Radiation 101: Effects on Hardware and Robotic Systems

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Objectives

• Increase knowledge of radiation effects amongst
  o Space weather professionals,
  o Space operations community, and
  o Other science and engineering stakeholders.

• Provide overview of
  o Total ionizing dose (TID),
  o Displacement damage (DD) / non-ionizing energy loss (NIEL), and
  o Single-event effects (SEE).

Stop me any time to ask questions
A little history…

• Much of our community’s history is captured in the evolution of the Nuclear and Space Radiation Effects Conference (NSREC), now an Institute of Electrical and Electronics Engineers (IEEE) meeting run by the Nuclear and Plasma Sciences Society.

  o First meetings were 1962/63, but still part of AIEE and IRE/AIEE. 1964 was first official IEEE NSREC.
  o In the beginning, lots of involvement from the nuclear weapons effects community in addition to the civil and military space communities.
  o Just celebrated our 50th anniversary.

A little more history…

- Radiation community started during the Cold War
- Sputnik, 4 Oct 1957
- Van Allen Belts, Jan & Mar 1958 (Explorer I and III)
  - Army Ballistic Missile Agency in Huntsville, AL
- Space Race started; Space Act signed into law by President Eisenhower on 29 Jul 1958
- President Kennedy was in office
  - “Going to the Moon Speech,” 25 May 1961 / 12 Sep 1962
- STARFISH PRIME (Ops. Fishbowl / Dominic), 9 Jul 1962
- Limited Test Ban Treaty, 5 Aug 1963

What are radiation effects?

• Energy deposition rate in a “box”
• Source of energy and how it’s absorbed control the observed effects
What makes radiation effects so challenging?

• Field is still evolving because of the technologies we want to use in space systems

• A problem of dynamic range
  
  ○ Length: $10^{16} \text{ m} \rightarrow 10^{-15} \text{ m}$ (1 light year, 1 fm)
    » $10^{31}$
  
  ○ Energy: $10^{19} \text{ eV} \rightarrow 1 \text{ eV}$ (extreme energy cosmic rays, silicon band gap)
    » $10^{19}$
  
  ○ That’s just two dimensions; there are others.
    » Radiation sources, electronic technologies, etc.

• Variability and knowledge of the environment
Radiation sources

• Primary
  o Galactic cosmic rays (GCRs),
  o Solar protons and heavy ions, and
  o Trapped particles in planetary magnetospheres.

Image credit: Solar Dynamics Observatory/NASA

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What is a rad?

- 1 rad = 100 erg/g = 0.01 J/kg; 100 rad = 1 Gy
  - Always specified for a particular material
  - 1 rad(SiO₂), 10 krad(Si), 100 Gy(H₂O)
- This is absorbed dose, not exposure (R), or dose equivalent (Sv)
- Missions have a wide range of absorbed dose requirements, driven in large part by persistent environment components
  - Trapped particles, solar protons, etc.
What is total ionizing dose?

- Total ionizing dose (TID) is the absorbed dose in a given material resulting from the energy deposition of ionizing radiation.
- Total ionizing dose results in cumulative parametric degradation that can lead to functional failure. This is analogous to wear out.
- In space, caused mainly by protons and electrons.

Examples

<table>
<thead>
<tr>
<th>Metal Oxide Semiconductors Devices</th>
<th>Bipolar Devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold voltage shifts</td>
<td>Excess base current</td>
</tr>
<tr>
<td>Increased off-state leakage</td>
<td>Changes to recombination behavior</td>
</tr>
</tbody>
</table>
Total ionizing dose

- Caused by the energy deposition of protons, electrons, energetic heavy ions, and photon-material interactions – focused on insulators
- Holes build up in deep traps and interface traps, which are manifest as electrical changes in device performance


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What is NIEL?

- Most always applies to protons and electrons.
- Vast majority of incident kinetic energy lost to ionization, creating TID and single-event effects.
- A small portion of energy lost in non-ionizing processes causes atoms to be removed from their lattice sites and form permanent electrically active defects (i.e., displacement damage) in semiconductor materials.
- NIEL (non-ionizing energy loss) is that part of the energy introduced via both Coulomb (elastic), nuclear elastic, and nuclear inelastic interactions, which produces the initial vacancy-interstitial pairs and phonons (e.g., vibrational energy).
What is NIEL?

• Non-ionizing energy causes cumulative damage, much like TID

NSREC: Nuclear and Space Radiation Effects Conference

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What is displacement damage?

- Displacement damage dose (DDD) is the **non-ionizing energy loss (NIEL)** in a given material resulting from a portion of energy deposition by impinging radiation.
- DDD is **cumulative parametric degradation** that can lead to **functional failure**. This is analogous to wear out.
- In space, caused mainly by **protons and electrons**.

<table>
<thead>
<tr>
<th>DDD Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degraded minority carrier lifetime (e.g., gain reductions, effects in LEDs and optical sensors, etc.)</td>
</tr>
<tr>
<td>Changes to mobility and carrier concentrations</td>
</tr>
</tbody>
</table>
Displacement damage, visually

- Pictorial relating the initial defect configuration to the primary knock-on atom (PKA) energy in Si material.
- For recoil energies above a couple of keV, the overall damage structure is relatively unchanged due to the formation of cascades and sub-cascades.
- Which defects are electrically active? Synergy with TID & SEE…

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What is linear energy transfer (LET)?

Stopping power ($S$), depends on target material; LET does not.

\[ S = -\frac{dE}{dx} \implies \text{LET} = -\frac{1}{\rho} \frac{dE}{dx} \]
What are single-event effects?

- A single-event effect (SEE) is a disturbance to the normal operation of a circuit caused by the passage of a single ion (proton or heavy ion) through or near a sensitive node in a circuit.

- SEEs can be either destructive or non-destructive.

### Examples

<table>
<thead>
<tr>
<th>Non-Destructive</th>
<th>Destructive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-Event Upset (SEU)</td>
<td>Single-Event Latchup (SEL)</td>
</tr>
<tr>
<td>Multiple-Bit Upset (MBU)</td>
<td>Single-Event Burnout (SEB)</td>
</tr>
<tr>
<td>Single-Event Transient (SET)</td>
<td>Single-Event Gate Rupture (SEGR)</td>
</tr>
<tr>
<td>Single-Event Functional Interrupt (SEFI)</td>
<td></td>
</tr>
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</table>

Proton SEE notes

• Proton LET is very low (<< 1 MeV-cm²/mg)
  o Upsets are usually dominated by indirect ionization – nuclear reactions
  o Reaction products have appreciable LETs, usually less than 15 MeV-cm²/mg, but short ranges compared to GCRs
  o Since 2007, low-energy proton SEE have become relevant

• Importance of proton SEE
  o In proton-dominated environments, can be a large portion of the overall SEE rate – LEO, for instance
Single-event effects processes

Single-event effects - latchup

• Events are likely due to proton indirect ionization and/or cosmic rays
Single-event effects – sensor corruption

Solar Particle Event Tracks on SOHO LASCO Instrument

• Transient imager corruption due to solar particle event ions striking the device


The SOHO/LASCO data used here are produced by a consortium of the Naval Research Laboratory (USA), Max-Planck-Institut fuer Aeronomie (Germany), Laboratoire d'Astronomie (France), and the University of Birmingham (UK). SOHO is a project of international cooperation between ESA and NASA.
Short history of single-event effects


• First observation of SEUs on earth was in 1978. Observed in RAM caused by the alpha particles released by U and Th contaminants within the chip packaging material and solder. Vendors took specific actions to reduce it. T. C. May and M. H. Woods, "A New Physical Mechanism for Soft Errors in Dynamic Memories", Proceedings 16 Int'l Reliability Physics Symposium, p. 33, April, 1978.


After S. Buchner, SERESSA 2011 Course, Toulouse, France.
Summary

- Radiation affects electronic, optical, optoelectronic, and material systems deployed into the space environment
- Performance impacts can be manifest as cumulative degradation (e.g., TID and DD) or transient effects (e.g., SEE)
- Mitigation is possible and requires a multifaceted, systematic approach
- Trading between cost, schedule, and technology will define the level of risk for the mission

Always remember your **MEAL**
Mission, Environment, Application, and Lifetime
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>AIEE</td>
<td>American Institute of Electrical Engineers</td>
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<tr>
<td>DD</td>
<td>Displacement Damage</td>
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<tr>
<td>ELDRS</td>
<td>Enhanced Low Dose Rate Sensitivity</td>
</tr>
<tr>
<td>GCR</td>
<td>Galactic Cosmic Ray</td>
</tr>
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<td>GEO</td>
<td>Geostationary Orbit</td>
</tr>
<tr>
<td>IRE</td>
<td>Institute of Radio Engineers</td>
</tr>
<tr>
<td>LASCO</td>
<td>Large Angle and Spectrometric Coronagraph Experiment</td>
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<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
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<td>LET</td>
<td>Linear Energy Transfer</td>
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<td>NASA Electronic Parts and Packaging program</td>
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<td>NESC</td>
<td>NASA Engineering &amp; Safety Center</td>
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<td>NIEL</td>
<td>Non-Ionizing Energy Loss</td>
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<td>NSREC</td>
<td>Nuclear and Space Radiation Effects Conference</td>
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<tr>
<td>PKA</td>
<td>Primary Knock-on Atom</td>
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<tr>
<td>RAM</td>
<td>Random Access Memory</td>
</tr>
<tr>
<td>SAA</td>
<td>South Atlantic Anomaly</td>
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<td>SOHO</td>
<td>Solar &amp; Heliospheric Observatory</td>
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<td>SRAM</td>
<td>Static Random Access Memory</td>
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<tr>
<td>TID</td>
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