

Steve Koontz, Ph. D. – ISS System Manager for Space Environments
NASA, Johnson Space Center, Houston, Texas
Outline

1) Space Radiation: What is it, where is it, and why is it so hard to manage?
   - The space radiation environment is radically different from Earth surface radiation environments
   - Space radiation effects are determined primarily by highly energetic (often relativistic) charged particles - the term “ray” is an historical misnomer from the early 1900s
     - Galactic cosmic “rays”, solar particle events, and radiation belts - high energy (fast) charged particles and a few high energy photons dominate the environment

2) How does space radiation interact with matter (i.e. us and our stuff)
   - Direct Ionization/Excitation (Particle Tracks) - health effects and microelectronics, materials
   - Nuclear Reactions and Secondary Particle Showers (and more ionization tracks) – health effects and microelectronics
   - Displacement damage – Optoelectronics (solar cells, light emitting diodes, photodiodes etc.

3) Space Station Zero - Space Radiation Shielding Specification, Shielding Mass, and Magnetic Shielding in Perspective with humanities oldest spacecraft
   - Shielding Mass and Magnetic field
   - Shielding performance - Earth Surface Environments
   - Shielding performance - Commercial and Military Aircraft Environments

4) International Space Station - Space Radiation Shielding Specification, Shielding Mass, and Magnetic Shielding
   - Geomagnetic field
   - Spacecraft Shielding Mass
   - Shielding performance - electronic systems - internal and external
   - Shielding performance - surface materials

5) Summary and Conclusions

6) Supporting Information and References
   - A listing of space radiation environment, transport, and analysis/modeling tools and where to obtain them
     - Monte Carlo Simulators – FLUKA and related Monte Carlo codes
     - Boltzmann codes – CRÈME-96, HZETRN 2015
   - A short bibliography and resource list
1.0: Space Radiation: What is it, where is it, and why is it so hard to manage?

- **Important space radiation characteristics**
  - **Origin** - Where are they from and how are they formed?
  - **Composition** – Ions, electrons, or photons and of what kind?
  - **Flux and Fluence (abundance)** - how many per square cm per unit time (isotropic in free space except photons)?
  - **Energy Spectrum** - how many particles in each energy interval over the relevant range of values. Energies measured in electron volts (eV) – usually millions (MeV), billions (GeV), and trillions (TeV) of electron volts

- **Galactic cosmic rays (GCR)**
  - **Origin** - outside the solar system but inside the Milky Way galaxy for the most part (supernovae & other extreme events)
  - **Composition** - atomic nuclei (and a few gamma rays) - the all elements of the periodic table are represented
    - 87% protons, 12% He nuclei, 1% heavier nuclei, smaller flux of energetic gamma ray photons
  - **Flux and fluence (abundance)** - about 0.1/(cm² sec) at the top of earth’s atmosphere and about 0.5/(cm² sec) in interplanetary space (geomagnetic shielding) - GCR flux modulated significantly by the 11 year solar cycle
  - **Energy spectrum** - Most energetic charged particle population – most are relativistic or ultra-relativistic, traveling very close to the speed of light - Most in the energy range between **100 MeV to 100 GeV and greater**

- **Solar particle events**
  - **Origin** - solar flares and coronal mass ejections (these can also produce high fluxes of X-rays that can damage spacecraft surface materials)
  - **Composition** - mostly protons/electrons with small percentage of heavier ions
  - **Flux and fluence** - $10^3$ to $10^4$ protons/(cm² sec) at $E > 100\text{MeV}$ - SPEs are of short duration – 2 to 3 days typically
  - **Energy and spectrum** - 10 MeV to 1 GeV

- **Trapped Radiation – confined to planetary radiation belts**
  - **Origin** – Uncertain at this time – some contribution from decay of neutrons produced by GCR interactions with Erth’s atmosphere and some from capture of solar particle event protons and electrons
  - **Composition** – Protons and electrons for the most part
  - **Flux and fluence** - up to $10^5$ per cm²/sec
  - **Energy and spectrum** – 10 MeV to 100 MeV
What kind, how much, when and where


Solar cycle modulation of galactic cosmic rays in the interplanetary environment. The Earth’s geomagnetic field further reduces GCR flux in LEO in a latitude dependent manner.
2.0: How does space radiation interact with matter?
(that is with us, our stuff, and our shielding materials)

Energetic charged particle interactions with target materials:
Three basic physical processes

1. Energy loss (dE/dx) by direct ionization/excitation of material along the particle track (The Electromagnetic Force – collision with electrons)
   - Direct ionization effects – linear energy transfer (LET) – “slowing down”
   - Primary cause of single event effects (SEE) in susceptible electronic devices
   - Primary cause of total ionizing dose effects in susceptible electronic devices
   - Primary cause of human health effects
   - Damage to some spacecraft materials

2. High energy collisions (inelastic/hadronic) triggering nuclear reactions (The Strong or Nuclear Force – collision with atomic nuclei)
   - Nuclear hadronic reactions initiate secondary particle showers in the target mass
   - Further collisions of secondary particles with target nuclei lead to expansion and propagation of the secondary particle shower
   - Secondary particles can produce direct ionization and more nuclear reactions

3. Collisions with material nuclei that produce displacement damage (The Electromagnetic Force again – collision with nuclei without nuclear reaction)
   - Displacement of target atoms so as to disrupt crystal structure (solids materials only – important for spacecraft optoelectronics, i.e. PV power systems)
The Electromagnetic Force - Direct ionization & excitation (electromagnetic force) of target substance

- High speed charged particles decelerate by losing energy to target substance electrons during cumblic collisions leaving an ionization/excitation damage track
  - Nuclear collisions make little contribution to deceleration except at the lowest kinetic energies near end of track (displacement damage) but are the cause of secondary particle showers and limit the distance traveled by very high energy primary CR particles

- \( \frac{dE}{dx} \) is the rate of energy transfer: keV/micron or MeV-cm\(^2\)/mg in a particular target substance
  - Linear and nearly constant over most of the particle range - **hence the term linear energy transfer (LET)**
  - Nonlinear near end of track – most of the energy is deposited near the end of track in the “Brag Peak”; basis of accelerator hadron therapy for certain cancers

- Quantified by the relativistic Bethe-Bloch equation

\[
- \frac{dE}{dx} = \frac{4\pi \cdot nz^2}{m_e c^2 \cdot \beta^2} \cdot \left( \frac{e^2}{4\pi \varepsilon_0} \right)^2 \cdot \ln \left( \frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2
\]

- **Projectile (space radiation particle) dependencies**
  \( \beta = v / c; \ v = \) velocity of the particle; \( E = \) energy of the particle; \( x = \) distance travelled by the particle in the target;
  \( c = \) speed of light; \( z = \) particle charge; \( \varepsilon_0 = \) vacuum permittivity

- **Target substance dependencies**
  \( I = \) mean excitation potential of the target = 10eV(Z), \( n = \) electron density of the target \( = \frac{N_A Z \rho}{A M_u} \); \( \rho = \) density of the target; \( Z = \) target atomic number; \( A = \) target atomic mass number; \( N_A = \) Avogadro number; and \( M_u = \) Molar mass constant = 1 in Si units; \( e = \) charge of the electron; \( m_e = \) rest mass of the electron
The Electromagnetic Force - Direct ionization & excitation (electromagnetic force) of target substance

Single event upset (SEU) in a MOS/CMOS Field effect transistor. The space radiation single event environment is an important consideration for spacecraft and aircraft reliability. The figure on the right should read high energy proton or neutron.
The Strong Force - Nuclear Reactions and Secondary Particle Showers

- Inelastic Nuclear collisions attenuate the primary flux exponentially and generate secondary particle showers via nuclear reactions
  - \( N(l) = N(0) \exp(-l/\lambda) \)
  - \( \lambda = \) inelastic collision length (grams/cm\(^2\))
  - \( l = \) thickness in g/cm\(^2\)
  - \( \lambda \) ranges from 42 g/cm\(^2\) to 118 g/cm\(^2\) for protons in various materials
  - At fixed target mass, number of collisions decreases with increasing atomic weight (i.e. fewer target nuclei per gram)
  - \( \lambda \) Scales as (projectile atomic number\(^{0.77}\))
  - \( \lambda \) increases with target atomic number
  - \( <n_{\text{event}}> \) = average number of secondary particles per single collision event
  - \( <n_{\text{collision}}> \) is proportional to \( A(\text{projectile}) \times A(\text{target}) \times \) (average nuclear thickness function) and collision energy
  - \( <n_{\text{shower}}> \) is proportional to primary projectile energy

Generic GCR secondary particle shower nuclear reaction products

Mg nucleus cosmic ray emulsion “star”, i.e. nuclear reaction event- Albert Lim (2000)

Danysz and Pniewski, Philosophical Magazine 44 348 (1953);
The interactions of 3 types of very-high-energy particles (gamma-ray, proton and Carbon-13 nucleus) were simulated. The fully developed atmospheric particle showers (red) are shown including the Cherenkov light (blue) just before impact on the ground. Even though the 3 particles have the same initial energy, the most intense Cherenkov light is produced by the gamma ray, less by the proton, and the least by the Carbon nucleus. Each time a very-high-energy particle interacts in the atmosphere, fluctuations cause the shower to develop differently. Shown here are pretty 'average' looking showers. (2012 Martin Schroedter, VERITAS and Harvard Smithsonian Center for Astrophysics)
And what does all this look like?

A photograph of the central region of a small, vertically incident air shower as seen by the University of Leeds close packed horizontal array of discharge chambers (5 x 5 meters) Leslie Hodson 1990 (from Gaisser, T. K.; Cosmic Rays and Particle Physics, Cambridge University Press, Cambridge, 1990, Frontpiece)
Some General Features of Space Radiation

- In free space, **charged particle flux is approximately isotropic, or nearly so, in all cases**, so no shadow shielding (except by planets, asteroids, moons etc.)
  - Fraction of $4\pi$ steradians covered by shielding mass is important
    - Any area on a sphere, totaling the square of its radius and observed from its center, subtends precisely one steradian.

- **Energetic photons are not isotropic: line-of-sight to source**
  - Shadow shielding can work for X-ray flares

- **Low energy particles/photons are much more abundant than high energy particles/photons**
  - Penetration of active or passive shielding depends on particle kinetic energy:
    - high energy => greater penetration so we have,
  - High spacecraft skin dose – and rapidly decreasing dose as shielding mass increases
    - Greatest % reduction in the first 1 to 10 g/cm$^2$
    - Much lower % reduction as shielding mass increases beyond 10 g/cm$^2$

- How and where the dose is distributed in a particular object (Dose/Depth for spacecraft, asteroids, moons, planetary surfaces and atmospheres etc.) depends on the ionizing radiation environment and how that environment interacts with that objects configuration and materials

ISS Design Environment - electron and proton dose to the center of an aluminum sphere of radius = shielding thickness in mils (1 mil = 0.025 mm)
Some Spacecraft Radiation Shielding Basics

- Shielding mass is measured in units of areal density (g/cm²)
  - Shielded spacecraft weight increases with spacecraft surface area
- Look for the material with the best total ionizing dose (TID) reduction per unit areal density to minimize spacecraft mass for a given dose or particle flux reduction
- Minimize magnitude of secondary particle showers
  - Minimize average atomic number and maximize hydrogen content
  - Chemically and thermodynamic stability are required (problem for LH2)
  - Avoid high Z materials like lead or tungsten (unless you really need to block energetic electrons and/or x/γ rays and the secondary particle shower cost is acceptable - e.g. Juno)
- Engineering Materials Examples:
  - Polyethylene, polypropylene, water, methane, ammonium borohydride (unstable) and related low Z hydrides, etc.
- Spacecraft materials that can also serve as shielding:
  - Low Z propellants and consumables (CH₄, hypergolics, H₂O, clothing, food, etc.)

https://srag.jsc.nasa.gov/Publications/TM104782/techmemo.htm

Point Dose (exaggerates material differences) calculations with HZETRN - Interplanetary environment

FLUKA calculation of Al vs PE shielding material effect on > 0.1 LET particle flux – interplanetary environment
Shielding materials effects and heliospheric (solar cycle) magnetic shielding compared for human interplanetary flight

NASA HZETRN 2010 estimates of crew dose vs. shielding mass for a 3 year interplanetary mission assuming solar maximum and solar minimum GCR environments and no SEP event contributions. Putative 10 cSv and 100 cSv flight crew career dose limits are compared.

3.0: Space Station Zero (aka Earth)
Space Radiation shielding specifications and performance summary

1) **Structural shielding mass**
- Diameter = 12,756.3 km
- Mass = $5.9736 \times 10^{24}$ kg
- Composition – silicate rock with iron core (slightly radioactive from naturally occurring radioisotopes)
- At surface, blocks all space radiation over $\sim 2\pi$ steradians (under your feet)

2) **Atmospheric shielding mass**
- Thickness = $\sim100$ km ($1033$ g/cm$^2$) measured along a radius
- Mass = $5.1480 \times 10^{18}$ kg
- Composition - 77% nitrogen, 21% oxygen, with traces of argon, carbon dioxide and water (note – low Z elements)
- Accounts for most space radiation shielding effect for the remaining $2\pi$ Sr (overhead) and synthesis of cosmogenic radioisotopes

3) **Geomagnetic field** - At the Earth's surface ranges from 25 to 65 microteslas (0.25 to 0.65 gauss). Effectively blocks solar wind. Mitigates GCR and SPE in an altitude and latitude dependent manner.
Shielding Performance - Earth Surface Environments

- Earth surface ionizing radiation dose environments are dominated by natural radioisotope decay and man-made radiation sources
  - **Radon gas is the most important contributor**
- CR contributions are on the order of 10% of the natural environment

Performance - Roughly 2 to 8 mSv (~ 0.2 to 0.8 rad) per year at/near the surface
Shielding performance - Earth’s atmosphere

The Pfotzer Maximum: GCR + Earth’s Atmosphere

Average ISS hourly crew dose rates are on the order of 20 µSv/hr – comparable to rates for high altitude aircraft at high latitudes

Want to experience space radiation? – buy a plane ticket for a polar route flight
Solar Cycle Modulation of GCR Flux: Monitoring GCR secondary particle shower neutrons (http://neutronm.bartol.udel.edu/)

![Graph showing smoothed sunspot number and neutron monitor data](http://sidc.be/silso/datafiles)

Source: WDC-SILSO, Royal Observatory of Belgium, Brussels

Thule, Greenland, Neutron Monitor
Bartol Research Institute, University of Delaware
27-day Averages - data through June 2016

R.Pyle, June 2016
Recent example of atmospheric neutron (GCR secondary shower products) effects on supercomputer and commercial aircraft systems (Steve Wender, LANL 2013)

Results of LANSCE/WNR measurements determine problem with ASCI Q-Machine

- The ASCI Q-Machine has 2048 nodes with a total of 8192 processors.
- During commissioning, it was observed that the Q-machine had a larger than expected failure rate. Approximately 20 fails / week (~3 fails / day).
- The question was whether this could be the result of neutron single-event upset.

The neutron environment and the system response was measured

- The neutron intensity was measured in the Q-Machine room. The values obtained agreed with the Goldhagen values.
- The system response was measured by putting one module of the Q-Machine in the LANSCE/WNR beam.
- Results of measurement accounted for approximately 80% of the failures. (IEEE Trans. Dev. Mat. Reliab. 5 2005)
- The failures were traced to a cache memory that was not error corrected.
- This result may have significant impact on future large computer systems.

One neutron can stop a calculation

The LANSCE neutron spectrum is very similar to the cosmic-ray-induced neutron spectrum, but it is more than five orders of magnitude more intense. The WNR flux is shown in red, and the Cosmic ray flux is shown in blue.
And what does all this look like (Solar Particle Event)?

Video clip of 7/14 to 7/15 2000
SEP as viewed by SOHO spacecraft

Video clip of 7/14 to 7/15 2000
SEP protons impacting of Earth as viewed by IMAGE spacecraft (SEP proton induced O fluorescence)
4.0: International Space Station
Space radiation shielding specification and performance summary

- ISS Space Radiation Control Design Requirements (SSP-41000) - \textbf{None}
  - Primary/secondary structure determined by launch loads and dynamics, pressure vessel safety, and MM/OD protection
  - Materials and avionics to meet performance/safety requirements for the life of the vehicle without special shielding mass considerations
    - Natural Environment Definition for Design – SSP-30512, 500 km/51.6°
      - Worst-Case - we don’t fly above 420 km (Soyuz/Progress certification limits)
    - ISS must fail safe and recover from a “worst case” SPE defined in 30512
  - Crew Radiation dose administrative limits enforced by tracking accumulated crew dose and \textit{limiting crew exposure time} (i.e. \textit{limiting stay time on ISS to limit total dose per expedition} – “number of safe days in space”)
    - Worst-case stay time must be compatible with planned crew change out flight rate
    - Safety requirements (SSP-50021) limits crew dose to less than 40 cSv per year

- So, how did this approach work?
  - No space radiation induced materials or avionics hard failures to date and none expected before end of Program
  - No documented exception to expedition crew dose limits (that I know of – check with the JSC/SRAG on this)
ISS shielding total ionizing dose performance

• External (outside the pressurized volume) Materials and Systems
  – Shielding mass distribution functions are highly anisotropic and median ranges from zero to more than 10 g/cm²
  – Trapped radiation (protons and electrons) dominates (SAA and high latitude regions) – GCR contribution negligible is compression
    • Highly variable environment – altitude, solar activity, and solar cycle effects
  – Boeing Radiation Effect Lab thermo-luminescent dosimeter measurements on MISSE-1, 2, and 3 ISS payloads (Wert, Normand, Perry, Pippin, Bartholet; NSMMS June 2010)
    • Median shielding mass ranges 0.0 to 0.9 g/cm²
    • 4-year-doses range from $3 \times 10^3$ rads (Si) at 0 g/cm² to $10^2$ rads (Si) at 0.9 g/cm²
      – All well below the annual worst-case Design/Verification Environment (SSP-30512) doses at the corresponding shielding thicknesses ($10^6$ rads (Si) @ 0.0 g/cm², and $3 \times 10^5$ rads (Si) @ 0.9g/cm²)

• Internal (inside the pressurized volume) Materials and Systems
  – Shielding mass distribution functions are more isotropic with ranges from 10 g/cm² to more than 100 g/cm² (aluminum with cargo, avionics and consumables) with median values of 40 to 50 g/cm² (e.g. US Lab module)
  – Pre-flight annual dose estimates (using the SSP-30512 Design/Verification Environment) for the US Lab module range from 8 rads (Si) to 21 rads (Si) with a median value of about 14 rads (Si) depending on location of the dose point
    • Variable environment – altitude, solar activity, and solar cycle effects
  – In-flight TLD measurements during solar max ranged from 4.5 rads (Si) to 8.2 rads (Si) per year. DOSTEL (particle hodoscope) measurements averaged to 7.1 rads Si per year (Reitz et al, AIAA 2001-4903)
  – In-flight solar minimum measurements (Kodiara et. Al, 2013) 11.1 rads (H2O)/year ~ 8.59 rads (Si)/year
ISS Crew Shielding Augmentation Work

- Modeled dosimetry – 4.7 g/cm² polyethylene, inside ISS, solar minimum – Annual dose to blood forming organs (BFO) in cGy (rads) - Calculated with HZETRN

Shavers, Mark; “Radiation Measurements and Shielding Analysis for ISS, Workshop on Radiation Monitoring for the International Space Station, Vienna Austria, Sept 8-10, 2004,
http://www.iss-casis.org/files/CASIS_RFP_2013-3_Radiation_Measurements_and_Shielding_Analysis_for_ISS.pdf

<table>
<thead>
<tr>
<th>Radiation source</th>
<th>Without poly shield</th>
<th>With poly shield</th>
<th>Percent reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trapped protons</td>
<td>4.234</td>
<td>2.664</td>
<td>37.2%</td>
</tr>
<tr>
<td>Galactic Cosmic Radiation</td>
<td>4.782</td>
<td>4.708</td>
<td>1.8%</td>
</tr>
<tr>
<td>Combined (GCR + Trapped)</td>
<td>9.016</td>
<td>7.373</td>
<td>18.4%</td>
</tr>
</tbody>
</table>

In-flight measurement results for “TeSS” poly shielded crew quarters:
1) ~ 20 percent reduction Equivalent dose in personal dosimeters
2) ~ 40% reduction in ISS crew chromosome damage via biosimetry
Cosmic Ray Exposure Environments: Low-Earth Orbit Vs Interplanetary Space at 1 AU
Eight most abundant GCR nuclei (98+\% of total flux) - Benefits of Geomagnetic Shielding for ISS

Interplanetary Environment at 1 AU: No geomagnetic shielding; direct solar particle event exposure; solar cycle modulation

Low-Earth orbit (ISS) environment: Latitude dependent geomagnetic shielding; Latitude dependent solar particle event exposure

Latitude dependence of GCR spectrum for ISS orbit - AMS-1/STS-91. Higher magnetic latitude \(\Rightarrow\) Reduced geomagnetic shielding and greater similarity to interplanetary GCR environment

Steve Koontz, Brandon Reddell, Paul Boeder:

Bobik, P., Boschini, M., Gervasi, M., Grandi, D., Kudela, K., Micelotta, E.;
And what does all this look like?
GCR and trapped proton single event upsets detected and corrected by Error Detection And Correction (EDAC) firmware in the ISS computer system (aka MDM) Dynamic Random Access Memory (DRAM). EDAC operation is part of the nominal system design, and does not indicate a failure or anomaly.

Multiplexer-De-Multiplexer (MDM)
MDM System monthly SEU count: Inside the SAA (trapped protons) Increasing shielding mass reduces internal MDM SEU count
MDM System monthly SEU count: Outside the SAA (GCR)
Increasing shielding mass increases internal MDM SEU count
GCR appears to be the leading cause of ISS SEE attributable MDM functional interrupts or “lock-ups” that require power cycling and rebooting/resynchronizing to correct, a process requiring 8 to 12 hours to complete.
Representative ISS T61P personal computer system (PCS) single event functional interrupt (SEFI) map – Recovered by power cycling and reboot.

Geographic distribution of 80 observed T61P PCS on-orbit lock-ups and disconnects - 2011 to 2014. Looking at the T61p lockup and disconnect data at ~400 km from July 2011 to July 2014, the shortest time interval between PCS lockups is 4.15 hrs The average interval is ~304 hrs and the maximum is >1800 hrs. About half of the events occur at high latitude and between 10-20% of the events occur in the SAA region.

Population Size = 7 T61Ps, mean MTBF = 82.1 days, standard deviation = 32.2 days

Note that there are a number of constraints on using the PCS system for safety critical operations given the expected and observed SEFI rate.
In-flight vs. calculated spacecraft device SEU rates


Shielding Mass Rate Ratio = \( \frac{10 \text{ g/cm}^2 \text{ Rate}}{40 \text{ g/cm}^2 \text{ Rate}} \)

<table>
<thead>
<tr>
<th>Device</th>
<th>Rate Ratio - Flight</th>
<th>Rate Ratio - FLUKA</th>
<th>Rate Ratio - CREME 96</th>
<th>Rate Ratio - FOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>TI (1M x 4) TMS44400</td>
<td>1.2</td>
<td>1.2</td>
<td>3.5</td>
<td>3.7</td>
</tr>
<tr>
<td>TI (4M x 4) TI SMJ41640</td>
<td>0.9</td>
<td>1.8</td>
<td>3.4</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Note that only FLUKA correctly quantifies the shielding mass (i.e. secondary particle shower) effects for the ISS TI CMOS DRAM.

\[
\sum_i \left[ \frac{(X_i - \text{FLUKA}_i)^2}{(X_i)^2} \right]^{0.5} = 5.7 \quad \sum_i \left[ \frac{(X_i - \text{CREME}_i)^2}{(X_i)^2} \right]^{0.5} = 10.6 \quad \sum_i \left[ \frac{(X_i - \text{FOM}_i)^2}{(X_i)^2} \right]^{0.5} = 26.8
\]

Using the same device parameters, the FLUKA based rate calculations show the smallest least squares error and overall acceptable performance compared to CREME-96 and the Peterson FOM, providing some validation for the FLUKA based methods described here.
A graphic example of how different it is on ISS:
CR-39 plastic nuclear track detectors (PNTDs) – 925 days inside the ISS US Lab.

Ground Control PNTD

Flight PNTD

Flight PNTD surface in contact with 0.005 cm Pb foil

High Z elements, like Pb, produce more secondary particle shower products than low Z elements

The obvious differences between the flight-PNTD and the Pb-foil-flight PNTD are expected as a result of nuclear reactions, caused by space radiation primary and secondary particles, in the Pb foil with smaller contribution from trace (ppm level) Th and U impurities in the Pb foil itself. Ag, Hf, and W foils produced many fewer nuclear reaction products in their PNTDs. Track area increases with increasing particle LET.
The effects of energetic cosmic ray, solar particle event, and trapped radiation charged particles on contemporary electronic systems as well as human health and safety depends on:

- The production of ionization/excitation tracks in target materials
- Nuclear collisions with target material nuclei to initiate secondary particle showers that create even more ionization/excitation

Secondary particle shower species, especially neutrons, can dominate effects on electronic systems and human health at high shielding mass

- Earth surface operating environments
- High altitude aircraft operating environments
- “Heavily” shielded human spacecraft, like ISS
- In massive targets, like the human body, secondary particle showers can contribute on the order of 50% of the total body dose expressed in Sv, and

SEE effects on electronic systems can be managed by: 1) selection of resistant parts, 2) EDAC and FDIR functions, and 3) robust/highly redundant system architectures

- State of the art radiation transport codes are accurate enough to support shielding design and avionics system reliability work

Shielding mass can mitigate electronic system TID and SEE effects from SPE and trapped radiation but is largely ineffective against GCR

5.0 Summary & Conclusions
6.0) Bibliography, Resources, and Back-up
Bibliography and Resources

- [https://srag.jsc.nasa.gov/](https://srag.jsc.nasa.gov/)  JSC Space Radiation Analysis Group (Human Health)
- [https://software.nasa.gov/software/LAR-18803-1](https://software.nasa.gov/software/LAR-18803-1)  HZETRN 2015 home page
- [https://creme.isde.vanderbilt.edu/](https://creme.isde.vanderbilt.edu/)  CREME-96 home page (avionics SEE/TID)
- [http://tec-ees.esa.int/ProjectSupport/ISO/CREME96.html](http://tec-ees.esa.int/ProjectSupport/ISO/CREME96.html)  ESA CREME-96 page
- [https://www.spenvis.oma.be/](https://www.spenvis.oma.be/)  ESA space environments modeling and analysis tools home page
- [http://dev.sepem.oma.be/](http://dev.sepem.oma.be/)  ESA Solar Particle Event modeling and analysis home page
- [http://holbert.faculty.asu.edu/eee560/see.html](http://holbert.faculty.asu.edu/eee560/see.html)  Arizona State university space flight environments effects and analysis home page
- [https://nepp.nasa.gov/](https://nepp.nasa.gov/)  NASA Electronic Parts and Packaging Program home page (SEE/TID effects, testing and analysis)


Typical ISS (Internal) US Lab Shielding Mass Distribution Functions

Typical ISS multiplexer - demultiplexer (MDM) integral shielding mass distribution functions

ISS US Lab HCOR SDRAM integral structural shielding mass distribution functions (typical of lab racks)
1.2: GCR Exposure Environments: Low Earth Orbit (LEO) – Primary CR and secondary particle showers

The differential LET spectra [#//(cm$^2$ week LET)] at various shielding depths in a concentric spherical shell model spacecraft is shown to the right.

LET spectra are calculated, using the FLUKA (1) Monte Carlo radiation transport code, as the number of particles entering each of the Si detector shells placed at various depths in the concentric spherical shell model (see the table below).

All secondary particle shower processes are enabled and full shielding mass distribution function for each Si shell is utilized in a fully three dimensional calculation. Total ionizing dose and nuclear reactions “star” density is also calculated but not reported here.

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**FLUKA (FLUktuierende Kaskade) differential LET Spectra at different shielding masses**

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<table>
<thead>
<tr>
<th>Detector Si Shell</th>
<th>SiDet1</th>
<th>SiDet2</th>
<th>SiDet3</th>
<th>SiDet4</th>
<th>SiDet5</th>
<th>SiDet6</th>
<th>SiDet7</th>
<th>SiDet8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Shell Radius (cm)</td>
<td>5037.4</td>
<td>5037.3</td>
<td>5037.1</td>
<td>5035.6</td>
<td>5033.7</td>
<td>5030.0</td>
<td>5018.9</td>
<td>5000.0</td>
</tr>
<tr>
<td>Si Detector Median Al Shielding Mass in g/cm$^2$</td>
<td>0.15</td>
<td>0.81</td>
<td>1.6</td>
<td>7.9</td>
<td>15.6</td>
<td>31.1</td>
<td>77.5</td>
<td>156.2</td>
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</table>

1.3 GCR Exposure Environments: Interplanetary Environment – Primary CR and secondary particle showers

The differential LET spectra [#/cm² week LET]) at various shielding depths in a concentric spherical shell model spacecraft is shown to the right.

LET spectra are calculated, using the FLUKA (1) Monte Carlo radiation transport code, as the number of particles entering each of the Si detector shells placed at various depths in the concentric spherical shell model (see the table below).

All secondary particle shower processes are enabled and the full shielding mass distribution function for each Si shell is utilized in a fully three dimensional calculation. Total ionizing dose and nuclear reactions “star” density is also calculated but not reported here.

Cosmogenic Nuclides example: $^{10}\text{Be}$ in arctic ice and the Maunder Minimum - Solar wind modulation of GCR
Biological Effects of Cosmic Radiation – Manned Space Flight Environments

**Spaceflight Radiation Examples - Human Spaceflight Mission Type Radiation Dose:**

Assuming 20 to 50 g/cm² Al shielding and not including secondary particle shower effects internal to the human body which can increase effective dose by about 50%.

- **Space Shuttle Mission 41-C** (8-day mission orbiting the Earth at 460 km) - 5.59 mSv
- **Apollo 14** (9-day mission to the Moon) - 11.4 mSv
- **Skylab 4** (87-day mission orbiting the Earth at 473 km) - 178 mSv
- **International Space Station (ISS) Mission** (up to 6 months orbiting Earth at 353 km) - 80 mSv
- **Estimated Mars mission (3 years)** - 1200 mSv

Slow accumulation of whole body dose from GCR (expressed in Effective equivalent Sv) and including secondary particle showers in the human body presently limits the duration of manned space operations outside earth’s magnetosphere to times on the order of 180 days (assuming 20 to 30 g/cm² shielding mass). The overall programmatic cost of the available active or passive shielding needed to extend that limit is likely prohibitive at this time. (Francis A. Cucinotta, Myung-Hee Y. Kim, Lei Ren; “Evaluating shielding effectiveness for reducing space radiation cancer risks,” Radiation Measurements 41 (2006) 1173 – 1185)
GCR Exposure Environments – Earth’s Atmosphere

- **Earth surface/atmospheric environments**
  - 1000 grams/cm² air shielding mass at sea level
  - Latitude dependent geomagnetic shielding
  - GCR secondary particle shower products dominate

- **Commercial and military aviation environments**
  - Altitude dependent air shielding mass
  - Latitude dependent geomagnetic shielding
  - Solar cycle modulation of GCR environment
  - Latitude dependent solar particle event exposure
  - Pfotzer secondary shower particle maximum at about 20 km altitude (mid latitudes)

Relative variation of cosmic ray flux at the earth’s surface as a function of altitude and latitude (Cosmogenic Nuclide Laboratory - University of Glasgow - [http://web2.ges.gla.ac.uk/~dfabel/CN_explain.html](http://web2.ges.gla.ac.uk/~dfabel/CN_explain.html))

A comparison of observed in-flight SPE SEU counts with estimates of SPE SEU counts calculated using the FLUKA radiation transport code and the concentric spherical shell spacecraft model for purposes of spacecraft design and verification, the agreement between the FLUKA based SPE rate estimates and the observed in-flight SPE upset rates is satisfactory, as shown below.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>Cassini/Solid State Recorder DRAM (16)</strong></td>
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<tr>
<td>1) Observed event upsets</td>
<td>1) $4.4 \times 10^{-7}$</td>
<td>1) $4.7 \times 10^{-5}$</td>
<td>1) $2.0 \times 10^{-6}$</td>
<td>1) $1.5 \times 10^{-6}$</td>
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<tr>
<td>2) Estimated event upsets</td>
<td>2) $1.4 \times 10^{-7}$</td>
<td>2) $2.1 \times 10^{-5}$</td>
<td>2) $2.8 \times 10^{-6}$</td>
<td>2) $3.8 \times 10^{-6}$</td>
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<tr>
<td>3) Estimated/Observed</td>
<td>3) 0.32</td>
<td>3) 0.4</td>
<td>3) 1.4</td>
<td>3) 2.5</td>
</tr>
<tr>
<td>4) Quiescent (no-event) daily upset rate</td>
<td>4) $5.8 \times 10^{-8}$</td>
<td>4) $5.9 \times 10^{-7}$</td>
<td>4) $5.3 \times 10^{-8}$</td>
<td>4) $5.3 \times 10^{-8}$</td>
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<td><strong>SOHO /Solid State Recorder DRAM (17)</strong></td>
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<tr>
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<td>1) $4.4 \times 10^{-6}$</td>
<td>1) $4.7 \times 10^{-5}$</td>
<td>1) $2.0 \times 10^{-6}$</td>
<td>1) $1.5 \times 10^{-6}$</td>
</tr>
<tr>
<td>2) Estimated event upsets</td>
<td>2) $2.1 \times 10^{-6}$</td>
<td>2) $2.1 \times 10^{-5}$</td>
<td>2) $2.8 \times 10^{-6}$</td>
<td>2) $3.8 \times 10^{-6}$</td>
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<tr>
<td>3) Estimated/Observed</td>
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<td>3) 0.4</td>
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<tr>
<td>4) Quiescent (no event) daily upset rate</td>
<td>4) $5.9 \times 10^{-7}$</td>
<td>4) $5.9 \times 10^{-7}$</td>
<td>4) $5.3 \times 10^{-8}$</td>
<td>4) $5.3 \times 10^{-8}$</td>
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<tr>
<td><strong>Thuraya/ DSP DRAM (15)</strong></td>
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<tr>
<td>1) Observed event upsets</td>
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<td>1) $2.0 \times 10^{-6}$</td>
<td>1) $1.5 \times 10^{-6}$</td>
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<td>2) Estimated event upsets</td>
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<tr>
<td>3) Estimated/Observed</td>
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<td>NA</td>
<td>3) 1.4</td>
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<td>4) $5.3 \times 10^{-8}$</td>
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