Benchmark Analysis for Space Radiation Transport Codes in Thick Shielding for GCR Environments

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Outline

- Background
- Simulation setup
- Results
- Summary
Background

• Updates to HZETRN revealed a minimum in the dose equivalent versus aluminum response curve
  – Mainly driven by neutron build-up in thick shielding in front of and behind target
  – Pion and electromagnetic cascade also contributes
  – Changes long standing shield design paradigm

• A program is underway to verify and validate this minimum
  – Verification: comprehensive and detailed benchmark calculation with transport models
  – Validation: thick shield experimental effort being conducted at NSRL
  – Both efforts are feeding into an uncertainty quantification effort that will inform risk assessment and probabilistic design
Background

• Previous benchmarks have been limited by computational resources
  - Monte Carlo simulations are computationally expensive
  - Comparisons typically focused on a limited set of shield configurations and inputs
  - Output quantities not always carefully aligned in Monte Carlo results

• Current set of benchmarks are more detailed and comprehensive than previously performed
  - Range of aluminum shield thicknesses being evaluated
  - “Important” components of the GCR environment considered separately
  - Range of output quantities (flux, dose, dose equivalent, LET spectra) being examined

• FY2015 benchmarks required ~100 years of CPU time (simple geometry)
  - 4 Monte Carlo codes run at LaRC and JSC on three different clusters
  - HZETRN results run on a desktop PC in minutes
Simulation Setup

• Slab with equal thickness of shielding in front and behind a thin (0.03 mm) water target
  - Considered a range of thicknesses from 0 g/cm² to 100 g/cm²
  - Aluminum and polyethylene considered as shielding materials

• 1977 solar minimum GCR environment boundary condition
  - Considered each ion individually with greater emphasis on more abundant ions
  - Connects with ions considered in measurement phase of project
Simulation Setup

- Utilized 3 Monte Carlo codes along with most recent version of HZETRN

- Geant4, FLUKA, PHITS
  - Utilized 2 different heavy ion physics packages in Geant4 (QMD and INCLXX)
  - Essentially like having an extra Monte Carlo code

- 3DHZETRN
  - Evaluated 3 different levels of physical transport approximations
    - N=1: Straight-ahead approximation
    - N=2: Bi-directional
    - N=34: 3D treatment for neutrons and light ions
Results

Dose equivalent from $Z > 8$ for the full GCR boundary condition

- Codes in very good agreement for heavy ions with $Z > 8$
  - Includes primary heavy ions and heavy projectile fragments
  - Excludes target fragments and light particles (neutrons and $Z \leq 2$)
  - Variation is driven by heavy ion nuclear physics model uncertainty
Results

Dose equivalent from $Z > 2$ for the full GCR boundary condition

- Heavy target fragments ($Z = 3-8$) increase variation in code results
  - Includes primary heavy ions, heavy projectile fragments, and heavy target fragments
  - Variation appears to be larger for aluminum than polyethylene
  - Variation is still driven mainly by nuclear physics model uncertainty
Results

Dose equivalent from *neutrons and ions* for the full GCR boundary condition

- Local minimum in aluminum shielding curve now apparent with neutron and light ions ($Z \leq 2$)
  - Includes everything except pion, muon, and electromagnetic components
  - 3D transport errors clearly visible
  - Variation is mainly driven by uncertainty in light ion production models
Results

*Total* dose equivalent for the full GCR boundary condition

- Monte Carlo codes showing deeper minimum in aluminum than 3DHZETRN
  - Minimum and variation would be suppressed in finite geometry with tissue shielding
  - Local minimum is shifted closer to 20 g/cm² instead of 40 g/cm²
  - Measurements plan has been adjusted accordingly
Results

$^3$He flux behind 20 g/cm$^2$ aluminum shielding for the full GCR boundary condition

- Large variation in secondary light ion fluxes ($^2$H, $^3$H, $^3$He)
  - Neutrons and protons do not show significant variation
  - Alphas show some variation, but not as large as $^2$H, $^3$H, $^3$He
  - Measurements focusing on light ion production (energy and angle)
Conclusions

• Updates to HZETRN revealed a minimum in the dose equivalent versus aluminum response curve

• A program is underway to verify and validate this minimum
  – Initial verification results were presented

• Both 3DHZETRN and Monte Carlo codes show a minimum in the dose equivalent versus aluminum thickness curve near 20 g/cm²
  – Large model uncertainties for light ion production
  – Nucleon and light ion production are the main contributors to the build-up in exposure beyond the minimum
  – Benchmark results are helping to guide and focus ongoing development of 3DHZETRN