Radiation Engineering for Designers

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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>AIEE</td>
<td>American Institute of Electrical Engineers</td>
</tr>
<tr>
<td>AO</td>
<td>Atomic Oxygen</td>
</tr>
<tr>
<td>ASIC</td>
<td>Application-Specific Integrated Circuit</td>
</tr>
<tr>
<td>CME</td>
<td>Coronal Mass Ejection</td>
</tr>
<tr>
<td>COTS</td>
<td>Commercial Off The Shelf</td>
</tr>
<tr>
<td>DDD</td>
<td>Displacement Damage Dose</td>
</tr>
<tr>
<td>DDR</td>
<td>Double Data Rate</td>
</tr>
<tr>
<td>DLA</td>
<td>Defense Logistics Agency</td>
</tr>
<tr>
<td>DRAM</td>
<td>Dynamic Random Access Memory</td>
</tr>
<tr>
<td>EEE</td>
<td>electrical, electronic, and electromechanical</td>
</tr>
<tr>
<td>ELDRS</td>
<td>Enhanced Low Dose Rate Sensitivity</td>
</tr>
<tr>
<td>EMI</td>
<td>Electromagnetic Interference</td>
</tr>
<tr>
<td>ESD</td>
<td>Electrostatic Discharge</td>
</tr>
<tr>
<td>ESP</td>
<td>Emission of Solar Protons</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
</tr>
<tr>
<td>GCR</td>
<td>Galactic Cosmic Ray</td>
</tr>
<tr>
<td>GEO</td>
<td>Geostationary Orbit</td>
</tr>
<tr>
<td>HEO</td>
<td>Highly Elliptical Orbit</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuit</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IRE</td>
<td>Institute of Radio Engineers</td>
</tr>
<tr>
<td>ISS</td>
<td>International Space Station</td>
</tr>
<tr>
<td>LDC</td>
<td>Lot Date Code</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
</tr>
<tr>
<td>LET</td>
<td>Linear Energy Transfer</td>
</tr>
<tr>
<td>MBU</td>
<td>Multiple Bit Upset</td>
</tr>
<tr>
<td>MCU</td>
<td>Multiple Cell Upset</td>
</tr>
<tr>
<td>MEO</td>
<td>Medium Earth Orbit</td>
</tr>
<tr>
<td>NEPP</td>
<td>NASA Electronic Parts and Packaging program</td>
</tr>
<tr>
<td>NESC</td>
<td>NASA Engineering &amp; Safety Center</td>
</tr>
<tr>
<td>NIEL</td>
<td>Non-Ionizing Energy Loss</td>
</tr>
<tr>
<td>NPSS</td>
<td>Nuclear and Plasma Sciences Society</td>
</tr>
<tr>
<td>NSREC</td>
<td>Nuclear and Space Radiation Effects Conference</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>NWEs</td>
<td>Nuclear Weapons Effects</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PKA</td>
<td>Primary Knock-On Atom</td>
</tr>
<tr>
<td>POC</td>
<td>Point of Contact</td>
</tr>
<tr>
<td>PSYCHIC</td>
<td>Prediction of Solar particle Yields for CHaracterizing Integrated Circuits</td>
</tr>
<tr>
<td>QML</td>
<td>Qualified Manufacturers List</td>
</tr>
<tr>
<td>QPL</td>
<td>Qualified Parts List</td>
</tr>
<tr>
<td>RDM</td>
<td>Radiation Design Margin</td>
</tr>
<tr>
<td>RH</td>
<td>Radiation Hardened</td>
</tr>
<tr>
<td>RHA</td>
<td>Radiation Hardness Assurance</td>
</tr>
<tr>
<td>RHBD</td>
<td>Radiation-Hardened By Design</td>
</tr>
<tr>
<td>RHBP</td>
<td>Radiation-Hardened By Process</td>
</tr>
<tr>
<td>RHBS</td>
<td>Radiation-Hardened By Serendipity</td>
</tr>
<tr>
<td>SAA</td>
<td>South Atlantic Anomaly</td>
</tr>
<tr>
<td>SAMPEX</td>
<td>Solar Anomalous Magnetospheric Explorer</td>
</tr>
<tr>
<td>SBU</td>
<td>Single Bit Upset</td>
</tr>
<tr>
<td>SDRAM</td>
<td>Synchronous Dynamic Random Access Memory</td>
</tr>
<tr>
<td>SEB</td>
<td>Single-Event Burnout</td>
</tr>
<tr>
<td>SEDR</td>
<td>Single-Event Dielectric Rupture</td>
</tr>
<tr>
<td>SEFI</td>
<td>Single-Event Functional Interrupt</td>
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<tr>
<td>SEGR</td>
<td>Single-Event Gate Rupture</td>
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<tr>
<td>SEU</td>
<td>Single-Event Upset</td>
</tr>
<tr>
<td>SiGe HBT</td>
<td>Silicon Germanium Heterojunction Bipolar Transistor</td>
</tr>
<tr>
<td>SMD</td>
<td>Standard Microcircuit Drawing</td>
</tr>
<tr>
<td>SOC</td>
<td>System-on-a-Chip</td>
</tr>
<tr>
<td>SOI</td>
<td>Silicon On Insulator</td>
</tr>
<tr>
<td>SOS</td>
<td>Silicon On Sapphire</td>
</tr>
<tr>
<td>SRAM</td>
<td>Static Random Access Memory</td>
</tr>
<tr>
<td>SSR</td>
<td>Solid State Recorder</td>
</tr>
<tr>
<td>TMR</td>
<td>Triple Modular Redundancy</td>
</tr>
</tbody>
</table>
Acknowledgements

- NASA Electronic Parts and Packaging (NEPP) program
- NASA Engineering & Safety Center (NESC)
- MSFC Electronic Design Branch
- MSFC Natural Environments Branch
- Many contributors across government and industry
What do you want to learn and gain from this tutorial?
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 IEEE meeting run by the Nuclear and Plasma Sciences Society (NPSS).
  
  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 (NWE) 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
  - “Address at Rice University on the Nation's Space Effort” – “Going to the Moon Speech,” Sep 1961
- STARFISH PRIME, 9 Jul 1962
- Limited Test Ban Treaty, 5 Aug 1963

Course objectives

• After this tutorial, you will have:
  o An overview of the natural space radiation environment,
  o An introduction to radiation effect types,
  o An overview of EEE parts selection, scrubbing, and radiation mitigation, and
  o An introduction to radiation testing.

• After this tutorial, you will not:
  o Know everything about radiation effects, or
  o Glow in the dark.
My goals

• Increase knowledge of radiation effects amongst electrical designers and systems engineers.

• Urge electrical designers, system engineers, and management (line and project) to reach out for radiation effects expertise early in the development cycle.

• Encourage engineers and management to ask questions. We are here to learn.

Stop me any time to ask questions
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 as are the technologies we want to use

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

- Variability and knowledge of the environment
Course sections

1. Introduction
2. Natural space radiation environment
3. Space environment impacts
4. Component selection and radiation effects mitigation
5. Radiation testing
6. Conclusion
NATURAL SPACE RADIATION ENVIRONMENT –

Particle Sources and Abundance
AR 1520 X1.4 flare and CME

07/15/2012: a Kp = 6 Geomagnetic Storm

Active Region 1520 circled

Left image captured with the NASA Solar Dynamics Observatory’s Atmospheric Imaging Assembly

http://aia.lmsal.com/
CME’s impact to Earth

Solar wind simulations from NASA/GSFC Integrated Space Weather Analysis System
http://iswa.ccmc.gsfc.nasa.gov/iswa/iSWA.html
Space environments

- **Particle radiation** – High-energy electrons, protons & heavy ions
  - Solar
  - Galactic cosmic rays (GCR)
  - Trapped in magnetospheres

- **Plasma**
  - Ionosphere
  - Plasmasphere – Magnetosphere
  - Solar wind

- **Neutral gas particles**
  - Lower – atomic oxygen (AO)
  - Higher – hydrogen & helium

- **Ultraviolet and X-ray**

- **Micrometeoroids & orbital debris**
Space radiation environment

- Space Weather
  - “conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health”
    [US National Space Weather Program]
- <Space> Climate
  - “The historical record and description of average daily and seasonal <space> weather events that help describe a region. Statistics are usually drawn over several decades.”
    [Dave Schwartz the Weatherman – Weather.com]
- Goal of Radiation Hardness Assurance (RHA)
  - Design systems tolerant to the radiation environment within the level of risk acceptable for the mission.
• Deep-space missions may also see neutrons and gamma rays from background or radioisotope sources
Solar Modulation

- 11- and 22-year solar activity cycles
  - 7 active years; 4 quiet years; polarity switch → 22-year cycle total
- Primarily affects cosmic rays and solar particles; not trapped particles

Data from the Solar Influences Data Analysis Center; http://sidc.oma.be/index.php
Galactic Cosmic Rays (GCRs)

- Originate outside the solar system (e.g., supernovae)
- Include all naturally-occurring elements
  - Drops off rapidly for $Z > 26$ (iron)
- Most energetic of all space environment radiation

Solar Particle Events

Severe proton events from cycles 20-22

- Solar flares & coronal mass ejections (CMEs)
  - Impulsive vs. gradual; magnetic field vs. plasma eruption
- CMEs primarily responsible for major interplanetary disturbances
- Energies are lower than galactic cosmic rays (GCR)


Maximum entropy model vs. data for cycles 20-22
Trapped Particles

Trapped Particles

Note that extent of trapped protons only includes practical energies for electronic device radiation effects purposes.

The proton and electron populations are equal in order to achieve charge neutrality. The difference is based on kinetic energy within the population.

- Note the extent of the trapped protons and outer zone electrons, as well as the penetration range of solar flare protons.
- L-value often describes the set of magnetic field lines which cross the Earth's magnetic equator at a number of Earth-radii equal to the L-value.


RADIATION ENGINEERING FOR DESIGNERS
J. A. Pellish, NASA GSFC

To be published on nepp.nasa.gov originally published on https://nen.nasa.gov/.
Trapped Particles – Protons

- Localized to Earth’s geomagnetic field
- Energies up to 100s of MeV
- > 10 MeV fluxes
  \( \sim 10^5 \text{ cm}^{-2} \text{ s}^{-1} \)
- \( L \)-shell 1.15 – 10
  - Higher energy protons < 20,000 km
- \textit{Dipole offset}


SPENVIS, http://www.spenvis.oma.be/, v4.6.5
Trapped Particles – Protons

- South Atlantic Anomaly (SAA) – dominates Earth’s space environment below about 1000 km
- Due to tilt and displacement between rotational and geomagnetic axes

E.J. Daly, et al., IEEE TNS, April 1996.
Effects of Trapped Protons

Solar Anomalous Magnetospheric Explorer (SAMPEX) Solid State Recorder


SAMPEX was NASA’s first Small Explorers mission

- Both the South Atlantic Anomaly and proton belts are visible in these on-orbit upset data

Cosmic Ray Upset Experiment (CRUX) Advanced Photovoltaic and Electronics Experiment (APEX)

Micron 256k: Altitude: 1750km - 1850km

Upsets/Bit/Day

1.0E-7 to 5.0E-7
5.0E-7 to 1.0E-6
1.0E-6 to 5.0E-6
5.0E-6 to 1.0E-5
1.0E-5 to 5.0E-5
5.0E-5 to 1.0E-4
1.0E-4 to 5.0E-4
5.0E-4 to 1.0E-3
1.0E-3 to 5.0E-3

Longitude

Latitute

Trapped Particles – Electrons

- Localized to Earth’s geomagnetic field
- Energies up to 10 MeV
- > 1 MeV fluxes up to \( \sim 10^6 \text{ cm}^{-2} \text{ s}^{-1} \)
- Two shells – inner and outer
  - Inner: L-shell 1 – 2.8
  - Outer: L-shell 2.8 – \( \sim 10 \)
- Dominant feature for medium Earth orbit and geostationary vehicles


After SPENVIS website, http://www.spennvis.oma.be
# Radiation environments for different trajectories

Table based on content developed by K. A. LaBel, NASA GSFC.

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Plasma (charging)</th>
<th>Trapped Protons</th>
<th>Trapped Electrons</th>
<th>Solar Particles</th>
<th>Cosmic Rays</th>
<th>Nuclear Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEO</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>LEO (low-incl)</td>
<td>No</td>
<td>Yes</td>
<td>Moderate</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>LEO Polar</td>
<td>No</td>
<td>Yes</td>
<td>Moderate</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>ISS</td>
<td>No</td>
<td>Yes</td>
<td>Moderate</td>
<td>Yes - partial</td>
<td>Minimal</td>
<td>No</td>
</tr>
<tr>
<td>Interplanetary</td>
<td>Phasing orbits; possible other planet</td>
<td>Phasing orbits; possible other planet</td>
<td>Phasing orbits; possible other planet</td>
<td>Yes</td>
<td>Yes</td>
<td>Maybe</td>
</tr>
<tr>
<td>Exploration - MPCV</td>
<td>Phasing orbits</td>
<td>Phasing orbits</td>
<td>Phasing orbits</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Exploration – Lunar, Mars</td>
<td>Phasing orbits</td>
<td>Phasing orbits</td>
<td>Phasing orbits</td>
<td>Yes</td>
<td>Yes</td>
<td>Maybe</td>
</tr>
</tbody>
</table>

General comments – not necessarily true in all cases. Yellow indicates hazard.
Relevant tools for simulation / prediction

- Trapped environments
  - SPENVIS (AP-8/AE-8, AP-9/AE-9, etc.)
  - CRÈME-MC (limited functionality)
  - Other packages

- Solar particle events (flares & CMEs)
  - SPENVIS (ESP, PSYCHIC, JPL-91, etc.)
  - Other packages

- Galactic Cosmic Rays
  - SPENVIS
  - CRÈME-MC
  - Other packages
Defining environment requirements

- Drives cost, schedule, and technical margin
- Must be comprehensive
- Complete early in the design cycle
Requirements process

- Reliability Requirements
  - System Requirements
  - Subsystem functionality
  - Flow down to modules/parts

- Design Hardening
  - Technology Selection
  - Part Selection
  - Fault Tolerance
  - Bias/operating conditions

- Performance Requirements

- Systems
  - Mission
  - Trajectory and timing

- Sub-system
  - Specific to Box

- Parts
  - Requirements Specific to Part
    - Vulnerability
    - Function
    - Reliability

- Internal Environment Definition

- Shielding

- Compliance

Space environment challenges

In the 2008-2010 minimum of solar activity, we saw a higher flux of Galactic Cosmic Rays (GCRs) at Earth than ever seen before in the Space Age.

Does this difference have implications for future missions, manned and/or robotic?
Top space environment challenges

• Loss of communications with STEREO-B spacecraft on 1 Oct 2014
  o Impacts space weather prediction capabilities

• Space climate vs. space weather
  o Designing mission requirements with a static environment – reality is quite dynamic
Environment topics not covered...

• Surface and deep dielectric charging
  o Including plasma effects (EMI, ESD, etc.)
• Atomic oxygen
• Micrometeoroids
• Orbital debris
Course sections

1. Introduction
2. Natural space radiation environment
3. Space environment impacts
4. Component selection and radiation effects mitigation
5. Radiation testing
6. Conclusion
SPACE ENVIRONMENT IMPACTS –

Radiation effects are caused by the deposition of energy in materials
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(SiO$_2$), 10 krad(Si), 100 Gy(H$_2$O)

- 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.
Photons deposit energy too

- Incoming particles – electrons, protons, heavy ions, and photons – can deposit energy in semiconductor materials
- Energy becomes “hot” electron-hole pairs
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.
- 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

Fractional Hole Yield by Particle Type

- 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

Processes Involved in TID Damage


ELDRS effects in bipolar devices

- First observed in bipolar devices and circuits in the early 1990s
- Amount of total dose degradation at a given total dose is greater at low dose rates than at high dose rates
  - True dose-rate effect as opposed to a time-dependent effect

Ions & linear energy transfer (LET)

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

$$S = - \frac{dE}{dx} \quad \Rightarrow \quad \text{LET} = - \frac{1}{\rho} \frac{dE}{dx}$$
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.

<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>
</tbody>
</table>

Examples

After S. Buchner, SERESSA 2011 Course, Toulouse, France.
Single-event effects processes

Short history of single-event effects

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


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

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

Calculating SEE rates

- Measure cross section ($\sigma$) vs. LET
  - Testing done with particle accelerators (protons and heavy ions)
  - Cross section based on circuit response
- Determine sensitive volume
  - Need to make assumptions about device construction
  - Used to determine the effect of ions that strike the device at angle (it’s an isotropic environment)

## SEE rate calculation development

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Date</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>First reported SEU in space</td>
<td>1975</td>
<td>Binder, Smith and Holman</td>
</tr>
<tr>
<td>LET distribution concept is introduced</td>
<td>1977</td>
<td>Heinrich</td>
</tr>
<tr>
<td>First reported alpha particle upset in ground-based ICs</td>
<td>1979</td>
<td>May and Woods</td>
</tr>
<tr>
<td>Development of heavy ion SEU rate prediction model based on distributions of path length and LET</td>
<td>1978, 1980</td>
<td>Pickel and Blandford</td>
</tr>
<tr>
<td>First observations of proton-induced SEU</td>
<td>1979</td>
<td>Wyatt, McNulty, Toumbas, Rothwell and Filz</td>
</tr>
<tr>
<td>Development of semi-empirical model for proton SEU rate</td>
<td>1983</td>
<td>Guenzer, Wolicki and Allas</td>
</tr>
<tr>
<td>CRÈME suite of codes combine environment and rate prediction tools in standardized package</td>
<td>1986</td>
<td>Bendel and Petersen</td>
</tr>
<tr>
<td>Development of Effective Flux approach for heavy ion SEU rate</td>
<td>1988</td>
<td>Binder</td>
</tr>
</tbody>
</table>

SEE rates – traditional vs. Monte Carlo

• Traditional rate calculation models and methods fall short in some cases – *work well in others*
  o Angular dependence & low-energy proton effects
  o Bipolar effects in SOI CMOS
  o Charge collection by diffusion
  o Heavy ion indirect ionization
  o Ion track structure effects
  o Thick sensitive volumes

• Solution requires representation of additional physics and an augmented description of the system under simulation
SEE rates – let’s roll dice

- Monte Carlo simulation provides a path forward since an analytical solution is not required. It can invoke:
  - Quantitative description of the relevant radiation environment(s)
  - Transport of the incident radiation through any materials or structures that surround the sensitive circuitry
  - Energy deposition in the electronic materials by the impinging radiation
  - Conversion of energy into charge
  - Charge transport and recombination in the semiconductor and insulator regions
  - Transistor-level response, including effects of charge deposited by incident radiation
  - Circuit response, including radiation-induced transients

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

Silicon Material System

After C. J. Marshall, 1999 IEEE NSREC Short Course.

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.

- 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>
NIEL, 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.
Course sections

1. Introduction
2. Natural space radiation environment
3. Space environment impacts
4. Component selection and radiation effects mitigation
5. Radiation testing
6. Conclusion
COMPONENT SELECTION AND RADIATION EFFECTS MITIGATION –

Protect this spacecraft
Before we get started…

• A significant amount of material in this section was developed by Ken LaBel, Code 561, NASA/GSFC (thank you!)
  
  o Practices we have used for many years, which may or may not fit the character of your program
  
  o In general, they are relevant and applicable
Perspective is everything

• The Design Engineer has the specialist's viewpoint. Views the system from the inside.
  o Concerned with other system elements only as they affect their own design task; but not necessarily how theirs may affect others

• The Systems Engineer has the systems viewpoint. Views the system from the outside.
  o Concerned with the effect of all system elements as they affect overall system design / performance / cost / schedule

• The Radiation Effects Engineer has to have both a systems viewpoint and a specialist’s viewpoint

Pieces of mission performance

• To achieve mission performance one must balance
  - Technology
  - Cost
  - Schedule

• Most engineers tend to focus on technology – at the expense of cost and schedule

• Most programs tend to focus on cost and schedule – at the expense of technology

The trades between cost, schedule & technology define the level of risk

Tiered defense strategy

Radiation Threats

Mission Planning/Design

Technology Selection/Design

Hardened by Design (part or circuit level)

System-Level Hardening

Mission Requirements

Environment design impacts

**Free Field Environments**

- Solar Protons
- Protons
- Electrons

- Displacement Damage
- Total Ionizing Dose (TID)
- Deep Electron Charging

**Environment Threats**

- Galactic Cosmic Rays
- Solar Flare Ions

- Single Event Effects (SEE)
  - Hard Errors
    - SEL
    - SEGR/SEB
  - Soft Errors
    - SET
    - SEFI
    - SBU
    - MBU

**Hardening & Mitigation Techniques**

- Part Selection (Heritage, Radiation Hardened)
- Dose/Fluence Map Analysis
- Shielding
- Part Placement (Maximize Inherent Shielding)
- Account for Enhanced Low Dose Rate Sensitivity (ELDRS)
- Account for Parameter Degradation in WCCA
- Characterization Tests (parts/materials)
- Apply Radiation Design Margin
- Perform Radiation Lot Acceptance Testing

- Shielding
- Ground floating metal

- Part Selection (Heritage, Radiation Hardened)
- UseLatchup Immune Parts
- Characterization Tests
- Power cycle
- Account for SEE
  - Gate Rupture (SEGR)
  - Burnout (SEB)
  - Latchup (SEL)

- Part Selection (Heritage, Radiation Hardened)
- Characterization Tests
- Error Detection and Correction
- Redundant Logic
- Utilize Hardened Latches
- Account for SEE
  - Single and Multi-Bit Upset (SBU, MBU)
  - Transients (SET)
  - Functional Interrupt (SEFI)

Sensible Programmatics for Flight RHA: A Two-Pronged Approach for Missions

- Assign a lead radiation POC to each spaceflight project
  - Treat radiation like other engineering disciplines
    - Parts, thermal,…
  - Provides a single point of contact for all radiation issues
    - Environment, parts evaluation, testing,…

- Each program follows a systematic approach to RHA
  - Develop a comprehensive RHA plan
  - RHA active early in program reduces cost in the long run
    - Issues discovered late in programs can be expensive and stressful
      - What is the cost of reworking a flight board if a device has RHA issues?
Flight Program RHA Managed via Lead Radiation Engineer

- **Environment Definition**
  - Environment in the presence of the spacecraft
  - Component Mechanical Modeling – 3D ray trace, Monte Carlo, NOVICE, etc.

- **Project Requirements and Specifications**
  - Technology Hardness
    - Design Margins
    - Box/system Level

- **Design Evaluation**
  - Parts List Screening
    - Radiation Characterizations, Instrument Calibration, and Performance Predictions
    - Mitigation Approaches and Design Reliability

- **In-Flight Evaluation**
  - Technology Performance
    - Anomaly Resolution
    - Lessons Learned

*Iteration over project development cycle*
Define the hazard

- The radiation environment **external** to the spacecraft
  - Trapped particles
    - Protons
    - Electrons
  - Galactic cosmic rays - GCRs (heavy ions)
  - Solar particles (protons and heavy ions)

- Based on
  - Time of launch and mission duration
  - Orbital parameters, …

- Provides as a minimum
  - GCR fluxes
  - Nominal and worst-case trapped particle fluxes
  - Peak “operate-through” fluxes (solar or trapped)
  - Dose-depth curve of total ionizing dose (TID)

*Note: We are currently using static models for a dynamic environment*
Evaluate the hazard

- Utilize mission-specific geometry to determine particle fluxes and TID at locations **inside** the spacecraft
  - 3-D ray trace (geometric sectoring)

- Typically multiple steps
  - Basic geometry (empty boxes,…) or single electronics box
  - Detailed geometry
    - Include printed circuit boards (PCBs), cables, integrated circuits (ICs), thermal louvers, etc…

- Usually an iterative process
  - Initial spacecraft design
  - As spacecraft design changes
  - Mitigation by changing box location
Define requirements

• Environment usually based on hazard definition with “nominal shielding” or basic geometry
  o Using actual spacecraft geometry sometimes provides a “less harsh” radiation requirement

• Performance requirements for “nominal shielding” such as 100 mil of Al or actual spacecraft configuration
  o TID
  o DDD (protons, neutrons)
  o SEE
    » Specification is more complex

• Inclusion of radiation design margin (RDM)
  o Factor of 2 for TID, for example
  o Often required to be higher due to device issues and environment uncertainties
System requirements

- For TID, parts can be given a single number (with margin)
  - SEE is much more application specific

- SEE is unlike TID
  - Probabilistic events, not long-term
    - For instance, equal probabilities for 1st day of mission or last day of mission
    - Requirements must be thoroughly defined – does it have to work, or would it be nice to have?
Notes on system requirements

• Requirements do NOT have to be for piece-part reliability
  o For example, may be viewed as a “data loss” specification
    » Acceptable bit error rates or system outage
  o Mitigation and risk are system trade parameters
  o Environment needs to be defined for YOUR mission (cannot use prediction for different timeframe, orbit, etc.)
Evaluate design and component usage

• Screen parts list
  o Use existing data sources
    » Evaluate test data: is it applicable?
    » Use historic data with CAUTION!
  o Look for processes or products with known radiation tolerance (beware of SEE and displacement damage!)
    » BAE Systems, Honeywell Solid State Electronics, Aeroflex, Intersil, etc.

• Radiation test unknowns or non-guaranteed devices

• Provide performance characteristics
  o Usually requires application-specific information: understand the designer’s sensitive parameters
    » SEE rates
    » TID/DDD
Radiation perspective on IC selection

- From the radiation perspective, ICs can be viewed as part of one of four categories:
  - Guaranteed hardness
    - Radiation-hardened by process (RHBP)
    - Radiation-hardened by design (RHBD)
  - Historical ground-based radiation data
    - Lot acceptance criteria
  - Historical flight usage
    - Statistical significance
  - Unknown assurance
    - New device or one with no data or guarantee
Archival radiation performance – ground-based test data

• General flow is shown below

Do data exist? YES NO

Has process/foundry changed? NO YES

Test

Same wafer lot? NO YES

Test

Test method applicable? YES NO

Test

Sufficient test data? YES NO

Test

Data usable

Test recommended but may be waived based on risk assumption
What does the radiation engineer need?

- The following is a list of information that should be provided to the radiation engineer to perform a scrub:
  - Manufacturer
    - Note: QPL or QML are not manufacturers
  - Part number (generic)
  - SMD or Mil procurement number
    - RH designator?
  - Function
  - Lot date code
  - Technology of the part will drive what to look for in radiation test results and methods. You may have to dig up this information.
    - e.g., bipolar: was TID testing performed at low dose rate (per standards) or is the device “ELDRS-free”?
  - Application information may be required as well
    - 1st scrub can look at just what data is available
    - 2nd pass looks at applying that data
What the radiation engineer provides back to the project

- If the part is guaranteed for radiation
  - Feedback whether the guaranteed radiation tolerance meets mission requirements
    » Forewarning: not all guaranteed parts will meet a mission requirement or application

- If the part has ground test data available
  - Synopsis of the tolerance levels noted
    » Forewarning: many database radiation results are application-specific
      Good results may be used as an indicator the part might be okay for selection, however, testing may be required
  - LDCs of the tested parts
    » Finding if it’s the same wafer and lot as being considered is a challenge, but unless it’s a known lot that’s being purchased, radiation qualification testing is often required
  - Testing recommendations based on requirements and part technology
  - Replacement recommendations

- If the part does not have data
  - Is there data on the process?
  - Is there data on a similar or more complex part on the same process?

- Flight heritage will be discussed later
- Beyond just the data, SEE rate predictions for the mission may be included as well
What can be on a parts list

• Military and procurement specs are often found on parts lists. These may be in the form of:
  o SMD
    » Standard Microcircuit Drawing
    There may also be Mil-38510 or vendor drawings
  o QPL
    » Qualified Parts List
  o QML
    » Qualified Manufacturers List
  o RHA
    » Radiation Hardened Assurance (RHA). This refers to the RHA designator for total ionizing dose (TID) only. Single event effects (SEE) are NOT guaranteed by the RHA designator as a rule.

• DLA Land & Maritime Standard Microcircuit Cross-Reference
  o http://www.dssc.dla.mil/programs/smcr/
  o Website and downloadable tools are useful in translating generic part numbers to/from military part numbers

• Other generic component information
1. SCOPE

1.1 Scope. This drawing documents two product assurance class levels consisting of high reliability (device class Q) and space application (device class V). A choice of case outlines and lead finishes are available and are reflected in the Part or Identifying Number (PIN). When available, a choice of Radiation Hardness Assurance (RHA) levels are reflected in the PIN.

1.2 PIN. The PIN shall be as shown in the following example:

```
      5962   R   10203   01   Q   X   A
Federal
stock class
designator

RHA
designator
(see 1.2.1)

Device
type
(see 1.2.2)

Device
class
designator
(see 1.2.3)

Case
outline
(see 1.2.4)

Lead
finish
(see 1.2.5)
```

Drawing number

1.2.1 RHA designator. Device classes Q and V RHA marked devices shall meet the MIL-PRF-38535 specified RHA levels and are marked with the appropriate RHA designator. A dash (-) indicates a non-RHA device.

1.2.2 Device types. The device types shall identify the circuit function as follows:

<table>
<thead>
<tr>
<th>Device type</th>
<th>Generic number</th>
<th>Circuit function</th>
<th>Access time</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>UT8ER2M32M</td>
<td>2M X 32-bit rad-hard SRAM master</td>
<td>22 ns</td>
</tr>
<tr>
<td>02</td>
<td>UT8ER2M32S</td>
<td>2M X 32-bit rad-hard SRAM slave</td>
<td>22 ns</td>
</tr>
<tr>
<td>03</td>
<td>UT8ER2M32M</td>
<td>2M X 32-bit rad-hard SRAM master, with additional screening</td>
<td>22 ns</td>
</tr>
<tr>
<td>04</td>
<td>UT8ER2M32S</td>
<td>2M X 32-bit rad-hard SRAM slave, with additional screening</td>
<td>22 ns</td>
</tr>
</tbody>
</table>

1.2.3 Device class designator. The device class designator shall be a single letter identifying the product assurance level as follows:

<table>
<thead>
<tr>
<th>Device class</th>
<th>Device requirements documentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q, V</td>
<td>Certification and qualification to MIL-PRF-38535</td>
</tr>
</tbody>
</table>
4.4.4 Group E inspection. Group E inspection is required only for parts intended to be marked as radiation hardness assured (see 3.5 herein). RHA levels for device classes Q and V shall be as specified in MIL-PRF-38535 and the end-point electrical parameters shall be as specified in Table IIA herein.

a. For device classes Q and V, the devices or test vehicle shall be subjected to radiation hardness assured tests as specified in MIL-PRF-38535 for the RHA level being tested. All device classes must meet the post-irradiation end-point electrical parameter limits as defined in Table IA at $T_A = +25^\circ C \pm 5^\circ C$, after exposure, to the subgroups specified in Table IIA herein.

4.4.4.1 Total dose irradiation testing. Total dose irradiation testing shall be performed in accordance with MIL-STD-883 method 1019 condition A, and as specified herein. The total dose requirements shall be as defined within paragraph 1.5 herein.

4.4.4.1.1 Accelerated annealing test. Accelerated annealing tests shall be performed on all devices requiring a RHA level greater than 5k rad(Si). The post-annal end-point electrical parameter limits shall be as specified in Table IA herein and shall be the pre-irradiation end-point electrical parameter limit at $25^\circ C \pm 5^\circ C$. Testing shall be performed at initial qualification and after any design or process changes which may affect the RHA response of the device.

4.4.4.2 Dose rate induced latch-up testing. When specified by the procuring activity, dose rate induced latch-up testing shall be performed in accordance with method 1020 of MIL-STD-883 and as specified herein (see 1.5). Tests shall be performed on devices, SEC, or approved test structures at technology qualification and after any design or process changes which may affect the RHA capability of the process.

4.4.4.3 Dose rate upset testing. When specified by the procuring activity, dose rate upset testing shall be performed in accordance with method 1021 of MIL-STD-883 and herein (see 1.5).

a. Transient dose rate upset testing shall be performed at initial qualification and after any design or process changes which may affect the RHA performance of the devices. Test 10 devices with 0 defects unless otherwise specified.

b. Transient dose rate upset testing for class Q and V devices shall be performed as specified by a TRB approved radiation hardness assurance plan and MIL-PRF-38535.

4.4.4.4 Single event phenomena (SEP). When specified in the purchase order or contract, SEP testing shall be required on class V devices (see 1.5 herein). SEP testing shall be performed on a technology process on the Standard Evaluation Circuit (SEC) or alternate SEP test vehicle as approved by the qualifying activity at initial qualification and after any design or process changes which may affect the upset or latchup characteristics. ASTM standard F1192 may be used as a guideline when performing SEP testing. The recommended test conditions for SEP are as follows:

a. The ion beam angle of incidence shall be between normal to the die surface and $60^\circ$ to the normal, inclusive (i.e. $0^\circ \leq \text{angle} \leq 60^\circ$). No shadowing of the ion beam due to fixtureing or package related effects are allowed.

b. The fluence shall be $\geq 100$ errors or $\geq 10^6$ ions/cm$^2$.

c. The flux shall be between $10^2$ and $10^9$ ions/cm$^2$/s. The cross-section shall be verified to be flux independent by measuring the cross-section at two flux rates which differ by at least an order of magnitude.

d. The particle range shall be $\geq 20$ microns in silicon.

e. The test temperature shall be $+25^\circ C \pm 10^\circ C$ for single event upset testing and at the maximum rated operating temperature $+10^\circ C$ for single event upset testing.

f. Bias conditions shall be defined by the manufacturer for latchup measurements.

g. Test four devices with zero failures.
1. SCOPE

1.1 **Scope.** This drawing documents five product assurance classes as defined in paragraph 1.2.3 and MIL-PRF-38534. A choice of case outlines and lead finishes which are available and are reflected in the Part or Identifying Number (PIN). When available, a choice of radiation hardness assurance levels are reflected in the PIN.

1.2 **PIN.** The PIN shall be as shown in the following example:

![PIN Diagram](image)

1.2.1 **Radiation hardness assurance (RHA) designator.** RHA marked devices shall meet the MIL-PRF-38534 specified RHA levels and shall be marked with the appropriate RHA designator. A dash (-) indicates a non-RHA device.

1.2.2 **Device type(s).** The device type(s) identify the circuit function as follows:

<table>
<thead>
<tr>
<th>Device type</th>
<th>Generic number</th>
<th>Circuit function</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>SLH2815D</td>
<td>DC-DC converter, 1.5 W, ±15V outputs</td>
</tr>
</tbody>
</table>

1.2.3 **Device class designator.** This device class designator shall be a single letter identifying the product assurance level. All levels are defined by the requirements of MIL-PRF-38534 and require QML Certification as well as qualification (Class H, K, and E) or QML Listing (Class G and D). The product assurance levels are as follows:

<table>
<thead>
<tr>
<th>Device class</th>
<th>Device performance documentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>K</td>
<td>Highest reliability class available. This level is intended for use in space applications.</td>
</tr>
<tr>
<td>H</td>
<td>Standard military quality class level. This level is intended for use in applications where non-space high reliability devices are required.</td>
</tr>
</tbody>
</table>
4.3.5. Radiation hardness assurance (RHA). RHA qualification is required only for those devices with the RHA designator as specified herein.

<table>
<thead>
<tr>
<th>Total ionizing dose tolerance level</th>
<th>RHA level L</th>
<th>RHA level R</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
<td>100</td>
<td>kRad (Si)</td>
</tr>
<tr>
<td>Single event upset survival level (LET)</td>
<td>No guarantee</td>
<td>40</td>
<td>MeV</td>
</tr>
</tbody>
</table>

a. Radiation dose rate is in accordance with condition C of method 1019 of MIL-STD-883. Unless otherwise specified, components are tested at a rate of 9 rad(Si)/s, in accordance with method 1019 of MIL-STD-750 or MIL-STD-883, as applicable. These parts may be dose rate sensitive in a space environment and may demonstrate enhanced low dose rate effects.

b. The manufacturer shall perform a worst-case and radiation susceptibility analysis on the device. This analysis shall show that the minimum performance requirements of each component have adequate design margin under worst-case operating conditions (extremes of line voltage, temperatures, load, frequency, radiation environment, etc.). This analysis guarantees the post-irradiation parameter limits specified in table 1.

c. RHA testing shall be performed at the component level for initial device qualification, and after design changes that may affect the RHA performance of the device. As an alternative to testing, components may be procured to manufacturer radiation guarantees that meet the minimum performance requirements. Component radiation performance guarantees shall be established in compliance with MIL-PRF-19500, Group D or MIL-PRF-38535, Group E, as applicable. For components with less than adequate performance margin, component lot radiation acceptance screening shall be performed.

d. The manufacturer shall establish procedures controlling component radiation testing, and shall establish radiation test plans used to implement component lot qualification during procurement. Test plans and test reports shall be filed and controlled in accordance with the manufacturer's configuration management system.

e. The device manufacturer shall designate a RHA program manager to oversee component lot qualification, and to monitor design changes for continued compliance to RHA requirements.
Guaranteed radiation tolerance

• So, we’ve started perusing the review of parts guaranteed by the vendor using the MIL system
  o Now let’s move on to a bit more detail
• A limited number of semiconductor manufacturers, either with fabs or fabless, will guarantee radiation performance of devices
  o Examples:
    » ATMEL, Honeywell, BAE Systems, Aeroflex, etc.
  o Radiation qualification usually is performed on either:
    » Qualification test vehicle,
    » Device type or family member, or
    » Lot qualification
  o Some vendors sell “guaranteed” radiation tolerant devices by “cherry-picking” commercial devices coupled with mitigation approaches external to the die
• The devices themselves can be hardened via
  o Process or material (RHBP or RHBM),
  o Design (RHBD), or
  o Serendipity (RHBS)
• Most foundries use a combination of techniques
Evaluating “guaranteed” parts

• Even guaranteed parts may have issues
  o For both TID and SEE?
  o Lot testing requirements
  o Application-specific issue (how was the qualification done?)
  o What about ELDRS if testing was done at high dose rate?

Part is not guaranteed. Move to data search.

Need to evaluate risk of not having lot data versus additional tests. For guaranteed parts, it’s usually lower.
Ground-based data

- Once we have determined if the part is guaranteed or not, we begin searching for available data
  - Note: using a “similar” device with data is risky, but sometimes considered (though not recommended)
    » This is known as “qual by similarity”
- We can consider “heritage” from other programs/projects, but this is risky too

```
Do data exist?  

YES: Has process/foundry changed?  
  NO: Test  
  YES: Same wafer lot?  

YES: Test method applicable?  
  NO: Data usable  
  YES: Sufficient test data?  

Test recommended but may be waived based on risk assumption
```
Data searches...

- Why not try Google?

![Google search for LM124 radiation](image)

- LM124-SP - Texas Instruments
  - www.ti.com › ... › General Purpose Amplifier › Texas Instruments › Download a datasheet or document on TI's LM124-SP Operational Amplifier (Op Amp), ... Radiation lot acceptance testing is available - contact factory for details.

- LM124 - Texas Instruments
  - www.ti.com › ... › General Purpose Amplifier › Texas Instruments › Download a datasheet or document on TI's LM124 Operational Amplifier (Op Amp), ... Space, LM124-SP, Radiation tolerant, ceramic packaging and qualified for ...

- [PDF] The Effects of Low Dose-Rate ionizing Radiation on the ...
  - https://nepp.nasa.gov/files/25355/Buchner_ins08_LM124.pdf › bipolar circuit (LM124) change with exposure to total ionizing dose (TID) radiation. SETs shape changes are a direct consequence of TID-induced degradation ...

- ESCIES: ESCC Radiation: Database - European Space ...

- [PDF] LM124 Low Dose Rate Test Report
  - https://www.escies.org/download/webDocumentFile?id=1542 › ANALOG TOTAL DOSE RADIATION REPORT. Customer: ELDRS Rad. Qual. Part Type: RM124AJRQMLV. Input Bias Circuit: 7106 IR. Dose Rate: 12 mrd(Si)/s ...
Archival radiation performance – heritage data

- Can we make use of parts with flight heritage and no ground data for new mission?
- Similar flow to using archival ground data exist, but consider:
  - Statistical significance of the flight data
    - Environment severity?
    - Number of samples?
    - Length of mission?
    - e.g., 1 part flying for 3 years in a LEO orbit doesn’t mean much on a 10-year mission to Mars!
  - Has storage of devices affected radiation tolerance or reliability?
- This approach is rarely recommended by the radiation expert

Some heritage designs last better than others
Components with no guarantee or heritage

- Radiation testing is required in the vast majority of cases
  - Challenge is to gather sufficient data in a cost and schedule effective manner
    - A backup plan should be made in case device fails to pass radiation criteria.
  - Hard question is when do we need to test
    - Consider:
      - Mission parameters
      - Application/operation
      - Process and device family knowledge
    - In some cases, we can estimate “worst-case,” such as transient size
Is testing always required?

- Exceptions for testing may include
  - Operational
    » Example: device is only powered on once per orbit and the sensitive time window for a single event effect is minimal
  - Acceptable data loss
    » Example: system-level error rate may be set such that data are gathered 95% of the time. Given physical device volume and assuming every ion causes an upset, this worst-case rate may be tractable.
  - Negligible effect
    » Example: 2 week mission to LEO may have a very low TID requirement. TID testing could be waived.

FLASH memory may be acceptable without testing if a low TID requirement exists or not powered on for the large majority of time.
Why lot-based qualification testing?

- Components used are illustrative – many examples exist
- Bimodality complicates analysis and limits confidence
Other complexities too…

- Dose rate dependence is just one aspect
- Could also consider operating frequency effects, bias, temperature, ion species, etc.

Data applicability – Example 1

• Most SEE data available is application-specific
  - Power supply voltages
  - Operating frequency
    » Fidelity of response measured
    Was the scope fast enough to capture “small” transients that might perturb sensitive data?
  - Circuit load
  - Test patterns
  - Temperature
  - Bias configuration

Transients in a linear device can vary with input parameters
Data applicability – Example 2

- SRAM used in a solid state recorder (SSR)
  - SEE ground test data may have been in dynamic mode with a 1 MHz operating frequency
  - Application may be quasi-static
    - Write once an orbit (collect data)
    - Read once an orbit (downlink data)
  - There is often a duty cycle effect for SEE sensitivity
    - Device may be more or less sensitive in a quasi-static mode of operation
  - Device may also have a prevalence of 0-1 vs. 1-0 upset
    - Implies SEU sensitivity is a function of data patterns
    - If test pattern is all 1’s or all 0s, data may not be applicable
    - Hitachi 1 Mbit SRAM was 49X more sensitive in one direction than the other!

Effect of temperature on SEE sensitivity

Risk is the name of the game

- **Rule**: there will always be risks associated with any use of electronics in a space radiation environment
  - We try to minimize and to determine what is reasonable
- Lot-specific information and guaranteed devices ARE the best choices
  - Risk is usually being assumed at all other times
  - Historical performance can be an indicator for usage, but is fraught with risk
    » How much is a judgment call based on available information?
    » It is your job to dig for the info and make a recommendation?
Levels of mitigation

- Mitigation can take place at many levels
  - Operational
    - No operation in SAA (proton hazard)
  - System
    - Redundant boxes/buses
  - Circuit/software
    - Error detection and correction (EDAC) scrubbing of memory devices by external device or processor
  - Device
    - Triple-modular redundancy (TMR) of internal logic
  - Transistor
    - Use of annular transistors for TID improvement
  - Material
    - Addition of an epitaxial substrate to reduce SEE charge collection (or other substrate engineering)

- Good engineers can invent infinite solutions, but…
Mitigation for destructive effects

• Do not use devices that exhibit destructive conditions in your environment and application
  o Difficulties:
    » May require redundant components/systems
    » Conditions such as low current SELs may be difficult to detect

• Mitigation methods
  o Current limiting
  o Current limiting with autonomous reset
  o Periodic power cycles
  o Device functionality checks

• Latent damage is also a grave issue
  o “Non-destructive” events may be a false statement
  o All devices that have SEL sensitivity even with circumvention circuits need to consider this
Takeaways

- Systematic approach is a must
- Coordinate with relevant parties (e.g., system engineer, parts engineer, etc.)
- Use all available data sources
- Don’t be afraid to ask if you don’t know
  - Don’t go forward without expertise
  - Don’t throw it over the fence completely
- Hopefully track successful performance in-flight
  - Invaluable for future efforts
Course sections

1. Introduction
2. Natural space radiation environment
3. Space environment impacts
4. Component selection and radiation effects mitigation
5. Radiation testing
6. Conclusion
RADIATION TESTING –

*Back the flux off!*
Radiation test fidelity

**Flight Test**
- Mixed particle species
- Combined environment effects
- Broad energy spectrum
- Actual particle rates

**Ground Test**
- Single particle sources
- Individual environment effects
- Unidirectional environment
- Accelerated particle rates

**Actual conditions** ↔ **Simulated conditions**

---

*How accurate is the ground test in predicting Space Performance?*

After graphic prepared by K. A. LaBel, NASA GSFC, 2008.
Landscape is always changing…

The missing memristor found


IEF2011: HP to replace flash and SSD in 2013

David Manners
Thursday 06 October 2011 12:17

HP intends to have an alternative technology to flash on the market in eighteen months, an alternative to DRAM in three to four years and, following DRAM, a replacement for SRAM, Stan Williams, Senior Fellow at HP, told the IEF2011 meeting in Seville this morning.

"We’re planning to put a replacement chip on the market to go up against flash within a year and a half," said Williams, "and we also intend to have an SSD replacement available in a year and a half."

"In 2014 possibly, or certainly by 2015, we will have a competitor for DRAM and then we’ll replace SRAM."


DDR4 makes its debut at ISSCC 2012

Servers in 2013, desktops the coming year
23 Feb 2012 18:47 | by Paul Taylor in Lisbon | Filed in Chips Samsung DDR3

http://news.techeye.net/chips/ddr4-makes-its-debut-at-isscc-2012

Elpida seeks bankruptcy protection

Kyodo, Bloomberg

Struggling semiconductor maker Elpida Memory Inc. filed for bankruptcy protection Monday after giving up on efforts to rebuild itself with government support.

http://www.japantimes.co.jp/text/nb20120228n1.html
Where we’re going…

<table>
<thead>
<tr>
<th>THEN</th>
<th>NOW</th>
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</thead>
<tbody>
<tr>
<td>Magnetic core memory</td>
<td>NAND flash, resistive random access memory (RAM), magnetic RAM,</td>
</tr>
<tr>
<td></td>
<td>phase-change RAM, phase-change RAM, programmable</td>
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<tr>
<td></td>
<td>metallization cell RAM, and double-data rate (DDR) synchronous</td>
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<td></td>
<td>dynamic RAM (SDRAM)</td>
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<tr>
<td>Single-bit upsets (SBUs) and single-</td>
<td>Multiple-bit upset (MBU), block errors, single-event functional</td>
</tr>
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<td>event transients (SETs)</td>
<td>interrupts (SEFIs), frequency-dependence, etc.</td>
</tr>
<tr>
<td>Heavy ions and high-energy protons</td>
<td>Heavy ions, high- and low-energy protons, delta rays, muons, ???</td>
</tr>
<tr>
<td>Radiation hardness assurance (RHA)</td>
<td>RHA what?</td>
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</tbody>
</table>
Where we’re going…

<table>
<thead>
<tr>
<th>THEN</th>
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<tbody>
<tr>
<td>Increases in capability introduce additional evaluation challenges</td>
<td></td>
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</tbody>
</table>

- FinFETs/Tri-gate devices
- Nanowire MOSFETs
- Organic transistors
- Ultra-thin body SOI
- Ge MOSFETs
- III-V MOSFETs
- Carbon nanotube FETs
- GaN, SiC,…
Two general types of electronics for space use

- Commercial-off-the-shelf (COTS) electronics
  - Designed with no attempt to mitigate radiation effects. COTS can refer to commodity devices or to application-specific integrated circuits (ASICs) designed using a commercially available system.

- Radiation-tolerant electronics
  - Designed explicitly to account for and mitigate radiation effects by process and/or design

Evaluation of Total Ionizing Dose in Advanced Electronics –
*Tolerance has gotten better, but device complexity increases faster*
Piece part hardness assurance

- We define piece-part hardness assurance as “the methods used to assure that microelectronic piece-parts meet specified requirements for system operation at specified radiation levels for a given probability of survival (P_S) and level of confidence (C)”.
  - Using this definition allows us to quantify the process.
  - Requirement for system operation allows for a failure definition that is determined by the application of the part in the system.
  - Requirement to meet a specified radiation level allows us to test parts as a function of a radiation environment and compare the radiation failure level of the part to the specification level.
  - Finally the specification of the P_S and C for the part will allow us to develop statistical approaches for sample testing of the parts.

Characterization vs qualification

• Engineering characterization test
  o Measuring device/material characteristics under the influence of an externally-imposed radiation environment stimulus
  o Not a “yes / no” answer
  o May be appropriate when: don’t know performance a priori, have limited samples, requirements are not well-defined

• Hardness assurance test
  o Test to assure requirements are met
  o “Yes / no” answer
  o Tends to imply statistical rigor – beware though
How do you approach radiation testing advanced electronics?

- Engineering Characterization
- Hardness Assurance

Radiation testing protocols for advanced electronics
Common TID testing themes

- Difficulty of in-situ evaluation
  - “Test as you fly” implies application realism – **maybe not the best approach**
- Component complexity creates “black boxes”
  - Does my test lack sensitivity/specificity?
    - Could refer to discrete devices or integrated circuits
- Component material systems now comprise most of the periodic table (equilibrium, dose enhancement,…)
- Existing test methods for bounding predictions rely on well-behaved results and controlled starting materials
  - Bimodal degradation/failure distributions
  - Part-to-part and lot-to-lot variability of commercial devices

"Lot" can be defined as the manufacturing or wafer/diffusion lot depending on context.
TID testing

• Why do TID testing?
  
  o To determine the type and magnitude of parametric degradation and check for functional failures
  
  o To calculate the suitability for a radiation environment

• TID testing is carried out with an ionizing radiation source
  
  o Photons: $^{60}$Co, $^{137}$Cs, and ARACOR X-ray sources
  
  o Electrons: LINAC and Van de Graaff accelerators
  
  o Protons: cyclotron and Van de Graaff accelerators

• Limited device preparation required in most cases
Available TID test methods

- Qualification methods that define total ionizing dose testing of microelectronics *(last update)*:
  - MIL-STD-883, Method 1019 (06/2013)
  - ESCC Basic Specification No. 22900 (10/2010)

- Specific methods cover radiation hardness assurance – this is *qualification*
  - Can be adapted for engineering characterization

- Both of the above methods have procedures to test for and measure enhanced low-dose-rate sensitivity (ELDRS), which can affect some types of bipolar/BiCMOS devices and integrated circuits

*Document dates are current as of 09/2015.*
Steps to perform a TID test

Flow diagram for ionizing radiation test procedure for MOS and digital bipolar devices

Flow diagram for ionizing radiation test procedure for bipolar (or BiCMOS) linear or mixed-signal devices.

MIL-STD-883 / Method 1019.9
June 2013

Document date is current as of 09/2015.
Issues with X-Rays vs. $^{60}\text{Co} \gamma$-Rays

**Photon Effects**

- Practical terms: X-rays get absorbed more readily than gamma rays. For example, in aluminum:
  - 50% attenuation @ 1 mm for x-rays and 5 cm for $\gamma$-rays

**Photon Cross Sections in Aluminum**


NIST XCOM Database; http://www.nist.gov/pml/data/xcom/index.cfm
In-situ evaluation

- Can be difficult to route high-bandwidth and/or low-voltage signals long distances
- Can consider other irradiation sources

K. G. Kerris, et al., IEEE TNS, 1985
Black box components

- Behavior indicates that failure dose not well correlated to observed degradation
- How do you track/predict potential failures?

Component variability

- Sources of variability
  - Process: defects, die position on wafer, implants,…
  - Design: how much margin is left?

LM111 Voltage Comparator at 50 krad(SiO₂)


OP484 Quad Op Amp at 100 krad(SiO₂)

Bayesian analysis approach

In this case, “lot” is the wafer or diffusion lot, not the packaging or manufacturing lot.

Possible TID testing solutions

Device complexity and dose rate sensitivity complicate TID evaluation and qualification

- Explore feasibility of non-photon radiation sources in some cases – can be good for comparison too
- Develop flexible interrogation methods for advanced, large-scale integration devices
- Increase lot test size to maximum practical extent
  - What distribution am I assuming? (normal, binomial, etc.)
- Leverage as much existing data as possible
- Track basic mechanisms research to maintain knowledge base on advanced material systems and latest simulation techniques
Evaluation of Single-Event Effects (SEE) in Advanced Electronics –
*The death of averages*
How do you approach testing advanced electronics?

Radiation testing protocols for advanced electronics

- Engineering Characterization
- Hardness Assurance
SEE complexity

These pictures are what got me into radiation effects.


100 MeV protons in silicon

1 GeV protons in silicon

1 μm silicon cubes
Common SEE testing themes

• Difficulty of in-situ evaluation
  o “Test as you fly” implies application realism – maybe not appropriate

• Component complexity creates expensive “black boxes”
  o Many operational modes and on-board smarts
  o Test costs are spiraling upwards – “full” characterization not possible

• Advanced electronics have lead to:
  o Enhanced angular sensitivity due to process or design techniques
  o Sensitivity to low-energy protons and ??? (e.g., muons and delta rays)

• Parameter space is HUGE
  o How do you evaluate an integral with 10s or 100s of dimensions?
SEE testing

• Why do testing?
  1. To determine the presence and characteristics of single events
     » Destructive or non-destructive
     » Voltage and temperature dependence
     » Amplitude and width of SETs
  2. To calculate the SEE rate for a radiation environment

• SEE testing is usually done at accelerator facilities, which irradiate the whole device with ions. Some in-air and some in vacuum.

• Package must be opened, de-processed, thinned…

• Other testing methods that provide spatial and temporal information include:
  o Focused, collimated ion beam
  o Focused, pulsed laser beam

After S. Buchner, SERESSA 2011 Course, Toulouse, France.
Available SEE test methods

- Test guideline documents that define SEE testing of microelectronic devices and circuits (*last update*):
  - ASTM F1192 (10/2011)
  - ESCC Basic Specification No. 25100 (10/2014)
  - JEDS57 (12/1996; reaffirmed 09/2003 – being updated now)
  - JESD89 (10/2007; reaffirmed 01/2012)
  - MIL-STD-750, Method 1080 (04/2013)

- Do a reasonable job of defining procedures for heavy ion testing – *HOWEVER*…
  - Do not yet cover recently documented effects (e.g., angular sensitivities, heavy ion indirect ionization) or proton SEE
  - Other guidelines and refereed publications exist

*Document dates are current as of 09/2015.*
Steps to perform a SEE test

• Understand device process technology and application conditions – SEE testing is most always application-specific
  o Could the device under test be susceptible to destructive effects?
  o Is there a target environment for qualification (requirements) or is the test an engineering characterization?

• Identify a suitable test facility and consider systematic variables
  o Ion selection, pulsed laser sources, energy range, flux range, dosimetry, beam profile and purity, and accelerator technology

• Develop a test matrix that covers necessary application space within allowable costs / schedule – the following can have large ranges:
  o Device function, data patterns, frequency, voltage/current, temperature, LET, energy, particle range, etc.

• Prepare devices for irradiation and travel to the test facility
Steps to perform a SEE test

- The majority of time before, during, and after a SEE test is spent
  1. Deciding what you want to measure and how;
  2. Verifying you can do 1.; and,
  3. Figuring out what you actually got.

- Because SEE testing is real-time, many aspects are dynamic, so contingency planning is essential.

- Always have a backup plan.
Device preparation

- Thinning and polishing for backside irradiation is not trivial
- As with any commercial technology, destructive effects are always a concern – statistics?!?
- Repeatability concerns from lot-to-lot (packaging)


Note cracks at edge
In-situ evaluation

- Special considerations for angle, bandwidth, and proton activation
- Similar approach with FPGA-based testers

IBM 5AM SiGe HBTs

Tilt and roll angle sensitivities

\[ \Omega = 2\pi \left[ 1 - \cos \left( \frac{a}{2} \right) \right] \]

Solid angle for a cone – When the apex, \( a \), is equal to 120°, \( \Omega = \pi \), which is half the solid angle subtended by the surface of a hemisphere. This means that half of the particles in an isotropic environment will be incident at angles below 60° and the other half at angles above 60°.


Device Sensitive Volumes

http://mathworld.wolfram.com/SphericalCoordinates.html
Tilt and roll angle sensitivities

32 nm SOI CMOS latch cross sections – contours are based on data & simulation


- Non-destructive SEE continue to be the most difficult aspect of advanced CMOS radiation effects
  - Varied angular sensitivity (test considerations)
Low-energy proton sensitivity

IBM 65 nm SOI SRAM – top-side irradiation

- First published low-energy proton soft errors in 2007
- Energy below Coulomb barrier – interactions are constrained to electromagnetic and nuclear elastic reactions
- Rapid cross section increase at grazing angles and energies below 2 MeV


Beyond low-energy protons

400 keV muons on a 65 nm SRAM


28 GeV iron ions on SRAM structure and ensuing delta ray energy deposition.

Radiation test costs

• It’s expensive!

• Unavoidable non-recurring engineering because of custom setups and destructive nature of evaluation
  
  o Can be mitigated if there’s economy of scale
  
  o Test plan, design, fabrication, assembly, debug, test, analyze, reduce, repeat…

• Many external test facilities are ~$1000/hr
  
  o Travel and shipping costs to remote facilities

• Complicated, multi-month evaluations can top several $100K – even ≥$1M for the most complex devices and SoCs
Testing wisdom

No one believes an analysis – except the person who did it
Everyone believes a test – except the person who did it

• A test without requirements or an objective is not a test
• A test without a report did not happen
Course sections

1. Introduction
2. Natural space radiation environment
3. Space environment impacts
4. Component selection and radiation effects mitigation
5. Radiation testing
6. Conclusion