Radiation Effects: Overview for Space Environment Specialists

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# Key to Abbreviations and Symbols

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>DSEE</td>
<td>Destructive single-event effect</td>
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<tr>
<td>GCR</td>
<td>Galactic cosmic ray</td>
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<tr>
<td>GPU</td>
<td>Graphics processing unit</td>
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<tr>
<td>IC</td>
<td>Integrated circuit</td>
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<tr>
<td>I/O</td>
<td>Input/output</td>
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<tr>
<td>LET</td>
<td>Linear energy transfer</td>
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<tr>
<td>p⁺</td>
<td>Proton</td>
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<tr>
<td>SEB</td>
<td>Single-event burnout</td>
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<tr>
<td>SEE</td>
<td>Single-event effect</td>
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<tr>
<td>SEGR</td>
<td>Single-event gate rupture</td>
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<tr>
<td>SEL</td>
<td>Single-event latchup</td>
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<tr>
<td>SV</td>
<td>Sensitive volume</td>
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<tr>
<td>VDS</td>
<td>Drain-source voltage</td>
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<tr>
<td>WC</td>
<td>Worst case</td>
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<tr>
<td>xstr</td>
<td>Transistor</td>
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<tr>
<td>Z</td>
<td>Ion atomic number</td>
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Radiation Effects and the Space Environment

Motivation: Mike Xapsos 2016 NSREC paper proposed replacing conventional margin-based RHA approach w/ choice of environment confidence + success probability for part

- Issue: Margin covers a lot of sins in addition to uncertainty on the environment
- What are implications for TID and SEE testing and analysis of an idea that makes sense?

Types of Radiation Effects and Environments Important for Them

- Cumulative—Total Ionizing Dose (TID) and Displacement Damage Dose (DDD)
- Single-Event Effects (SEE)
  - Destructive SEE
  - Nondestructive SEE

Sources of Error

- Cumulative Effects
- SEE

Hardness Assurance Methodologies

- TID and DDD
- SEE
One Slide: Cumulative Effects of Radiation Environments

- **Main particles of concern are protons and electrons**
  - Trapped proton, Cumulative Solar Protons
  - Trapped electrons (Earth, Jovian...)
  - GCR, solar heavy ion fluxes too low to worry about
  - Transported environment important
- **Cumulative effect, so short-term fluctuations not a concern except for short missions (<2 years)**
- **Greater concern on longer missions**
- **Hardness Assurance Approach**
  - Test sample representative of flight lot w/ x/γ rays
  - Looks like wear-out (failure rate increases w/ dose)
    - Overtest and RDM effective mitigations by ensuring failure rate remains low
  - Redundancy ineffective as a mitigation
- **Affects mainly minority-carrier devices**
- **Main concern: protons + electrons for some devices**
  - Trapped proton, Cumulative Solar Protons
  - Trapped electrons (Earth, Jovian...)
  - GCR, solar heavy ion fluxes too low to worry about
- **Cumulative effect, so short-term fluctuations not a concern except for short missions (<2 years)**
- **Greater concern on longer missions**
- **Hardness Assurance approach similar to TID**
  - Less dependence on bias, dose rate, etc
  - Less part-to-part variation...usually

Charge trapped in oxides alters electrical properties of transistors and other devices.

Displaced atoms in semiconductor crystal lattice form vacancies and interstitials that alter semiconductor electrical properties.

One Slide: Single-Event Effects (SEE)

• SEE caused by ionizing particle traversing device SV
  • Direct ionization—particle from mission environment
    • GCR heavy-ion, solar heavy-ion environments
    • Charge depends on linear energy transfer (LET) and path length
  • Indirect ionization—secondary particle produced by particle (usually proton) from mission environment
    • Solar and Trapped proton environments
  • Low-energy proton (direct ionization)
    • Transported environment for deep-submicron CMOS
    • Multiple scattering important for mechanism
• Poisson process, so constant probability (per ion)

• Consequences of SEE
  • Momentary disturbance of device output (SET)
  • Corruption of one or more bits of data (SEU)
  • Corruption of large amounts of data (block error)
  • Permanent corruption of data bit (stuck bit)
  • Recoverable loss of device functionality (SEFI)
  • Catastrophic failure

• RHA approach: Any SEE can happen any time—Need to test to expose susceptibilities, not to the environment
  • \(10^7 \text{ ions/cm}^2 \sim 913\) years at ISS (LET>1 MeVcm²/mg)
  • \(\sim 347\) years at GEO (LET>1 MeVcm²/mg)

• Constant failure rate → redundancy is effective mitigation
  • Need worst case (e.g. WC SPE) SEE rates as well as mean rates
    • CRÈME-96 has used October ‘89 SPE
    • Ability to get Solar Event LET spectra vs. confidence to feed into CRÈME-96 would be interesting
  • Redundancy implemented at all levels—cell to spacecraft
    • Must pay in currency of the realm—bits for bits, functional parts to maintain availability, cold spares to improve survivability
RHA is About Error Sources and Control

• **Space Environment**
  • Models only good if data underlying them is representative of current conditions
  • Environment is constantly fluctuating—not reflected in all models
  • Goodness of models depends on mission duration, shielding, etc.

• **Sample Variation (part-to-part, lot-to-lot, part-type-to-part-type)**
  • Basic question: Is test sample sufficiently representative of flight parts?
  • Quandary: Sample size must be large enough to define distribution...but...size required to define distribution depends on what the distribution is
  • Pathological distribution (e.g. multiple modes) require binomial sampling

• **Other Statistical Errors**
  • Poisson errors on event counts determining SEE cross sections
  • Sampling errors on time-dependent, intermittent or rare errors/failures

• **Systematic errors**
  • “Mistakes” in measurement, test procedure, etc.
  • Incorrect assumptions in analysis (e.g. assuming incorrect distribution form).
TID RHA Errors

- Environment is only one source of error
  - Mainly issue for short missions
- Binomial sampling errors may dominate
  - 5 parts → 41% CL that \( P_s \geq 0.9 \), 83% CL \( P_s > 0.7 \)
  - Valid even for multimodal distributions
  - Margin does not help—only looks at proportions above and below test level—not how much

- Most TID RHA assumes failure distributions well behaved
  - Parameter estimates converge rapidly w/ sample size
  - Much higher confidence and \( P_s \) possible w/ smaller samples
  - Overtest, design margin effective strategies to avoid failure

- But…trade confidence + \( P_s \) for possibility of systematic error
  - How common are pathological failure distributions?
  - How likely is a small sample-size test to detect pathology?
  - What should we look for? (technology? data characteristics?)

TID RHA: Pathological Distributions Do Occur

- Many parts known to exhibit pathological TID response (ADI OP484, OP400, AD590, National LM111, many discretes, commercial parts such as SDRAMs)
- Bimodal distributions (e.g. OP484), thick tailed distributions (2N5019 JFET)
- What to do?
  - Similarity is not a reliable indicator—several ADI bipolar devices show anomalies; most do not
  - Test larger samples
  - Look for “outliers”
  - Combine lots to see if “outliers” resolve into thick tails or multiple modes

Conventional RHA Approach Uses Radiation Design Margin (RDM)

Max Dose = “Worst-Case” TID Failure Level/RDM

Not where you want to be.

• Conventional approach to TID RHA defines part TID capability or failure level for a part type (WCFL)
• Radiation Design Margin (RDM) defined by project requirements
• Maximum allowed dose for part type =WCFL/RDM

What is WCFL?
• Mean, Median and Mode of failure distribution are not appropriate—failure probability too high

1) Worst performing part in TID lot test
   • Advantage—has an empirical basis—does not assume a statistical model
   • Disadvantage—Odd statistical properties—testing more parts improves knowledge of failure distribution, but WCFL gets worse with sample size

2) $P_s=X\%, \; CL=Y\%$ one-sided tolerance limit (KTL)
   • $\mu \pm KTL(n,P_s,CL) \times \sigma$ (Example 99/90 limit)
   • Advantage—good statistical properties
   • Disadvantage—assumes normal or lognormal distribution

3) Worst performing part for all lots of part tested
   • Advantage—Empirical and more conservative than 1); well suited to high-volume qualification program
   • Disadvantage—still has same odd statistical properties as 1)—more lots tested gives more conservative value

• 2) best in most cases; or 3) in high-production operations or if normality in doubt
Radiation Design Margin vs. Confidence and Success Probability

- Xapsos proposed replacing RDM with requirement at success probability exceed X% in Y% CL environment
  - Offers improved flexibility and ability to combine radiation and reliability +it is really what we want to know
  - Need to understand why current system works (mostly) to assess impact of change.

- So, why does a fixed 2x-4x RDM work as well as it does?
  - For short missions:
    - Environmental uncertainty is higher—less margin available for uncertainty in TID failure distribution
    - But, TID is lower, so fewer parts to worry about failing
  - For longer mission:
    - Higher TID means more parts prone to failure
    - Lower environmental uncertainty—more margin available for uncertainty in TID failure distribution

- Any approach must reflect uncertainties in failure distribution as well as radiation environment

- Part-to-part, lot-to-lot and part-type-to-part-type variation also require statistical treatment
  - Confidence level applies to inference of WCFL from data
  - What does 90% CL on failure distribution in a 90% WC environment mean?
    - Note: Same question also applied when dealing with RDM—it was just more hidden

- And as with any method assuming a distribution, how do we deal with the risk of systematic errors?
SEE Hardness Assurance

• Goals of SEE Hardness Assurance
  1) Identify all SEE modes to which part is susceptible
     a) Spatial coverage—ions/cm² or ions per device (transistor, gate, etc.)
     b) Temporal and Logic masking also affect coverage
  2) Map out dependence of SEE modes vs. collected charge/LET/(Z, energy, angle)
  3) Estimate SEE rate using above information (if possible)
     a) Use CRÈME-96 and $\sigma$ vs. LET curve if
        i. Sensitive Volume (SV) is rectangular parallelepiped
        ii. Susceptibility depends only on LET (or effective LET)—no nuclear/secondary processes
        iii. LET in SV~constant
     b) Otherwise, use Monte Carlo SEE rate estimation (CRÈME-MC, MRED) and $\sigma$ vs. Ion energy, species, angle..., or
     c) Bound using lethal-ion type calculation (SEGR and SEB)
     d) Assess implications for mitigation strategies

• What environments are interesting?
  • Background Environment to answer: “Will the device be able to perform its function in the environment?”
    • GCR + Average Solar and trapped protons
  • “Peak” Environment to answer: Will redundancy mitigation be compromised by peak environment?
    • SPE Heavy-ion + proton environments (but which SPE?)
Spatial Coverage: How Much is Enough?

Simulated Ion Strikes in 60x70 µm² portion of 512 Mbit SDRAM

- If fluence too low, SEE modes go undiscovered—mode could be seen on orbit even if not seen in test
- “Good enough” depends on device feature sizes, device complexity, application, but also on track size and how often susceptible features repeated within device
  - Measure of device complexity may be total # of transistors, or transistors/µm², although function (e.g. processor, memory, FPGA...) also an indicator
  - More on track size later.

What Makes a Good SEE Test?

• A Good SEE Test
  • # of LET values ≥ 6; 12 values reduces errors ~60%
  • # events per cross section enough to make error bars negligible
  • Both # events and # LET values improve fit

• Errors on rate scale ~square of errors on LET\textsubscript{0} or width
  • Worse for very small limiting cross sections

• Errors on rate scale ~linearly w/ error on σ\textsubscript{lim}
  • Again, worse for very small σ\textsubscript{lim}

• Typical test
  • ≥2 parts
  • >>6-12 runs at different LET values
  • ≥ 1 low-LET run w/ fluence >10\textsuperscript{7} ions/cm\textsuperscript{2} to find LET\textsubscript{0}
  • ≥ 1 high-LET run w/ fluence >10\textsuperscript{7} ions/cm\textsuperscript{2} to preclude presence of undetected destructive/disruptive SEE modes

• Total coverage of typical SEE test usually ≥10\textsuperscript{8} ions/cm\textsuperscript{2} for all ions of all Z, energy, angle

Each curve represents flux vs. energy for a different ion in the radiation environment.

IRPP rate estimation separates device response and environment portions of integral

Fit to device response (σ vs. LET) usually “worst case” — same independent of environment

At least 4 parameters, onset LET (LET\textsubscript{0}), limiting cross section (σ\textsubscript{lim}), Weibull width and shape parameters
How Good Are SEE Rates?

• Statistical errors for SEE can be controlled, so accurate SEE rate estimation should be possible

• Ed Petersen found on-orbit rates agreed with predicted rates within ~2x (CRÈME-96 and AP8)

• SDRAMs (Ladbury-2009 and Miller-2009) agree w/in ~3-5x if knowledge of shielding, statistics adequate
  • Rates for disruptive errors (SEFI, block errors, etc) due to poor statistics
  • Rates for parts in Van Allen Belts sensitive to shielding
  • Fabricated in CMOS processes w/ feature sizes down to ~130 nm, so CRÈME-96 can be adequate to this level

• For smaller feature sizes, situation is more muddled
  • Expect departures from RPP, but rate estimation also more sensitive to errors on fit

• Above indicates errors due to environment over long term <~2x

• So, we’re good, right?

• Multiple Sources of Systematic Error
  • Nuclear Effects
    • Scattering of high-Z nuclei by light nuclei
    • p + Au fission events
  • Departures from LET
    • High-energy ion tracks have more energetic delta rays
      • More MBUs
      • Ultra-high energy events
      • Multi-node upsets in hardened logic
  • Proton upset via direct ionization
    • Low-energy proton environment variable and uncertain
    • Detailed shielding model essential to determine low-energy proton flux in the device SV
      • Multiple scattering plays critical role in mechanism
  • CRÈME-96 won’t work for these mechanisms
  • Monte Carlo methods can work, but we’re still figuring out how to use them.
Track Structure: Wild Card of the Future (and always will be?)

- Track structure has always been a wild card
  - Up to now a wild card with few consequences
- Transistors now have dimensions ~100 µm
  - Energy deposition not uniform @ high energy
  - $\delta$ ray can traverse dozens of transistors
  - $\delta$ ray multiple scattering important
  - Implications for MBU and SEE hardening

28 GeV Fe ion (500 MeV/u)  280 MeV Fe ion (5 MeV/u)

$\delta$-rays

90% of Track Energy contained within this radius
50% of Track Energy contained within this radius

Courtesy of Robert Reed, Vanderbilt University
Conclusions: TID and DDD

• Different environments important for different missions
  • TID: All ionizing particles contribute—solar and trapped protons and electrons dominate
    • Long missions—average environment dominates
    • Short missions—one large solar particle event can dominate TID for missions <1-2 years
  • DDD: Massive, energetic particles—protons (trapped and solar) usually the main contributors, also electrons
    • Situation similar to TID—long missions dominated by average; short missions can be dominated by SPE
    • Jupiter—electrons energetic and plentiful...can contribute to DDD

• Environmental uncertainty is only one source of error; usually not dominant
  • TID: Part-to-part variation usually the dominant source of error
    • Very large sample sizes required to have high confidence of high success probability
      • Binomial sampling has to work for even pathological distributions
      • Increased Radiation Design margin does not help
    • Assuming well behaved distribution allows reduced sample size for higher Ps at higher confidence
      • Replaces sampling error with systematic error if distribution is pathological—which can occur
      • Important to look for signs of pathology
      • Going to environmental confidence + success probability may force more rigorous treatment of variability and pathologies

• Displacement damage somewhat more tractable
  • Pathological distributions less common; fewer application conditions
Conclusions: Single-Event Effects

• Important fact about SEE—can happen any time, regardless of probability
  • First goal of testing is to identify SEE susceptibilities, NOT to bound relevant environments
  • Second goal: Rate estimation combines device susceptibilities + Environment Models

• Environments important for Single-event effects: GCR+ solar heavy ions + protons + trapped protons
  • Average environment important for ensuring part meets its requirements
  • Peak environment (for given confidence) important because redundancy is the predominant mitigation for SEE
    • SEE rate for a redundant system scales as a power of particle flux, rather than linearly
  • Low-energy protons highly variable, uncertain, and role of multiple scattering makes mechanism “fuzzy”
  • Electrons starting to cause SEE as well—multiple scattering even more important (no Bragg peak)

• Many sources of error other than environment
  • Poisson errors on cross section can dominate for small event counts (especially for DSEE, SEFI, disruptive errors)
  • Deviations from CRÈME-96 model assumptions (constant LET in single RPP SV, no nuclear/secondary effects)
    • Monte Carlo with accurate physics needed if deviations significant.

• Track structure effects may assume greater importance as devices continue to shrink
  • Less containment of ionization within any given track radius
  • Process more random
  • Mostly important for multi-node effects (MBU and upset of cells hardened by redundant nodes)