (2000)

# Maximum Mission Lengths with a 95% CI in Deep Space at Solar Max (GCR and Median SPE Exposure)

| | Current NASA Model* | NAS-BEIRVII | UNSCEAR | Preliminary NASA update |
|---|---|---|---|---|
| | Males | | | |
| 35 | 353 | 377 | 289 | 384 |
| 45 | 467 | 390 | 376 | 451 |
| 55 | 681 | 420 | 520 | 536 |
| | Females | | | |
| 35 | 307 | 259 | 229 | 268 |
| 45 | 437 | 272 | 325 | 328 |
| 55 | 664 | 299 | 518 | 412 |

*Based on NCRP 132 Report (2000)

# Maximum Mission Lengths with a 95% CI on Mars Surface** at Solar Min

| | Current NASA Model* | NAS-BEIRVII | UNSCEAR | Preliminary NASA update |
|---|---|---|---|---|
| | Males | | | |
| 35 | 342 | 361 | 277 | 364 |
| 45 | 448 | 373 | 361 | 427 |
| 55 | 651 | 405 | 499 | 507 |
| | Females | | | |
| 35 | 274 | 246 | 199 | 244 |
| 45 | 369 | 257 | 274 | 294 |
| 55 | 552 | 284 | 410 | 362 |

*Based on NCRP 132 Report (2000)

** Assumes $CO_2$ Mars atmosphere (20 $g/cm^2$ Vertical depth)

# Maximum Mission Lengths with a 95% CI on Mars Surface** at Solar Max

| | Current NASA Model* | NAS-BEIRVII | UNSCEAR | Preliminary NASA update |
|---|---|---|---|---|
| | Males | | | |
| 35 | 693 | 739 | 564 | 763 |
| 45 | 914 | 761 | 739 | 896 |
| 55 | 1338 | 823 | 873 | 1063 |
| | Females | | | |
| 35 | 565 | 509 | 411 | 510 |
| 45 | 761 | 531 | 566 | 615 |
| 55 | 1144 | 585 | 851 | 761 |

* Based on NCRP Report No. 132 (2000)

** Assumes $CO_2$ Mars atmosphere (20 $g/cm^2$ Vertical depth)

# Radiation and Non-Cancer Effects

- Early Acute Death is very unlikely:
  - Low or modest dose-rates for SPE's insufficient for risk of early death
  - SPE doses are greatly reduced by tissue or vehicle shielding
- Late Non-Cancer risks are well known at high doses and recently a concern at doses below 1 Sv (100 rem)
  - Significant Heart disease in Japanese Survivors and patient, and reactor workers
    - estimates showing number of excess heart deaths about half of that of excess cancer deaths
  - Concern for Mars or lunar missions due to higher GCR and SPE doses
  - Qualitative differences between GCR and gamma-rays in causing cellular and tissue damage a further concern

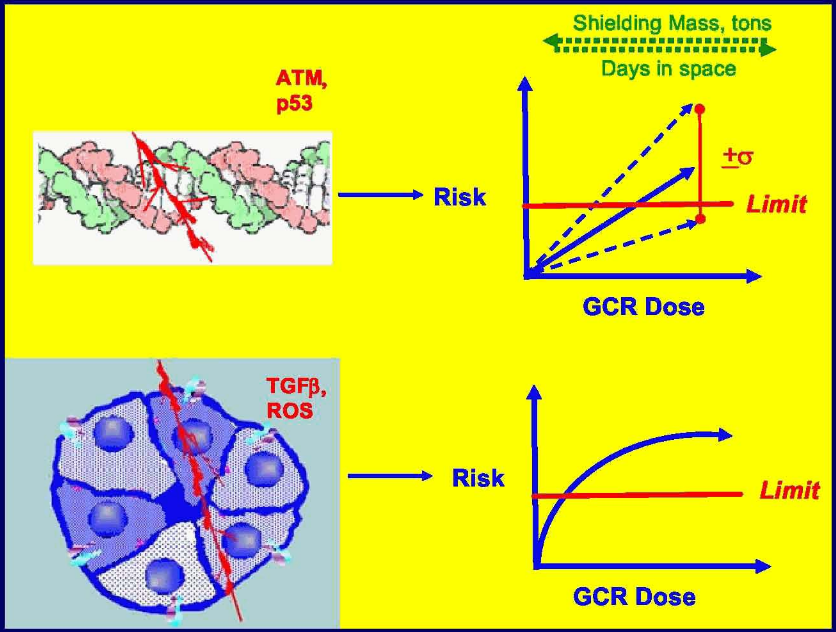
| Cohort | ERR for Heart Disease/Sv |
|---|---|
| A-bomb Survivors | 0.17 [0.08,0.26] |
| Radiotherapy and Peptic Ulcer Patients | 0.11 [0.01,0.22] |
| Chernobyl Emergency Workers | 0.41 [0.05,0.78] |
| Canadian Nuclear and other Workers (Males) | 2.3 [0.9,3.7] |

Excess relative risk (ERR) and 95% CI per 1-Sv (100 rem) exposure

# New Biology of Non-Targeted Effects

- Non-targeted effects show radiation damage occurs to tissue matrix not to DNA alone
  - Leads to new dose and age pattern paradigms
- Cancer occurs in stages of initiation, promotion and progression
  - Non-targeted models support role for radiation in promotion and progression
- Major Implications
  - Risk has non-linear increase with exposure (similar to cigarette smoking)
    - **reduces dependence on mission length with higher risk at lower dose while saturating at higher dose**
  - Reduces age dependence of risk

**Current vs Non-Targeted Model**



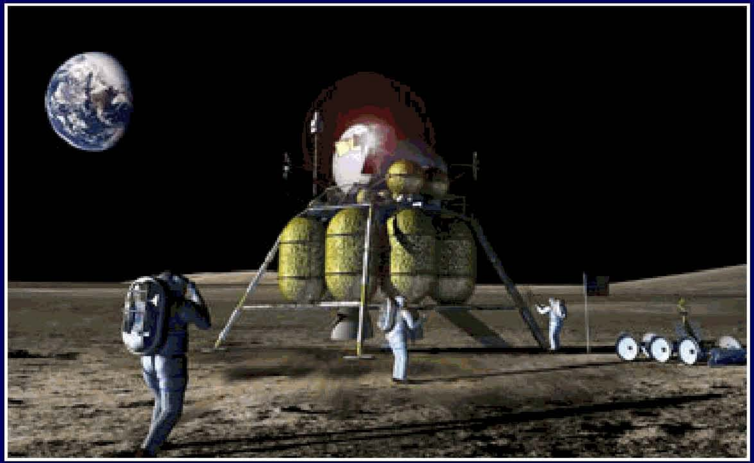
# Summary

**Space radiation is a major challenge to exploration:**

- Risks are high limiting mission length or crew selection
- Large mission cost to protect against risks and uncertainties
- New findings may change current assumptions

**NASA approach to solve these problems:**

- Probabilistic risk assessment framework for ISS and Exploration Trade Studies
- Ground-based research focused on uncertainty reduction and new mitigation approaches at NASA Space Radiation Laboratory (NSRL)
- Collaborative research with DoE, NSBRI, and ESA
- Ongoing external reviews by authoritative bodies
- Well defined deliverables to Cx, ISS, and CHMO



# Authors and Points of Contacts


- Authors: Francis A. Cucinotta, Edward Semones, Myung-Hee Kim, and Lori Jackson

- Point of Contact:

Dr. Francis A. Cucinotta

NASA Lyndon B. Johnson Space Center

Mail Code SK

2101 NASA Parkway, Houston TX, 77058

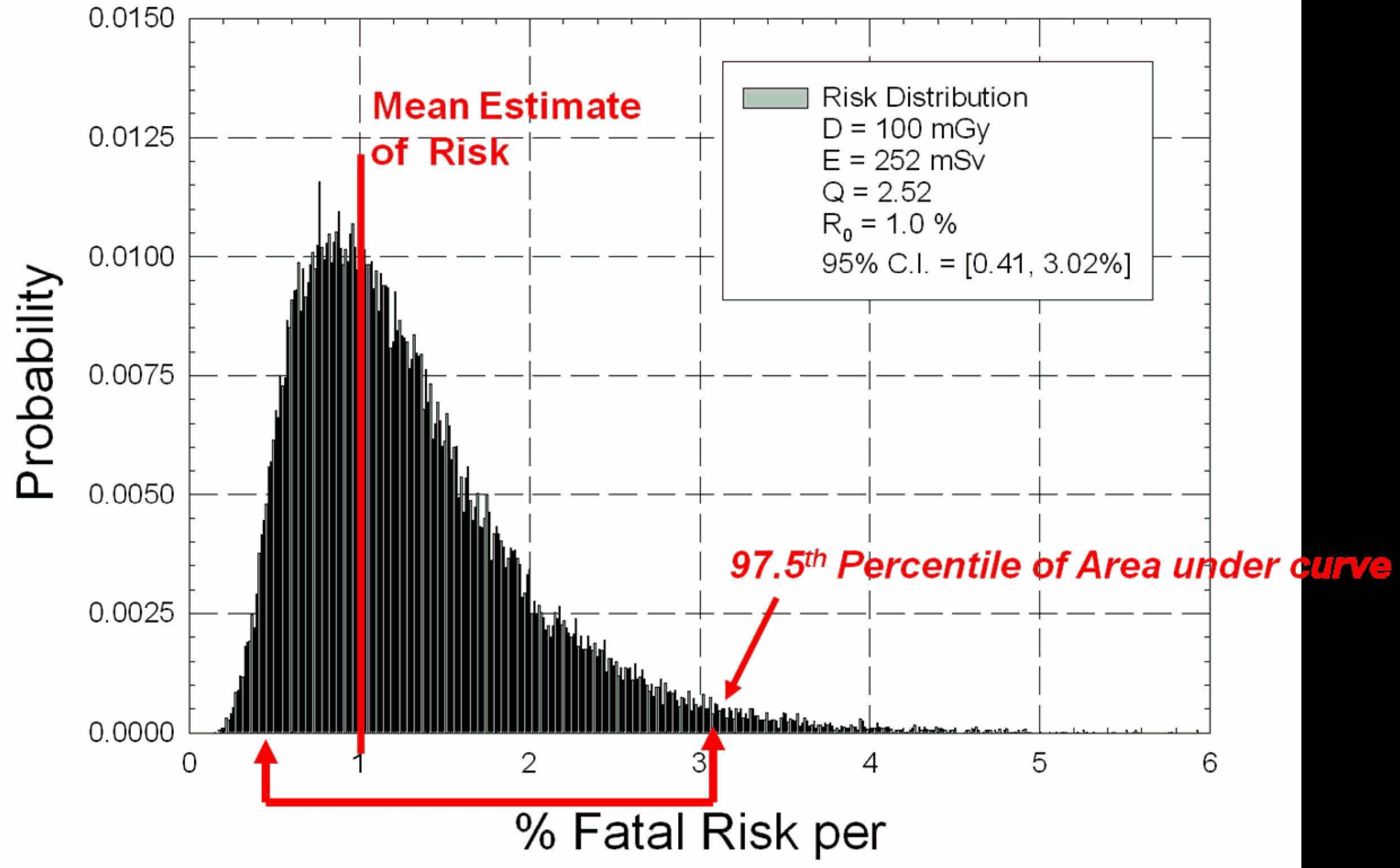
- Email: Francis.A.Cucinotta@NASA.gov

# Backup Charts

# Key References

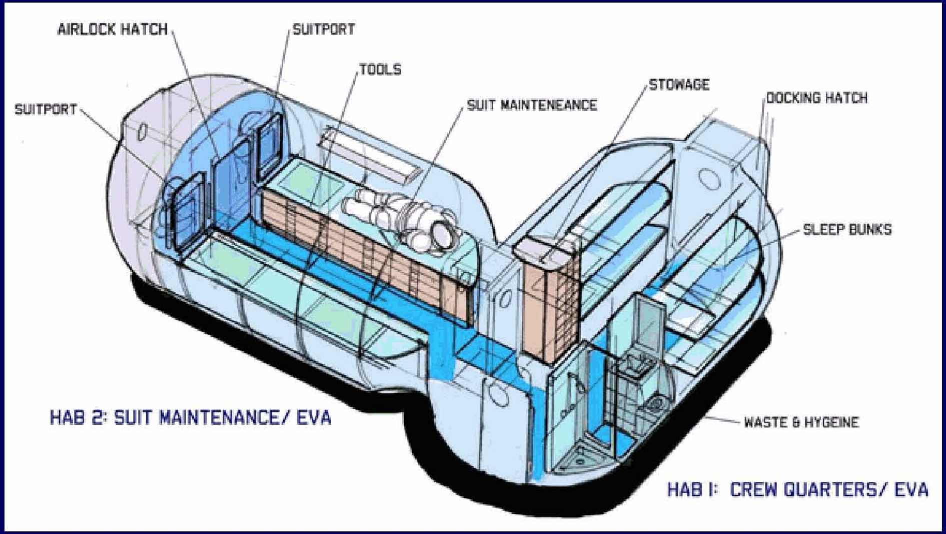

- National Council on Radiation Protection and Measurements, NCRP. Uncertainties in fatal cancer risk estimates used in radiation protection, NCRP Report 126, Bethesda MD (1997).
- National Council on Radiation Protection and Measurements, NCRP. Recommendations of dose limits for low Earth orbit. NCRP Report 132, Bethesda MD (2000).
- Cucinotta FA, Schimmerling W, Wilson JW, Peterson LE, Saganti P, Badhwar GD, Dicello JF. Space radiation cancer risks and uncertainties for Mars missions. *Radiat Res* **156**, 682–688 (2001).
- Preston, DL, Shimizu Y, Pierce DA *et al.* Studies of mortality of atomic bomb survivors. Report 13: Solid cancer and noncancer disease mortality: 1950–1997. *Radiat Res* **160**, 381–407 (2003).
- Cucinotta FA, Kim MY & Ren L, Managing Lunar and Mars mission radiation risks, Part I: Cancer risks, uncertainties, and shielding effectiveness. Washington DC, NASA TP 2005-213164 (2005).
- Barcellos-Hoff MH, Park C, and Wright EGT, Radiation and the microenvironment - tumorigenesis and therapy. *Nat Rev Cancer* **5**, 867-75 (2005).
- National Council on Radiation Protection and Measurements, NCRP. Information needed to make radiation protection recommendations for space missions beyond Low-Earth Orbit. NCRP Report No. 153, Bethesda, MD (2006).
- Cucinotta FA, Durante M, Cancer risk from exposure to galactic cosmic rays: Implications for space exploration by human beings. *Lancet Oncol.* **7**, 431-434(2006).
- Health Risks from exposure to low levels of ionizing radiation: BEIR VII. National Academy of Sciences Press, Washington D.C. (2006).
- United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (2006).
- Little MP, *et al.* A systematic review of epidemiological associations between low and moderate doses of ionizing radiation and late cardiovascular effects, and their possible mechanisms. *Radiat Res* **169**, 99-109 (2008).

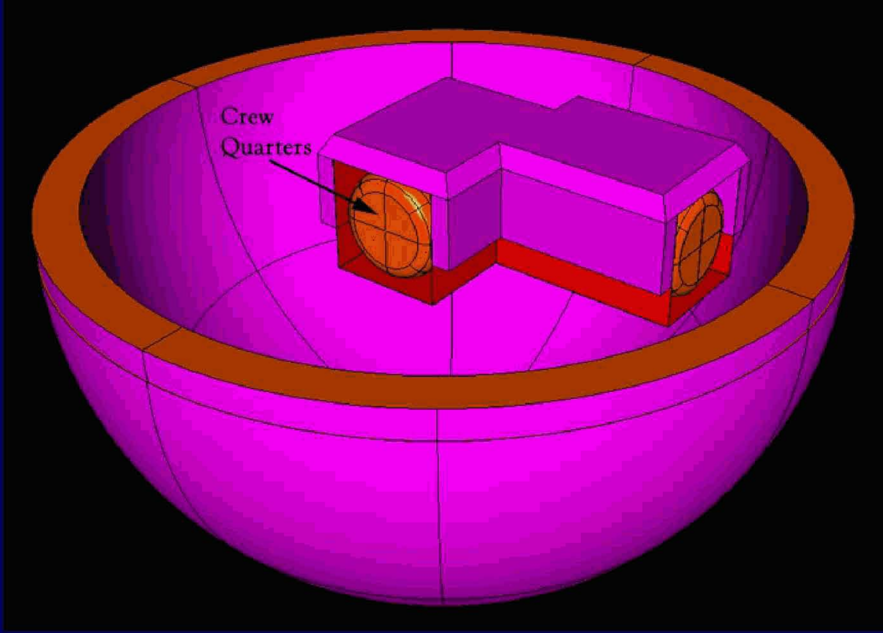
# ISS Mission Nominal Fatal Cancer Risk




**95% Confidence Interval: 1 in 20 Chance True Answer falls outside this interval from 2.5th to 97.5th Percentiles (95% Area under Curve)**

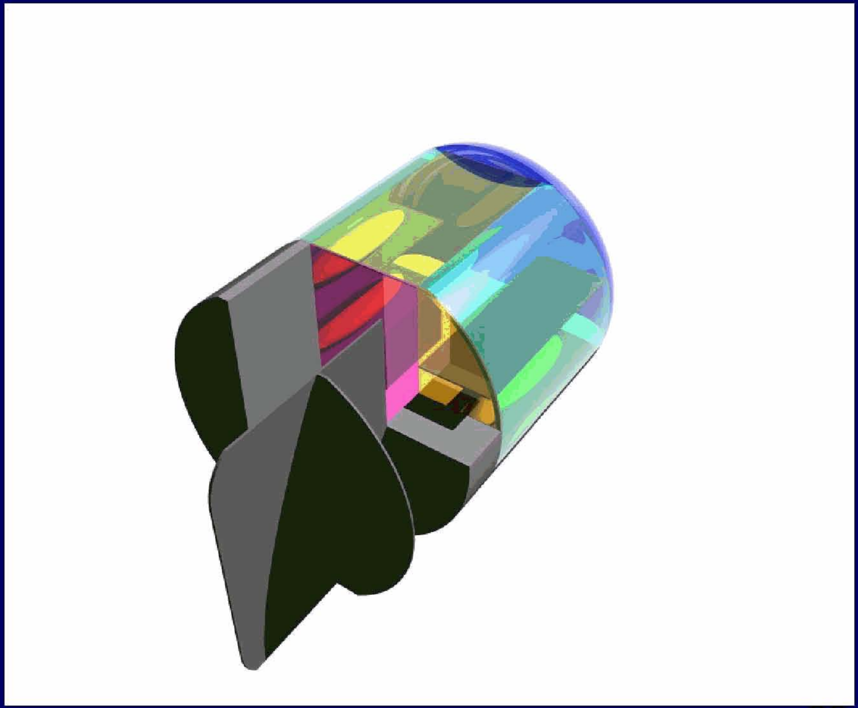
# Lunar Mini-Hab at LARC




Shielding approach developed for the Lunar Surface Architecture Studies (CAT-III) :

This is a view from an end of the module, showing some of the objects inside the pressure vessel. The water wall segments have been given different colors to make them easier to distinguish.



# Estimates of Cancer Risks at Solar Minimum

(%)REID and 95% Confidence Intervals at Solar Minimum
For 180 day Lunar Outpost with CAT III Mini-Hab Shielding

| Age | Current NASA Model* | BEIR-VII Model | UNSCEAR Model | Preliminary NASA Update |
|---|---|---|---|---|
| | **Males** | | | |
| 35 y | 0.71 [0.21, 2.6] | 0.68 [0.28, 2.5] | **0.86 [0.25, 3.2]** | 0.70 [0.32, 2.3] |
| 45 | 0.53 [0.16, 2.0] | 0.65 [0.27, 2.4] | 0.66 [0.19, 2.5] | 0.60 [0.27, 2.0] |
| 55 | 0.36 [0.11,1.35] | 0.60 [0.25, 2.2] | 0.48 [0.14, 1.8] | 0.49 [0.21, 1.7] |
| | **Females** | | | |
| 35 y | **0.86 [0.25, 3.2]** | **0.96 [0.4, 3.5]** | **1.19 [0.35, 4.4]** | **1.05 [0.48, 3.5]** |
| 45 | 0.64 [0.19, 2.4] | **0.92 [0.38, 3.4]** | **0.86 [0.25, 3.2]** | **0.86 [0.38, 2.9]** |
| 55 | 0.43 [0.13,1.6] | **0.83 [0.35, 3.1]** | 0.57 [0.17, 2.1] | 0.68 [0.28, 2.5] |

*Based on NCRP 132 Report (2000)

# Estimates of Cancer Risks at Solar Maximum

## (%)REID and 95% Confidence Intervals for 180 Day Lunar Outpost CAT III Mini-Hab Shielding. SPE exposure inside 10 cm Water Shelter

| Age | Current NASA Model* | BEIR-VII Model | UNSCEAR Model | Preliminary NASA Update |
|---|---|---|---|---|
| | **Females for GCR and Median SPE Exposure** | | | |
| 35 y | 0.44 [0.15, 1.4] | 0.49 [0.17, 1.6] | 0.6 [0.21, 2.0] | 0.6 [0.22, 1.6] |
| 45 | 0.33 [0.11, 1.1] | 0.47 [0.16,1.5] | 0.44 [0.15, 1.4] | 0.5 [0.18, 1.4] |
| 55 | 0.22 [0.08, 0.7] | 0.42 [.15, 1.4] | 0.33 [0.12, 1.1] | 0.42 [0.14, 1.2] |
| | **Females for GCR and 95th percentile SPE exposure*** | | | |
| 35 y | **1.1 [0.39, 3.2]** | **1.2 [0.42, 3.5]** | **1.6 [0.54, 4.4]** | **1.4 [0.5, 3.9]** |
| 45 | 0.85 [0.29, 2.4] | **1.2 [0.42, 3.4]** | **1.1 [0.39, 3.2]** | **1.2 [0.4, 3.3]** |
| 55 | 0.56 [0.19, 1.6] | **1.1 [0.38, 3.1]** | 0.76 [0.26, 2.1] | 0.95 [0.33, 2.7] |

*95th Percentile Fluence with 1972 SPE Spectra (~70th percentile spectral hardness)

# Estimates of Cancer Risks at Solar Maximum

(%)REID and 95% Confidence Intervals for 180 Day Lunar Outpost
CAT III Mini-Hab Shielding SPE exposure inside 10 cm Water Shelter

| Age | Current NASA Model* | BEIR-VII Model | UNSCEAR Model | Preliminary NASA Update |
|---|---|---|---|---|
| | **Males for GCR and Median SPE Exposure** | | | |
| 35 y | 0.36 [0.13, 1.2] | 0.33 [0.12, 1.1] | 0.44 [0.15, 1.4] | 0.4 [0.14, 1.1] |
| 45 | 0.27 [0.1, 0.89] | 0.32 [0.11,1.1] | 0.34 [0.12, 1.1] | 0.34 [0.12, 0.93] |
| 55 | 0.19 [0.07, 0.61] | 0.3 [0.11, 1.0] | 0.24 [0.09, 0.8] | 0.28 [0.1, 0.78] |
| | **Males for GCR and 95$^{th}$-percentile SPE exposure** | | | |
| 35 y | 0.93 [0.32, 2.6] | 0.87 [0.3, 2.5] | **1.1 [0.39, 3.2]** | 0.93 [0.33, 2.5] |
| 45 | 0.71 [0.24, 2.0] | 0.85 [0.29, 2.4] | 0.87 [0.3, 2.5] | 0.79 [0.28, 2.2] |
| 55 | 0.48 [0.17, 1.4] | 0.78 [0.27, 2.2] | 0.63 [0.22, 1.8] | 0.65 [0.22, 1.8] |

*Based on NCRP 132 Report (2000)

# Radiation and Risk Uncertainties

**What could we do about risk?**

- Optimize Mission Operations & Shielding
- Biological countermeasures (C.M.)
- Limit mission parameters

**What are impacts of uncertainties?**

- Increase costs due to excessive safety margins
- Limits ability to judge mitigation approaches
- Inadequate information to advise Astronauts on risks

**What could we do about uncertainties?**

- Probabilistic risk assessment
  - Approved by NASA Medical Policy Board
- Narrow the knowledge gap on biological effects to achieve uncertainty reduction

# Major Sources of Uncertainty

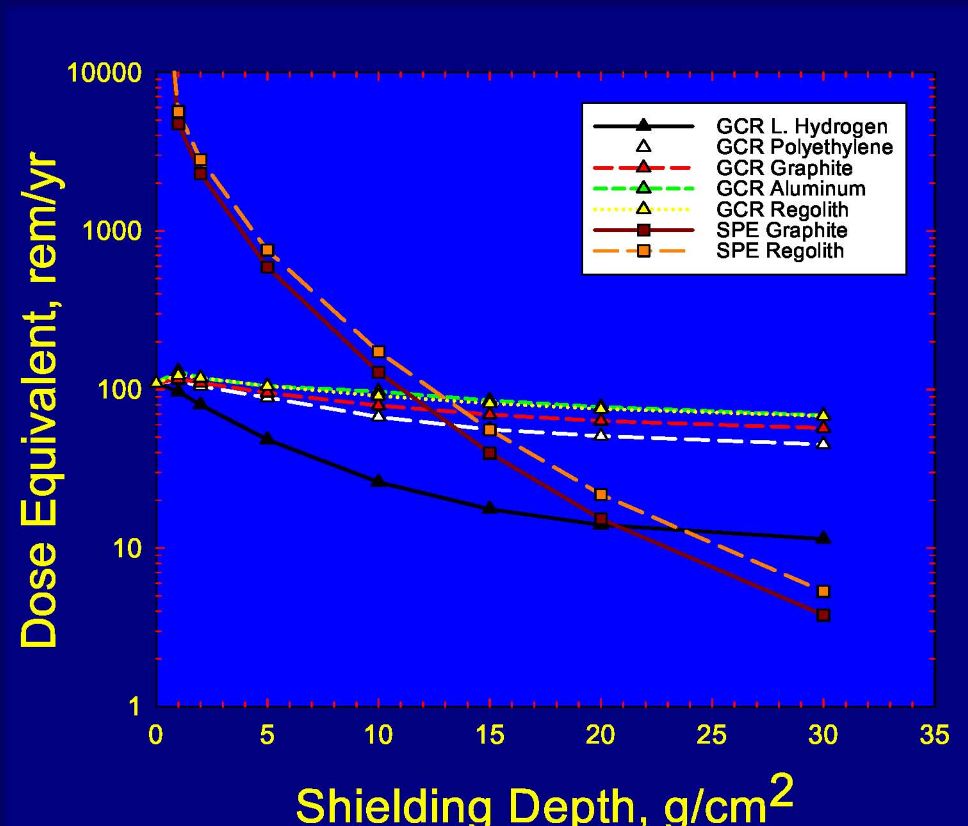
- Radiation quality effects on biological damage
  - Qualitative and quantitative differences of Space Radiation compared to x-rays
- Dependence of risk on dose-rates in space
  - Biology of DNA repair, cell regulation
- Predicting solar events
  - Temporal and size predictions
- Extrapolation from experimental data to humans
- Individual radiation-sensitivity
  - Genetic, dietary and "healthy worker" effects

# Minor Sources of Uncertainty

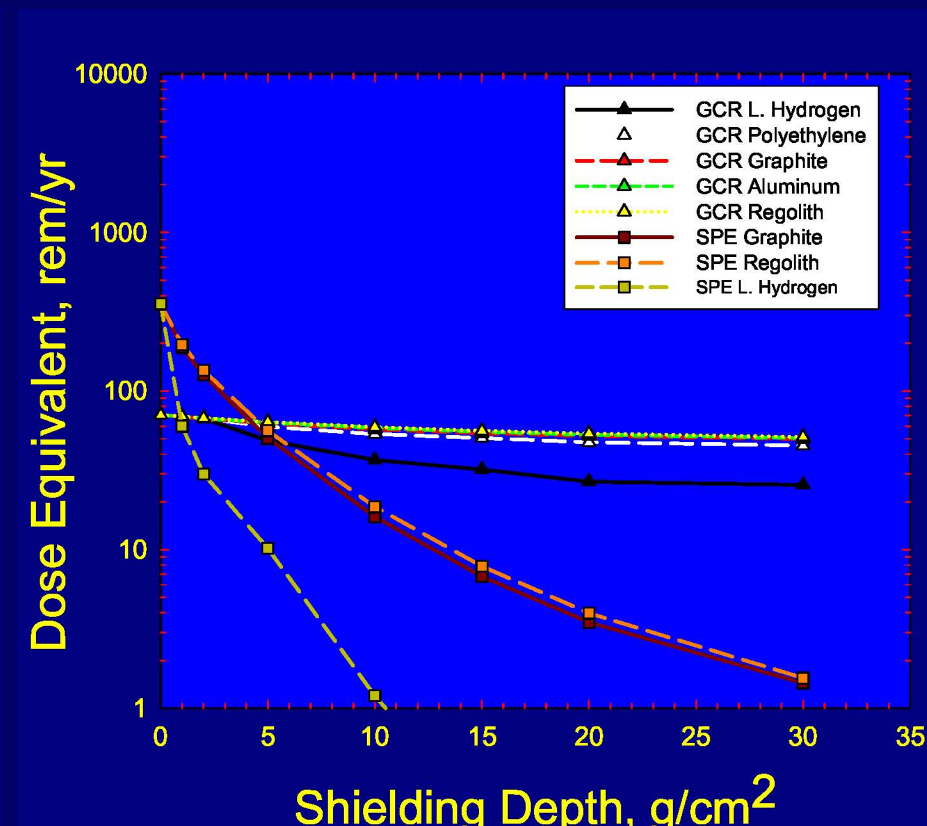
- Data on space environments
  - Knowledge of GCR and SPE environments for mission design
- Physics of shielding assessments
  - Transmission properties of radiation through materials and tissue
- Microgravity effects
  - Possible alteration in radiation effects due to microgravity or space stressors
- Errors in human data
  - Statistical, dosimetry or recording inaccuracies

# GCR and SPE Doses: Materials & Tissue
## - GCR much higher energy producing secondary radiation

### No Tissue Shielding




### With Tissue Shielding




August 1972 SPE and GCR Solar Min