Radiation Effects on Electronics 101: Simple Concepts and New Challenges

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Outline

• The Space Radiation Environment
• The Effects on Electronics
• The Environment in Action
• Commercial Electronics
  – The Mission Mix
  – Radiation Sensitivity
  – Flight Projects
  – Proactive Research
• Space Validations of Models and Test Protocols
• Final Thoughts

Atomic Interactions
  – Direct Ionization

Interaction with Nucleus
  – Indirect Ionization
  – Nucleus is Displaced

The Space Radiation Environment

STARFISH detonation – Nuclear attacks are not considered in this presentation

Space Environments and Related Effects

- Plasma
- Neutral gas particles
- Ultraviolet & X-ray
- Micro-meteoroids & orbital debris

- Charging
- Drag
- Surface Erosion

- Ionizing & Non-Ionizing Dose
- Single Event Effects
- Neutral gas particles

- Degradation of micro-electronics
- Degradation of optical components
- Degradation of solar cells

- Data corruption
- Noise on images
- System shutdowns
- Circuit damage

- Torques
- Orbital decay
- System shutdowns
- Circuit damage

- Degradation of thermal, electrical, optical properties
- Degradation of structural integrity

- Structural damage
- Decompression

Space Radiation Effects after Barth

NASA/GSFC Eng Seminar: Radiation Effects 101 presented by Kenneth A. LaBel – Oct 28, 2005
Space Radiation Environment

Deep-space missions may also see: neutrons from background or radioisotope thermal generators (RTGs) or other nuclear source. Atmosphere and terrestrial may see GCR and secondaries.

Sunspot Cycle: An Indicator of the Solar Cycle

Length Varies from 9 - 13 Years
7 Years Solar Maximum, 4 Years Solar Minimum
Solar Particle Events

- Cyclical (Solar Max, Solar Min)
  - 11-year AVERAGE (9 to 13)
  - Solar Max is more active time period
- Two types of events
  - Gradual (Coronal Mass Ejections – CMEs)
    - Proton rich
  - Impulsive (Solar Flares)
    - Heavy ion rich
- Abundances Dependent on Radial Distance from Sun
- Particles are Partially Ionized
  - Greater Ability to Penetrate Magnetosphere than GCRs

Solar Proton Event - October 1989

Proton Fluxes - 99% Worst Case Event

Counts/cm²/s/ster/MeV

nT

October
November

GOES Space Environment Monitor
Free-Space Particles: Galactic Cosmic Rays (GCRs) or Heavy Ions

- **Definition**
  - A GCR ion is a charged particle (H, He, Fe, etc)
  - Typically found in free space (galactic cosmic rays or GCRs)
    - Energies range from MeV to GeVs for particles of concern for SEE
    - Origin is unknown
  - Important attribute for impact on electronics is how much energy is deposited by this particle as it passes through a semiconductor material. This is known as Linear Energy Transfer or LET (dE/dX).

Trapped Particles in the Earth’s Magnetic Field: Proton & Electron Intensities

- **AP-8 Model**
  - $E_p > 10$ MeV
- **AE-8 Model**
  - $E_e > 1$ MeV

A dip in the earth’s dipole moment causes an asymmetry in the picture above: The South Atlantic Anomaly (SAA)
SAA and Trapped Protons:
Effects of the Asymmetry in the Proton Belts on SRAM Upset Rate at Varying Altitudes on CRUX/APEX

Solar Cycle Effects:
Modulator and Source

- **Solar Maximum**
  - Trapped Proton Levels Lower, Electrons Higher
  - GCR Levels *Lower*
  - Neutron Levels in the Atmosphere Are Lower
  - Solar Events More Frequent & Greater Intensity
  - Magnetic Storms More Frequent -- > Can Increase Particle Levels in Belts

- **Solar Minimum**
  - Trapped Protons Higher, Electrons Lower
  - GCR Levels *Higher*
  - Neutron Levels in the Atmosphere Are Higher
  - Solar Events Are Rare
The Effects

DNA double helix
Pre and Post Irradiation
Biological effects are a key concern
for lunar and Mars missions

Radiation Effects and Spacecraft

- Critical areas for design in the natural space radiation environment
  - Long-term effects causing parametric and/or functional failures
    - Total ionizing dose (TID)
    - Displacement damage
  - Transient or single particle effects (Single event effects or SEE)
    - Soft or hard errors caused by proton (through nuclear interactions) or heavy ion (direct deposition) passing through the semiconductor material and depositing energy

An Active Pixel Sensor (APS) imager under irradiation with heavy ions at Texas A&M University Cyclotron

To run this video see http://radhome.gsfc.nasa.gov/radhome/papers/D3_030_2100_2199.avi
Total Ionizing Dose (TID)

- Cumulative long term ionizing damage due to protons & electrons
  - keV to MeV range
- Electronic Effects
  - Threshold Shifts
  - Leakage Current
  - Timing Changes
  - Functional Failures
- Unit of interest is krads(material)
- Can partially mitigate with shielding
  - Reduces low energy protons and electrons

Displacement Damage (DD)

- Cumulative long term non-ionizing damage due to protons, electrons, and neutrons
  - keV to MeV range
- Electronic Effects
  - Production of defects which results in device degradation
  - May be similar to TID effects
  - Optocouplers, solar cells, charge coupled devices (CCDs), linear bipolar devices
    - Lesser issue for digital CMOS
- Unit of interest is particle fluence for each energy mapped to test energy
  - Non-ionizing energy loss (NIEL) is one means of discussing
- Can partially mitigate with shielding
  - Reduces low energy protons and electrons
Single Event Effects (SEEs)

• An SEE is caused by a *single charged particle* as it passes through a semiconductor material
  - Heavy ions (cosmic rays and solar)
    - Direct ionization
  - Protons (trapped and solar - >10 MeV)/neutrons (secondary or nuclear) for sensitive devices
    - Nuclear reactions for electronics
    - Optical systems, etc are sensitive to direct ionization

• Unit of interest: linear energy transfer (LET). The amount of energy deposited/lost as a particle passes through a material.
  - Total charge collected may be more appropriate

• Effects on electronics
  - If the LET of the particle (or reaction) is greater than the amount of energy or critical charge required, an effect may be seen
    - Soft errors such as upsets (SEUs) or transients (SETs), or
    - Hard (destructive) errors such as latchup (SEL), burnout (SEB), or gate rupture (SEGR)

• Severity of effect is dependent on
  - type of effect
  - system criticality

Radiation Effects on Electronics and the Space Environment

• Three portions of the natural space environment contribute to the radiation hazard
  - Solar particles
    - Protons and heavier ions
      - SEE, TID, DD
  - Free-space particles
    - GCR
      - For earth-orbiting craft, the earth’s magnetic field provides some protection for GCR
      - SEE
  - Trapped particles (in the belts)
    - Protons and electrons including the South Atlantic Anomaly (SAA)
      - SEE (Protons)
      - DD, TID (Protons, Electrons)
  - The sun acts as a modulator and source in the space environment

Destructive event in a COTS 120V DC-DC Converter

The sun acts as a modulator and source in the space environment
The Environment in Action

“There’s a little black spot on the sun today”

Solar Events –
A Few Notes and Implications

• In Oct-Nov of 2003, a series of X-class (BIG X-45!) solar events took place
  – High particle fluxes were noted
  – Many spacecraft performed safing maneuvers
  – Many systems experienced higher than normal (but correctable) data error rates
  – Several spacecraft had anomalies causing spacecraft safing
  – Increased noise seen in many instruments
  – Drag and heating issues noted
  – Instrument FAILURES occurred
  – Two known spacecraft FAILURES occurred
• Power grid systems affected, communication systems affected...

![Graph showing solar activity over time]
SOHO LASCO C2 of the Solar Event

To run this video see http://radhome.gsfc.nasa.gov/radhome/papers/c2_SOHO.mpg

Solar Event Effect - Solar Array Degradation on CLUSTER Spacecraft

Many other spacecraft to noted degradation as well.
### Science Spacecraft Anomalies During Halloween 2003 Solar Events

<table>
<thead>
<tr>
<th>Type of Event</th>
<th>Spacecraft/Instrument</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spontaneous Processor Resets</td>
<td>RHESSI</td>
<td>3 events; all recoverable</td>
</tr>
<tr>
<td></td>
<td>CLUSTER</td>
<td>Seen on some of 4 spacecraft; recoverable</td>
</tr>
<tr>
<td></td>
<td>ChipSAT</td>
<td>S/C tumbled and required ground command to correct</td>
</tr>
<tr>
<td>High Bit Error Rates</td>
<td>GOES 9,10</td>
<td></td>
</tr>
<tr>
<td>Magnetic Torquers Disabled</td>
<td>GOES 9, 10, 12</td>
<td></td>
</tr>
<tr>
<td>Star Tracker Errors</td>
<td>MER</td>
<td>Excessive event counts</td>
</tr>
<tr>
<td></td>
<td>MAP</td>
<td>Star Tracker Reset occurred</td>
</tr>
<tr>
<td>Read Errors</td>
<td>Stardust</td>
<td>Entered safe mode; recovered</td>
</tr>
<tr>
<td>Failure?</td>
<td>Midori-2</td>
<td></td>
</tr>
<tr>
<td>Memory Errors</td>
<td>GENESIS</td>
<td>19 errors on 10/29</td>
</tr>
<tr>
<td></td>
<td>Many</td>
<td>Increase in correctable error rates on solid-state recorders noted in many spacecraft</td>
</tr>
</tbody>
</table>

### Science Instrument Anomalies During Halloween 2003 Solar Events

<table>
<thead>
<tr>
<th>Type of Event</th>
<th>Spacecraft/Instrument</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument Failure</td>
<td>GOES-8 XRS</td>
<td>Under investigation as to cause</td>
</tr>
<tr>
<td>Mars Odyssey/Marie</td>
<td></td>
<td>Under investigation as to cause; power consumption increase noted; S/C also had a safehold event – memory errors</td>
</tr>
<tr>
<td>NOAA-17/AMSU-A1</td>
<td></td>
<td>Lost scanner; under investigation</td>
</tr>
<tr>
<td>Excessive Count Rates</td>
<td>ACE, WIND</td>
<td>Plasma observations lost</td>
</tr>
<tr>
<td>GALEX UV Detectors</td>
<td></td>
<td>Excess charge – turned off high voltages; Also Upset noted in instrument</td>
</tr>
<tr>
<td>ACE</td>
<td></td>
<td>Solar Proton Detector saturated</td>
</tr>
<tr>
<td>Integral</td>
<td></td>
<td>Entered Safe mode</td>
</tr>
<tr>
<td>POLAR/TIDE</td>
<td></td>
<td>Instrument reset spontaneously</td>
</tr>
<tr>
<td>Hot Pixels</td>
<td>SIRTF/IRAC</td>
<td>Increase in hot pixels on IR arrays; Proton heating also noted</td>
</tr>
<tr>
<td>Safe Mode</td>
<td>Many</td>
<td>Many instruments were placed in Safe mode prior to or during the solar events for protection</td>
</tr>
</tbody>
</table>
Selected Other Consequences

- Orbits affected on several spacecraft
- Power system failure
  - Malmo, Sweden
- High Current in power transmission lines
  - Wisconsin and New York
- Communication noise increase
- FAA issued a radiation dose alert for planes flying over 25,000 ft

A NASA-built radiation monitor that can aid anomaly resolution, lifetime degradation, protection alerts, etc.

NASA Approaches to Electronics:
Flight Projects and Proactive Research

It doesn’t matter where you go as long as you follow a programmatic assurance approach
NASA Missions – A Wide Range of Needs

- NASA typically has over 200 missions in some stage of development
  - Range from balloon and short-duration low-earth investigations to long-life deep space
  - Robotic to Human Presence
- Radiation and reliability needs vary commensurately

Implications of NASA Mission Mix

- >90% of NASA missions require 100 krad(Si) or less for device total ionizing dose (TID) tolerance
  - Single Event Effects (SEEs) are prime driver
    - Sensor hardness also a limiting factor
  - Many missions could accept risk of anomalies as long as recoverable over time
- Implications of the Vision for Space Exploration are still TBD for radiation and reliability specifics, however,
  - Nuclear power/propulsion changes radiation issues (TID and displacement damage)
  - Long-duration missions such as permanent stations on the moon require long-life high-reliability for infrastructure
    - Human presence requires conservative approaches to reliability
      - Drives stricter radiation tolerance requirements and fault tolerant architectures
### Summary of Environment Hazards for Electronic Parts in NASA Missions

<table>
<thead>
<tr>
<th>Environment</th>
<th>Plasma (Charging)</th>
<th>Trapped Protons</th>
<th>Trapped Electrons</th>
<th>Solar Particles</th>
<th>Cosmic Rays</th>
<th>Human Presence</th>
<th>Long Lifetime (&gt;10 years)</th>
<th>Nuclear Exposure</th>
<th>Restarted Launch</th>
<th>Extreme Temperature</th>
<th>Planetary Contaminates (Dust, etc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEO</td>
<td>Yes</td>
<td>No</td>
<td>Severe</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</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>
<td>No</td>
<td>Not usual</td>
<td>No</td>
<td>No</td>
<td>Yes</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>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Shuttle</td>
<td>No</td>
<td>Yes</td>
<td>Moderate</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Rocket Motors</td>
</tr>
<tr>
<td>ISS</td>
<td>No</td>
<td>Yes</td>
<td>Moderate</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Interplanetary</td>
<td>During phasing orbits; Possible Other Planet</td>
<td>During phasing orbits; Possible Other Planet</td>
<td>During phasing orbits; Possible Other Planet</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Maybe</td>
<td>No</td>
<td>Yes</td>
<td>Maybe</td>
</tr>
<tr>
<td>Exploration – CEV</td>
<td>Phasing orbits</td>
<td>During phasing orbits</td>
<td>During phasing orbits</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Rocket Motors</td>
<td>No</td>
</tr>
<tr>
<td>Exploration – Lunar, Mars</td>
<td>Phasing orbits</td>
<td>During phasing orbits</td>
<td>During phasing orbits</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Maybe</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Yellow indicates significant Exploration hazards

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### Approach to Insertion of Electronics

*IBM CMOS 8SF ASIC*
A Critical Juncture for Space Usage – Commercial Changes in the Electronics World

Over the past decade plus, much has changed in the semiconductor world. Among the rapid changes are:

- **Scaling of technology**
  - Increased gate/cell density per unit area (as well as power and thermal densities)
  - Changes in power supply and logic voltages (<1V)
    - Reduced electrical margins within a single IC
  - Increased device complexity, # of gates, and hidden features
  - Speeds to >> GHz (CMOS, SiGe, InP...)

- **Changes in materials**
  - Use of antifuse structures, phase-change materials, alternative K dielectrics, Cu interconnects (previous – Al), insulating substrates, ultra-thin oxides, etc...
  - Increased input/output (I/O) in packaging
    - Use of flip-chip, area array packages, etc
  - Increased importance of application specific usage to reliability/radiation performance
Implications for Electronics in Space

- With all these changes in the semiconductor world, what are the implications for usage in space? Implications for test, usage, qualification and more
  - Speed, power, thermal, packaging, geometry, materials, and fault/failure isolation are just a few for emerging challenges for radiation test and modeling.
    - Reliability challenges are equally as great
  - The following chart (courtesy of Vanderbilt University) looks at some of the recent examples of test data that imply shortfalls in existing radiation performance models.
    - Technology assumptions in tools such as CREME96 are no longer valid

Sample Modeling Shortfalls
### Current Status of Radiation Knowledge
#### Maturity for Electronics

<table>
<thead>
<tr>
<th>Radiation Response</th>
<th>Guideline Document</th>
<th>Test Method</th>
<th>Data Base</th>
<th>Modeling &amp; Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEU/MBU</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>~ mature</td>
</tr>
<tr>
<td>SET</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>SEL</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>SEGR</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>SEFI</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>TID</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Displacement Damage</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

**Microelectronics: Categories**

- Microelectronics can be split several ways
  - Digital, analog, mixed signal, other
  - Complementary Metal Oxide Semiconductor (CMOS), Bipolar, etc...
  - Function (microprocessor, memory, …)
- There are only two commercial foundries (where they build devices) in the US dedicated to building radiation hardened digital devices
  - Efforts within DoD to provide alternate means of developing hardened devices
    - Hardened-by-design (HBD)
    - Provides path for custom devices, but not necessarily off-the-shelf devices
  - Commercial devices can have great variance in radiation tolerance from device-to-device and even on multiple samples of same device
    - No guarantees!
  - Analog foundry situation is even worse
- New technologies have many unknowns
  - Ultra-high speed, nanotechnologies, microelectromechanical systems (MEMS and the optical versions – MOEMS), …
- Note: Commercial-off-the-shelf (COTS) assemblies (e.g., commercial electronic cards or instruments) also may be considered
  - Screening is more complicated than with single devices due to test complexities

*A MOEMS in action*
The Digital Logic Trends

- Standard CMOS
  - Feature sizes are scaling (shrinking) to sub-0.1 micron sizes
    - Faster devices, lower operating voltages
      - Reduced electrical margins within devices
  - New dielectrics are being used
  - Thickness of gate oxide is being diminished
- Implications (general)
  - Improved TID tolerance
    - Low dose rate type effect has now been observed
    - Does not previously an issue, now suspect
  - SEL tolerance expected to increase, but HAS NOT
  - Increased SEU sensitivity
    - Technology speed increase drives this issue (SETs in logic propagate)
    - Unknown effect of other technology changes
  - Increased use of silicon-on-insulator (SOI) substrates

Effects of protons in SOI with varied angular direction of the particle; Blue line represents expected response with “standard” CMOS devices.

The New Challenge: Changes in CMOS Technology and Design

SEU – Single Event Upset
SEFI – Single Event Functional Interrupt
SEL – Single Event Latchup

Notional graph of COTS RAM SEE Trends

*Electronics manufacturers are concerned with soft error rates (SER) on the ground and are beginning to insert means of reducing SER

Speed kills – SETs drive SEU increase

Feature size shrinkage

> 1 um to < 0.1 um

1995 Time 2005
Analog/mixed signal

- Not scaled as aggressively (need higher voltages to get analog range)
  - Efforts to improve electrical performance have reduced reliability and signal margins within the device
  - Increased sensitivity to
    - SETs (noise propagation that can be invasive to operations)
      - The higher the resolution or speed, the worse this becomes
    - TID and DD
      - Commercial device failure noted as low as 1 krads(Si)
        - Even short duration missions would have concerns without test data

New Technologies – Sample Issues

- Ultra-high speed
  - Devices that may be relatively tolerant at low-speed (<100 MHz) have vastly increased SEU sensitivity at high-speeds (>1 GHz)
    - Speed can defeat HBD methods
    - New technologies don’t fit old models
- Sensors
  - Noise, damage, etc. can limit device performance (such as an imager) and lifetime
    - Small effort at DoD to provide hardened solutions
- MEMS
  - Combined effects of electrical, optical, and mechanical degradation
- Nanotechnologies
  - A great unknown for radiation effects and protection
Radiation Hardness Assurance (RHA) for Natural Space

- With commercial technology sensitivity to SEE increasing and limited radiation hardened offerings, a dual approach to RHA needs to be installed
  - A systems approach at the flight mission level, and
  - Proactive investigation into new technologies

Rockwell/Hawaii 2048x2048
5μm HgCdTe NGST FPA (ARC)

Candidate James Webb Space Telescope (JWST)
IR array preparing for rad tests. The ultra-low noise requirement of JWST is the driver.

A Systematic Approach to Flight Project Radiation Hardness Assurance (RHA)

Size, complexity, and human presence are among the factors im deciding how RHA is to be implemented
Sensible Programmatics for Flight RHA:
A Two-Pronged Approach for Missions

- Assign a lead radiation engineer 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 Radiation Hardness Assurance (RHA) Flow

- Flight Program RHA Managed via Lead Radiation Engineer
- Environment Definition
- External Environment
- 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

Cradle to Grave!
Define the Environment
- External to the spacecraft

Evaluate the Environment
- Internal to the spacecraft

Define the Requirements
- Define criticality factors

Evaluate Design/Components
- Existing data/Testing/Performance characteristics

“Engineer” with Designers
- Parts replacement/Mitigation schemes

Iterate Process
- Review parts list based on updated knowledge

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

The Physics Models of Space Radiation – Environment to Target

- Predictive model of the external space radiation environment that impinges on the spacecraft
- Predictive model of the interaction of that environment with the spacecraft
  - This is the induced or internal environment that impinges on electrical, mechanical, or biological systems
  - May need to consider spacecraft transport and local material transport separately
- Predictive model for the effects of the interactions of the induced environment with semiconductor, material, or biological systems (the target)
Define Requirements

- Environment usually based on hazard definition with “nominal shielding” or basic geometry
  - Using actual spacecraft geometry sometimes provides a “less harsh” radiation requirement
- Performance requirements for “nominal shielding” such as 70 mils of Al or actual spacecraft configuration
  - TID
  - DDD (protons, neutrons)
  - SEE
    - Specification is more complex
    - Often requires SEE criticality analysis (SECA) method be invoked
- Must include radiation design margin (RDM)
  - At least a factor of 2
  - Often required to be higher due to device issues and environment uncertainties (enhanced low dose rate issues, for example)

Sample TID Top Level Requirement: Dose-Depth Curve

Total dose at the center of Solid Aluminum Sphere
ST5: 200-35790 km, 0 degree inclination, three months

![Dose-Depth Curve Graph](image-url)
System Requirements - SEE Specifications

- For TID, parts can be given A number (with margin)
  - SEE is much more application specific
- SEE is unlike TID
  - Probabilistic events, not long-term
    - Equal probabilities for 1st day of mission or last day of mission
      - Maybe by definition!

Sample Single Event Effects Specification (1 of 3)

1. Definitions and Terms

   **Single Event Effect (SEE)** - any measurable effect to a circuit due to an ion strike. This includes (but is not limited to) SEUs, SHEs, SELs, SEBs, SEGRs, and Single Event Dielectric Rupture (SEDR).

   **Single Event Upset (SEU)** - a change of state or transient induced by an energetic particle such as a cosmic ray or proton in a device. This may occur in digital, analog, and optical components or may have effects in surrounding interface circuitry (a subset known as Single Event Transients (SETs)). These are “soft” errors in that a reset or rewriting of the device causes normal device behavior thereafter.

   **Single Hard Error (SHE)** - an SEU which causes a permanent change to the operation of a device. An example is a stuck bit in a memory device.

   **Single Event Latchup (SEL)** - a condition which causes loss of device functionality due to a single event induced high current state. An SEL may or may not cause permanent device damage, but requires power strobing of the device to resume normal device operations.

   **Single Event Burnout (SEB)** - a condition which can cause device destruction due to a high current state in a power transistor.

   **Single Event Gate Rupture (SEGR)** - a single ion induced condition in power MOSFETs which may result in the formation of a conducting path in the gate oxide.

   **Multiple Bit Upset (MBU)** - an event induced by a single energetic particle such as a cosmic ray or proton that causes multiple upsets or transients during its path through a device or system.

   **Linear Energy Transfer (LET)** - a measure of the energy deposited per unit length as a energetic particle travels through a material. The common LET unit is MeV·cm²/mg of material (Si for MOS devices, etc.).

   **Onset Threshold LET (LET_{th})** - the minimum LET to cause an effect at a particle fluence of $1E7$ ions/cm² (per JEDEC). Typically, a particle fluence of $1E5$ ions/cm² is used for SEB and SEGR testing.
Single Event Effects Specification (2 of 3)

2. Component SEU Specification

2.1 No SEE may cause permanent damage to a system or subsystem.

2.2 Electronic components shall be designed to be immune to SEE induced performance anomalies, or outages which require ground intervention to correct. Electronic component reliability shall be met in the SEU environment.

2.3 If a device is not immune to SEUs, analysis for SEU rates and effects must take place based on LET, of the candidate devices as follows:

<table>
<thead>
<tr>
<th>Device Threshold</th>
<th>Environment to Be Assessed</th>
</tr>
</thead>
<tbody>
<tr>
<td>LET&lt;sub&gt;th&lt;/sub&gt; &lt; 15 MeV·cm&lt;sup&gt;2&lt;/sup&gt;/mg</td>
<td>Cosmic Ray, Trapped Protons, Solar Proton Events</td>
</tr>
<tr>
<td>LET&lt;sub&gt;th&lt;/sub&gt; = 15 - 100 MeV·cm&lt;sup&gt;2&lt;/sup&gt;/mg</td>
<td>Galactic Cosmic Ray Heavy Ions, Solar Heavy Ions</td>
</tr>
<tr>
<td>LET&lt;sub&gt;th&lt;/sub&gt; &gt; 100 MeV·cm&lt;sup&gt;2&lt;/sup&gt;/mg</td>
<td>No analysis required</td>
</tr>
</tbody>
</table>

2.4 The cosmic ray induced LET spectrum which shall be used for analysis is given in Figure TBD.

2.5 The trapped proton environment to be used for analysis is given in Figures TBD. Both nominal and peak particle flux rates must be analyzed.

2.6 The solar event environment to be used for analysis is given in Figure TBD.

2.7 For any device that is not immune to SEL or other potentially destructive conditions, protective circuitry must be added to eliminate the possibility of damage and verified by analysis or test.

*This number is somewhat arbitrary and is applicable to “standard” devices. Some newer devices may require this number to be higher.*

Single Event Effects Specification (3 of 3)

2. Component SEU Specification (Cont.)

2.8 For SEU, the criticality of a device in its specific application must be defined into one of three categories: error-critical, error-functional, or error-vulnerable. Please refer to the /radhome/papers/seecai.htm Single Event Effect Criticality Analysis (SEECA) document for details. A SEECA analysis should be performed at the system level.

2.9 The improper operation caused by an SEU shall be reduced to acceptable levels. Systems engineering analysis of circuit design, operating modes, duty cycle, device criticality etc. shall be used to determine acceptable levels for that device. Means of gaining acceptable levels include part selection, error detection and correction schemes, redundancy and voting methods, error tolerant coding, or acceptance of errors in non-critical areas.

2.10 A design's resistance to SEE for the specified radiation environment must be demonstrated.

3. SEU Guidelines

Wherever practical, procure SEE immune devices. SEE immune is defined as a device having an LET<sub>th</sub> > 100 MeV·cm<sup>2</sup>/mg.

If device test data does not exist, ground testing is required. For commercial components, testing is recommended on the flight procurement lot.
Notes on System Requirements

- Requirements do NOT have to be for piecepart reliability
  - For example, may be viewed as a “data loss” specification
    - Acceptable bit error rates or system outage
  - Mitigation and risk are system trade parameters
  - Environment needs to be defined for YOUR mission (can’t use prediction for different timeframe, orbit, etc…)

Radiation Design Margins (RDMs)

- How much risk does the project want to take?
- Uncertainties that must be considered
  - Dynamics of the environment
  - Test data
    - Applicability of test data
      - Does the test data reflect how the device is used in THIS design?
    - Device variances
      - Lot-to-lot, wafer-to-wafer, device-to-device
- Risk trade
  - Weigh RDM vs. cost/performance vs. probability of issue vs. system reliability etc…
Evaluate Design/Component Usage

- Screen parts list
  - Use existing databases
    - RADATA, REDEX, Radhome, IEEE TNS, IEEE Data Workshop Records, Proceedings of RADECS, etc.
    - Evaluate test data: is it applicable?
      - Use historic data with CAUTION!
  - Look for processes or products with known radiation tolerance (beware of SEE and displacement damage!)
    - BAE Systems, Honeywell Solid State Electronics, UTMC, Harris, etc.
- Radiation test unknowns or non-RH guaranteed devices
- Provide performance characteristics
  - Usually requires application specific information: understand the designer’s sensitive parameters
    - SEE rates
    - TID/DDD

Data Search and Definition of Data Usability Flow

1. Does data Exist? NO
2. Yes: Has process/foundry changed? YES
3. Same wafer lot? YES
4. Test method applicable? YES
5. Sufficient test data? YES
6. Data usable

After  K LaBel, IEEE TNS vol45-6, 1998
System Radiation Test Requirements

- All devices with unknown characteristics should be ground radiation tested (TID and SEE)
- All testing should be performed on flight lot, if possible
  - COTS assemblies have many risks and challenges including
    - Fault isolation, statistics, die access, and many more
- Testing should mimic or bound the flight usage, if possible
  - Beware of new technology issues...

Sample Heavy Ion Test Results

Radiation Test Issue – Fidelity of a Ground Test

How accurate is the ground test in predicting Space Performance?
Engineer with the Designer

- Just because a device’s radiation hardness may not meet requirements, does NOT necessarily make it unusable
  - Many concerns can be dealt with using mitigative approaches
    - Hardened by design (HBD) approaches
    - Circuit level tolerance such as error detection and correction (EDAC) on large memory arrays
    - Mechanical approaches (shielding)
    - Application-specific effects (ex., single bad telemetry point or device is only on once per day for 10 seconds or degradation of parameter is acceptable)
    - System tolerance such as 95% “up-time”
  - The key is what is the effect in THIS application
  - If mitigation is not an option, may have to replace device

*Warning: Not all effects can be mitigated safely*

Diatribe: Levels of Mitigative Actions

- Mitigation can take place at many levels
  - Operational
    - Ex., no operation in SAA (proton hazard)
  - System
    - Ex., redundant boxes/busses
  - Circuit/software
    - Ex., error detection and correction (EDAC) scrubbing of memory devices by external device or processor
  - Device
    - Ex., triple-modular redundancy (TMR) of internal logic
  - Transistor
    - Ex., use of dogbone structure for TID improvement
  - Material
    - Ex., addition of an epi substrate to reduce SEE charge collection (or other substrate engineering)
  - Good engineers can invent infinite solutions, but...
Destructive Conditions - Mitigation

- Recommendation 1: Do not use devices that exhibit destructive conditions in your environment and application
- Difficulties:
  - May require redundant components/systems
  - Conditions such as low current SELs may be difficult to detect
- Mitigation methods
  - Current limiting
  - Current limiting w/ autonomous reset
  - Periodic power cycles
  - Device functionality check
- Latent damage is also a grave issue
  - “Non-destructive” events may be a false statement!

Latent Damage: Implications to SEE

- SEL events are observed in some modern CMOS devices
  - Device may not fail immediately, but recover after a power cycling
  - However, in some cases
    - Metal is ejected from thin metal lines that may fail catastrophically at some time after event occurrence

SEL test qualification methods need to take latent damage into consideration;
Post-SEL screening for reliability required;
Mitigative approaches may not be effective
Final Comments and Future Considerations

RHA – A Few Final Comments

- Technology complicates testing
  - Speed, Thermal, Fault Isolation, Packaging: die access!, etc
    - SETs are the “new” effect in digital devices
- A proactive radiation test and modeling program is required to allow successful system RHA
  - Test planning needs to take place early in mission design for critical devices/systems
  - Typical test requires 3 months or more to plan, test, and complete
    - Complex devices can take > 6 months!
  - Integrated approach provides the lowest risk
    - Designers, radiation lead, systems engineer, etc.