Recent Advances and Future Challenges in Risk-Based Radiation Engineering

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Overview

• Introduction to hardness assurance (HA).
  o From a robotic space system perspective, starting at the piece-part level.

• Systematic and statistical issues inherent to HA.
  o We are risk-averse.

• Moving towards risk-tolerant system design approaches.

• Future challenges.

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Introduction

- HA defines 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 \( (C) \).


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Additional HA Details

• HA applies to both single-particle and cumulative degradation mechanisms.
  o Total ionizing dose (TID),
  o Total non-ionizing dose (TNID) / displacement damage dose (DDD), and
  o Single-event effects (SEE) – both destructive and non-destructive.

• Historically, HA is controlled by radiation design margin (RDM) – particularly for TID and TNID.
  o RDM is defined as the ratio of the mean part failure level to the radiation specification level derived from the environment. We will return to RDM.

\[
RDM = \frac{R_{mf}}{R_{spec}}
\]
System Level HA

- Always faced with conflicting demands between “Just Make It Work” (designer) and “Just Make It Cheap” (program).
- Many system-level strategies pre-date the space age (e.g., communications, fault-tolerant computing, etc.).
- Tiered approach to validation of mission requirements.

Why Are We So Risk Averse?

• HA, in general, relies on statistical inference to quantitatively reduce risk.
  o Number of samples, number of observed events, number/type of particles, etc.
• Decisions are often based on a combination of test data with simulation results, technical information, and expert opinion.
• Use “as-is” or remediate?
• Risk aversion tends to be driven by the cost/consequences of failure in the presence of necessarily incomplete information.


Costs for:
- Testing ($C_t$),
- Remediation ($C_r$), and
- Failure ($C_f$).

Two cases:
1) Fly “as-is” when risk is too high
2) Remediate when risk is acceptable
Sources of Radiation Effects

Uncertainty

- Uncertainty sources are both systematic and statistical.

- Effective radiation testing/evaluation must address these sources in the failure probability.

- For TID and TNID, the main sources of statistical uncertainty are lot-to-lot and part-to-part variability.
  - Traditional mitigation: measure more parts

- For SEE, probabilities scale with rates, and rate uncertainties are dominated by systematic errors in rate calculation methods as well as Poisson fluctuations in the observed error counts that determine SEE cross sections.
  - Traditional mitigation: measure more events


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Solution Strategies for SEE Risk Mitigation

- Maintain existing failure distributions (e.g., Weibull, Lognormal, Exponential, etc.) and increase insight using advanced techniques such as maximum likelihood (ML).
  
  
  - Potentially solves traditional test method data analysis gaps (e.g., JESD57) for small event counts – particularly important for destructive events.

### Table

<table>
<thead>
<tr>
<th>Effective LET</th>
<th>Cross Section</th>
<th>Events Observed</th>
<th>Effective Fluence</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.80</td>
<td>0.00x10^6</td>
<td>0</td>
<td>1.00x10^7</td>
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<td>11.03</td>
<td>0.00x10^6</td>
<td>0</td>
<td>1.00x10^7</td>
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<td>15.60</td>
<td>0.00x10^6</td>
<td>0</td>
<td>1.00x10^7</td>
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<td>28.80</td>
<td>1.00x10^-7</td>
<td>1</td>
<td>9.99x10^6</td>
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<td>40.73</td>
<td>6.29x10^-6</td>
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<td>53.10</td>
<td>2.79x10^-3</td>
<td>100</td>
<td>3.59x10^6</td>
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<td>57.60</td>
<td>4.01x10^-5</td>
<td>100</td>
<td>2.50x10^6</td>
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<td>75.09</td>
<td>1.06x10^-4</td>
<td>100</td>
<td>9.46x10^5</td>
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<td>106.20</td>
<td>2.36 x10^-4</td>
<td>100</td>
<td>4.23x10^5</td>
</tr>
</tbody>
</table>

Log likelihood ratios determine not only the best-fit (black square) parameters for the Weibull fit, but also the confidence intervals for these parameters, as shown for this slice through the 95% confidence contour.

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Solution Strategies for SEE Risk Mitigation

- Small number of data points, large parameter spaces, and expense of component loss in destructive testing leads to conservative approaches – e.g., safe operating areas.

- Develop additional SEE rate calculation approaches for destructive effects that better account for and manage risk.

Infineon / International Rectifier
Gen5 MOSFET
Safe Operating Area (SOA)

Solution Strategies for TID/TNID Risk Mitigation

- RDM for TID and TNID driven by component-level and environmental uncertainty as well as program goals.
  - Historically, the radiation environment specification (e.g., 25 krad(Si)) was assumed to be a fixed quantity – driven largely by the static AP-8/AE-8 trapped particle models.
    - Resulted in integer RDMs, such as 2, 3, 4, etc.
Solution Strategies for TID/TNID Risk Mitigation

- New AP-9/AE-9 trapped particle models are probabilistic and permit full Monte Carlo calculations for evaluating environment dynamics.
  - Outputs parameters are similar to solar proton fluence models, though derivation process is different.
- For applicable missions, combined environment modeling capability allows us to replace RDM with failure probability.

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Future Challenges

• Evaluating space systems with commercial-off-the-shelf (COTS) components vs. space systems of COTS components.

• Performing radiation testing/evaluation at various levels of component, board, sub-system, and system integration.
  - Particle type, energy, flux, etc.
  - Component, board, sub-system, system preparation.

• Discovering and quantifying additional mechanisms and/or failure modes. Examples include, but are not limited to:
  - Destructive failures in Schottky diodes, silicon carbide, gallium nitride, etc.
  - Proton fission in high-Z packaging materials.

• Coping with test facility bottlenecks for access to both heavy ions and protons.
  - Facility availability, maintainability, and use cost.
  - Increasing user community.

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### Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>COTS</td>
<td>Commercial Off The Shelf</td>
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<tr>
<td>DC</td>
<td>Direct current</td>
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<tr>
<td>DDD</td>
<td>Displacement damage dose</td>
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<td>GEO</td>
<td>Geostationary Orbit</td>
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<tr>
<td>HA</td>
<td>Hardness assurance</td>
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<tr>
<td>IEEE</td>
<td>Institute for Electrical and Electronics Engineers</td>
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<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
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<tr>
<td>LET</td>
<td>Linear Energy Transfer</td>
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<td>ML</td>
<td>Maximum likelihood</td>
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<tr>
<td>MOSFET</td>
<td>Metal Oxide Semiconductor Field Effect Transistor</td>
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<td>NEPP</td>
<td>NASA Electronic Parts and Packaging program</td>
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<td>NESC</td>
<td>NASA Engineering and Safety Center</td>
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<tr>
<td>RDM</td>
<td>Radiation design margin</td>
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<td>SEE</td>
<td>Single-event effects</td>
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<td>SEGR</td>
<td>Single-event gate rupture</td>
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<td>SRAM</td>
<td>Static random access memory</td>
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<tr>
<td>SOA</td>
<td>Safe Operating Area</td>
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<tr>
<td>TID</td>
<td>Total ionizing dose</td>
</tr>
<tr>
<td>TNID</td>
<td>Total non-ionizing dose</td>
</tr>
<tr>
<td>TNS</td>
<td>Transactions on Nuclear Science</td>
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