Description of Transport Codes for Space Radiation Shielding

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NCRP 2011 Annual Meeting
Scientific and Policy Challenges of Particle Radiations in Medical Therapy and Space Missions
March 7-8, 2011
Introduction

• Radiation transport codes, when combined with Risk Projection models, are main tool for shielding study and design.

• Approaches to assess the accuracy of Transport Codes:
  – Ground-based studies with defined beams and material layouts
  – Inter-comparison of transport code results for matched boundary conditions
  – Comparisons to flight measurements

• NASA’s HZETRN/QMSFRG code has a very high degree of congruence for each of these criteria.
Components of Space Radiation Shield Design

Environmental Models
- Trapped Radiations
- Solar Energetic Particles
- Galactic Cosmic Rays
- Laboratory Ion Beams

Shield Transmission Characteristics
- Boltzmann Transport Equation/Monte Carlo Techniques
- Atomic Interactions
- Nuclear Interactions

Body Tissue Transmission Characteristics
- Boltzmann Transport Equation/Monte Carlo Techniques
- Atomic Interactions
- Nuclear Interactions

Physical Dosimetry Models
- Energy Absorption
- Events in Specific Sites

Biological Risk Models
- Cellular and Tissue Responses

Shield Materials Nuclear Database

External Environment

Internal Environment

Shield Geometry Model

Astronaut Geometry Model

Detector and Device Response
- Spectrometers
- Dosimeters
- TEPC
- Single Event Upsets
- Latchup
- Displacement Damage

Body Tissue Nuclear Database

Cellular and Tissue Response
- Acute Symptom
- Cancer
- CNS
- Heart Disease
Approximate Composition

\[ N_{101.7}O_{33.1}Al_{36} \]

Density: 0.00194 g/cm³
Thickness: 1.2166 g/cm²

N: \(2.09 \times 10^{22}\) atoms/g
O: \(6.81 \times 10^{21}\) atoms/g
Al: \(7.41 \times 10^{21}\) atoms/g

NSRL for Biophysics Applications
Heavy Ion Reactions

Abrasion = projectile-target overlap (n, p, and cluster knock-out)
Ablation = pre-fragment decay (n, p, d, t, h, alphas de-excitation)
Coalescence = p and n knockout form bound states in coupled phase space
Fragmentation Cross Sections:
Comparison of QMSFRG to Si and Fe Beams

- $\sigma_F$ (measured), mb
- $\sigma_F$ (QMSFRG), mb
- $^{28}$Si + $^{12}$C $\rightarrow Z_F$
- $^{28}$Si + $^{27}$Al $\rightarrow Z_F$

Data from Zeitlin et al. (2006)
NSRL Bragg Curve Comparison to GCR Event-based Risk Model (GERM)

Cucinotta FA et al., Radiat Prot Dosimetry, 2011

**$^{56}$Fe (0.59 GeV/u)**

- **Primaries**
- **Fragments**
- **Total - GERM**
- **NSRL Data**

**$^{48}$Ti (0.98 GeV/u)**

- **Primaries**
- **Fragments**
- **Total - GERM**
- **NSRL Data**

**$^{37}$Cl (0.50 GeV/u)**

- **Primaries**
- **Fragments**
- **Total - GERM**
- **NSRL Data**

**$^{28}$Si (0.403 GeV/u)**

- **Primaries**
- **Fragments**
- **Total - GERM**
- **NSRL Data**
Thick Target Comparison with NASA’s GERMCode* and GRNTRN Code*

Iron (1 GeV/u) on Polyethylene

\[ F(Z) \]

\[ 0.01 \quad 0.1 \quad 1 \]

GERM 4.2 g/cm²
17 g/cm²
Expt 4.2 g/cm²
17 g/cm²

*HZETRN uses identical Nuclear Cross Sections and Atomic Data*
Space Weather Prediction Center, NWS, NOAA

NOAA Scales Activity
Range 1 (minor) to 5 (extreme)

<table>
<thead>
<tr>
<th>NOAA Scale</th>
<th>Past 24 hours</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geomagnetic Storms</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Solar Radiation Storms</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Radio Blackouts</td>
<td>none</td>
<td>none</td>
</tr>
</tbody>
</table>
Space Environmental Models

Fit to Proton Measurements for Continuous Spectrum

Functional Forms with Measurements

- Exponential in Rigidity or Energy: \( \Phi(>R) = J_0 \exp(-R/R_0) \) or \( \Phi(>E) = J_0 \exp(-E/E_0) \)
- Sum of Two Exponentials: \( \Phi(>E) = J_1 \exp(-E/E_1) + J_2 \exp(-E/E_2) \)
- Weibull Function in Energy: \( \Phi(>E) = J_0 \exp(-\kappa E^\alpha) \)

Band Function with 4 Parameters \( (J_0, \gamma_1, \gamma_2, R_0) \):

Double Power Law in Rigidity

\[
\Phi(>R) = J_0 R^{-\gamma_1} e^{-R/R_0} \quad \text{for} \quad R \leq (\gamma_2 - \gamma_1) R_0 \\
\Phi(>R) = J_0 R^{-\gamma_2} \left\{ \left( (\gamma_2 - \gamma_1) R_0 \right)^{\gamma_2 - \gamma_1} e^{(\gamma_1 - \gamma_2)} \right\} \quad \text{for} \quad R \geq (\gamma_2 - \gamma_1) R_0
\]
Badhwar-O’Neill Model fit of ACE CRIS oxygen energy spectra measurements near solar minimum and near solar maximum

Solar modulation parameter:
- ACE CRIS oxygen measurements (line);
- IMP-8 (Z>8) channel 7 measurements (○)

O’Neil PM, 2010
Geometry Models

Shield Geometry Model and Shielding Analysis by CAD

Structural Distribution Model for Layers of Spacecraft Using ProE™/Fishbowl

Ray Tracing inside Spacecraft

Color-coded Representation of Directional Shielding
Human Geometry Models and Active Marrow Distributions

Computerized Anatomical Male

- Head and Neck: 12.2%
- Chest: 26.1%
- Abdomen: 24.9%
- Pelvis: 33.4%
- Thighs/Upper Legs: 3.4%
- Lower Legs and Arms: n/a

Male Adult voXel

- All Vertebrae: 42.3%
- Thorax: 24%
- Legs: 3.4%
- Pelvic Region: 20.9%
- Skull and Arms: 9.4%
Inter-Comparisons of Transport Codes

Heinbockel JH et al., NASA TP 2009-215560, 2009
Comparisons with Flight Measurements

RMS 15%

1.5-2.7X

Albedo protons
Albedo neutrons
Secondary neutron Geomagnetic transmission function

25%
Albedo protons
Secondary pions
Kaons

Accuracy within 30%

Badhwar GD, 1997
Evaluation of Detector Response
- TEPC Response for Trapped Protons on STS-89 -

Integral Flux, (cm² sr day⁻¹)

without TEPC response

with TEPC response

0† (x100)
5† (x10)
7† (x1)
9† (x0.1)
Phantom Torso Experiment (PTE) of ISS/STS

TLD Dose Contours of Brain Slice

Yasuda et al., 2002

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Measured</th>
<th>HZETRN/QMSFRG</th>
<th>Difference (%)</th>
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</thead>
<tbody>
<tr>
<td>Skin</td>
<td>4.5±0.05</td>
<td>4.7</td>
<td>4.4</td>
</tr>
<tr>
<td>Thyroid</td>
<td>4.0±0.21</td>
<td>4.0</td>
<td>0</td>
</tr>
<tr>
<td>Bone surface</td>
<td>5.2±0.22</td>
<td>4.0</td>
<td>-23.1</td>
</tr>
<tr>
<td>Esophagus</td>
<td>3.4±0.49</td>
<td>3.7</td>
<td>8.8</td>
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<tr>
<td>Lung</td>
<td>4.4±0.76</td>
<td>3.8</td>
<td>-13.6</td>
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<tr>
<td>Stomach</td>
<td>4.3±0.94</td>
<td>3.6</td>
<td>-16.3</td>
</tr>
<tr>
<td>Liver</td>
<td>4.0±0.51</td>
<td>3.7</td>
<td>-7.5</td>
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<tr>
<td>Bone marrow</td>
<td>3.4±0.40</td>
<td>3.9</td>
<td>14.7</td>
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<tr>
<td>Colon</td>
<td>3.6±0.42</td>
<td>3.9</td>
<td>8.3</td>
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<tr>
<td>Bladder</td>
<td>3.6±0.24</td>
<td>3.5</td>
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<tr>
<td>Gonad</td>
<td>4.7±0.71</td>
<td>3.9</td>
<td>-17.0</td>
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<tr>
<td>Chest</td>
<td>4.5±0.11</td>
<td>4.5</td>
<td>0</td>
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<tr>
<td>Remainder</td>
<td>4.0±0.57</td>
<td>4.0</td>
<td>0</td>
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<tr>
<td>Effective dose</td>
<td>4.1±0.22</td>
<td>3.9</td>
<td>-4.9</td>
</tr>
</tbody>
</table>

Yasuda et al., 2002

Active Dosimetry Data, mGy/d

<table>
<thead>
<tr>
<th>Organ</th>
<th>Trapped</th>
<th>GCR</th>
<th>Total</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain</td>
<td>0.051</td>
<td>0.066</td>
<td>0.077</td>
<td>0.127</td>
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<tr>
<td>Thyroid</td>
<td>0.062</td>
<td>0.072</td>
<td>0.074</td>
<td>0.136</td>
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<tr>
<td>Heart</td>
<td>0.054</td>
<td>0.061</td>
<td>0.075</td>
<td>0.129</td>
</tr>
<tr>
<td>Stomach</td>
<td>0.050</td>
<td>0.057</td>
<td>0.076</td>
<td>0.126</td>
</tr>
<tr>
<td>Colon</td>
<td>0.055</td>
<td>0.056</td>
<td>0.073</td>
<td>0.128</td>
</tr>
</tbody>
</table>

Cucinotta FA et al., 2008
Annual Effective Dose for Male

- Annual GCR at Solar Minimum in Interplanetary Space
- Annual GCR at Solar Maximum in Interplanetary Space
- Annual Exposure at LEO (51.6°x400 km) at Solar Minimum
- Annual Exposure at LEO (51.6°x400 km) at Solar Maximum
Model-based Prediction of SPE Occurrence

Cycle 19                    Cycle 20                        Cycle 21                     Cycle 22                      Cycle 23

SPE onset date

Date

\( \lambda(t) \), events/day

0.005 0.01 0.015 0.02 0.025 0.03 0.035 0.04

2/1/54 2/1/58 2/1/62 2/1/66 2/1/70 2/1/74 2/1/78 2/1/82 2/1/86 2/1/90 2/1/94 2/1/98 2/1/02 2/1/06
Model-based Prediction of SPE Fluence

Propensity of SPEs: Hazard Function of Offset $\beta$ Distribution Density Function

$$\lambda(t) = \frac{\lambda_0}{4000} + \frac{K}{4000} \frac{\Gamma(p + q)}{\Gamma(p)\Gamma(q)} \left( \frac{t}{4000} \right)^{p-1} \left( 1 - \frac{t}{4000} \right)^{q-1} \quad (0 \leq t \leq 4000)$$

[Graph showing fluence vs. mission duration with percentile markers and the Carrington Event]
Effective dose on Mars Surface with MOLA Topography

<table>
<thead>
<tr>
<th>Altitude, km</th>
<th>T, °C</th>
<th>p, kPa</th>
<th>Atmospheric shielding thickness, g/cm²</th>
<th>Low density model</th>
<th>High density model</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.0</td>
<td>-41.16</td>
<td>0.34</td>
<td>0.14</td>
<td>0.19</td>
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<tr>
<td>4.0</td>
<td>-34.99</td>
<td>0.49</td>
<td>6.73</td>
<td>9.25</td>
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<tr>
<td>2.0</td>
<td>-33.00</td>
<td>0.58</td>
<td>10.97</td>
<td>15.08</td>
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<tr>
<td>0.0</td>
<td>-31.00</td>
<td>0.7</td>
<td>16.00</td>
<td>22.00</td>
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<tr>
<td>-2.0</td>
<td>-29.00</td>
<td>0.84</td>
<td>19.04</td>
<td>26.17</td>
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<tr>
<td>-4.0</td>
<td>-27.01</td>
<td>1.00</td>
<td>22.64</td>
<td>31.13</td>
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</tr>
<tr>
<td>-8.0</td>
<td>-23.02</td>
<td>1.44</td>
<td>32.00</td>
<td>44.00</td>
<td></td>
</tr>
</tbody>
</table>

August 1972 SPE

Annual GCR at Solar Minimum
Conclusion

• Highly accurate descriptions of space environment models are available:
  ➢ Inter-stellar GCR composition accuracy: ~5% for abundant elements (oxygen, carbon, and iron); less than 10% for all major GCR components; and solar modulation parameters with the 98.9% correlation in various spacecraft measurements.
  ➢ Probabilistic SPE occurrence model as a tool for managing the risk.
    ➢ Comprehensive catalogue of GLE fluences and spectra assembled for shielding design application using satellites and NM spectra;
• Radiation transport codes have been validated extensively:
  ➢ QMSFRG model agrees for absorption $\sigma$-section within +5% and elemental fragment $\sigma$-section ±25%.
  ➢ Good agreement found from inter-comparisons of transport codes.
  ➢ Comparison of model prediction to flight measurements: accuracy less than 15% for GCR dose rates; ~25% for secondary particles; and ±30% for quality factors by TEPC.
  ➢ Minor scientific questions remained: low-energy light ion cross section, albedo protons, secondary pions, and kaons.
• Space Radiation Shield Design Tool for the reliable and realistic radiation simulation in the early design process of exploration missions:
  ➢ Environmental models, shielding and body geometry models, atomic and nuclear interaction and fragmentation models are incorporated.