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Recent Advances and Future Challenges in Risk-Based Radiation Engineering

Jonathan A. Pellish

NASA Goddard Space Flight Center
Greenbelt, MD USA

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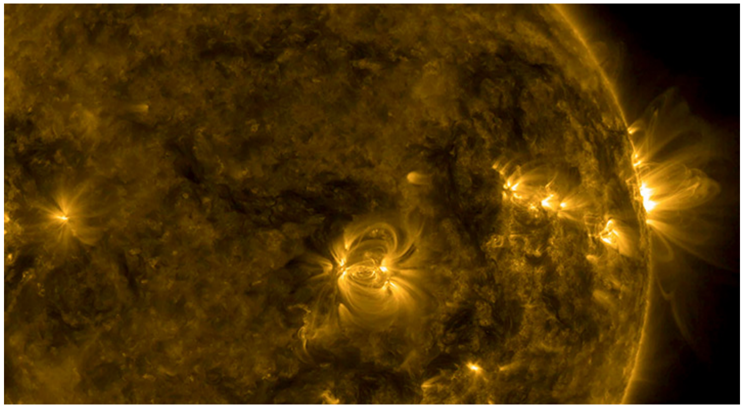
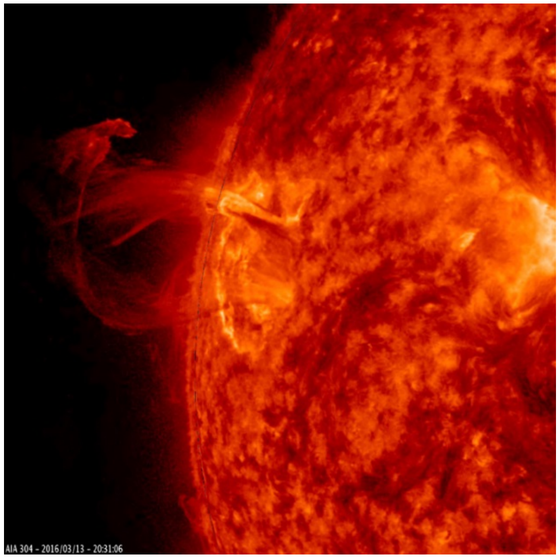
Overview

- Introduction to hardness assurance (HA).
  - From a robotic space system perspective, starting at the piece-part level.
- Systematic and statistical issues inherent to HA.
  - We are risk-averse.
- Moving towards risk-tolerant system design approaches.
- Future challenges.



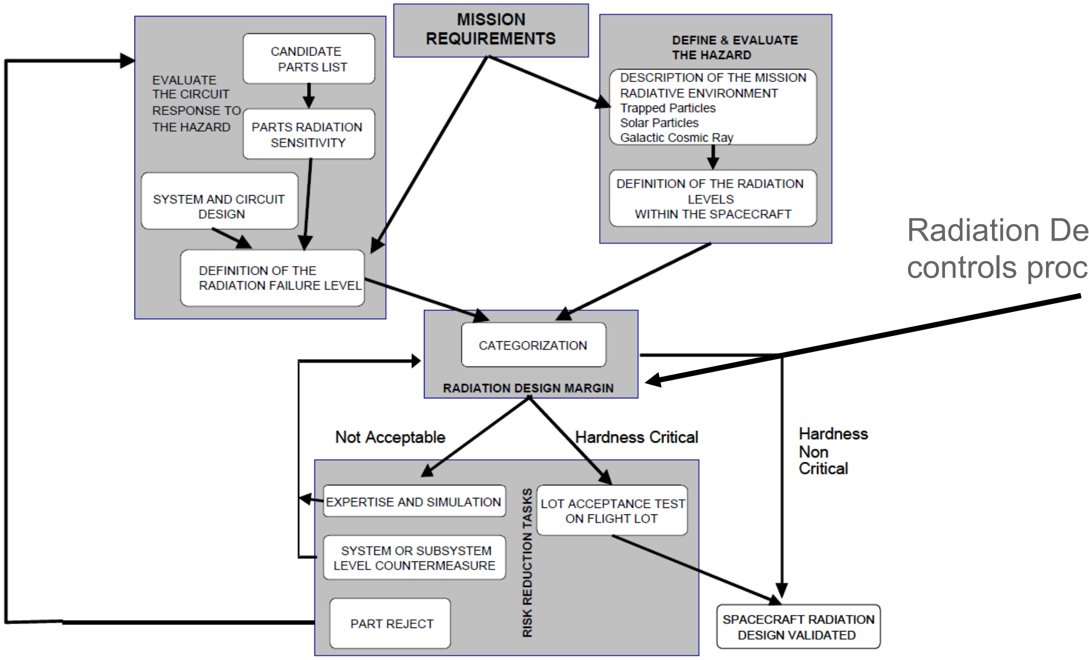


Credit: Solar Dynamics Observatory, NASA

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).

R. Pease, *IEEE NSREC Short Course*, "Microelectronic Piece Part Radiation Hardness Assurance for Space Systems," Atlanta, July 2004.



MISSION REQUIREMENTS

EVALUATE THE CIRCUIT RESPONSE TO THE HAZARD

CANDIDATE PARTS LIST

PARTS RADIATION SENSITIVITY

SYSTEM AND CIRCUIT DESIGN

DEFINITION OF THE RADIATION FAILURE LEVEL

DEFINE & EVALUATE THE HAZARD

DESCRIPTION OF THE MISSION RADIATIVE ENVIRONMENT
Trapped Particles
Solar Particles
Galactic Cosmic Ray

DEFINITION OF THE RADIATION LEVELS WITHIN THE SPACECRAFT

CATEGORIZATION

RADIATION DESIGN MARGIN

Not Acceptable

Hardness Critical

Hardness Non Critical

RISK REDUCTION TASKS

EXPERTISE AND SIMULATION

SYSTEM OR SUBSYSTEM LEVEL COUNTERMEASURE

PART REJECT

LOT ACCEPTANCE TEST ON FLIGHT LOT

SPACECRAFT RADIATION DESIGN VALIDATED

Radiation Design Margin controls process

Overview of the radiation hardness assurance process

C. Poivey, *IEEE NSREC Short Course*, "Radiation Hardness Assurance for Space Systems," Phoenix, July 2002.

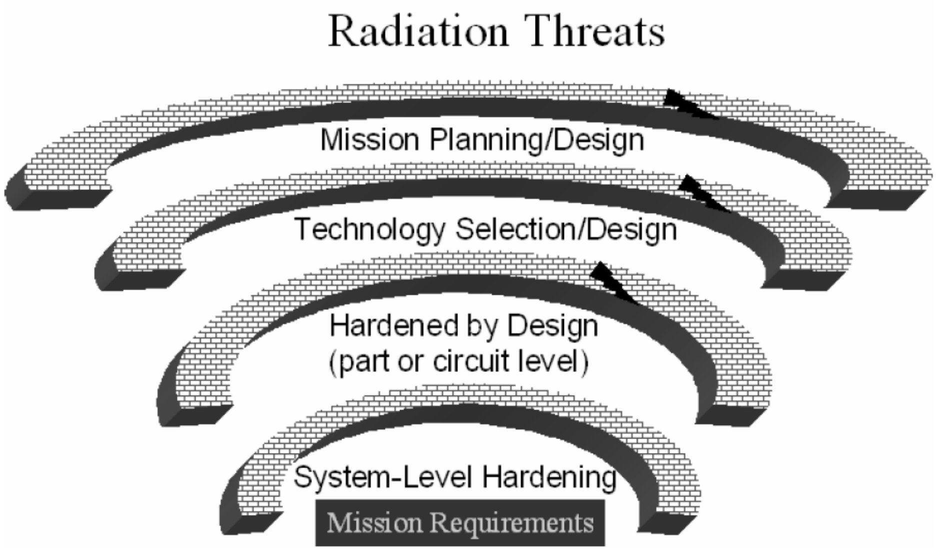
Additional HA Details

- HA applies to both single-particle and cumulative degradation mechanisms.
  - Total ionizing dose (TID),
  - Total non-ionizing dose (TNID) / displacement damage dose (DDD), and
  - Single-event effects (SEE) – both destructive and non-destructive.
- Historically, HA is controlled by radiation design margin (RDM) – particularly for TID and TNID.
  - 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.

$$\mathrm{RDM} = \frac{R_{\mathrm{mf}}}{R_{\mathrm{spec}}}$$

System Level HA

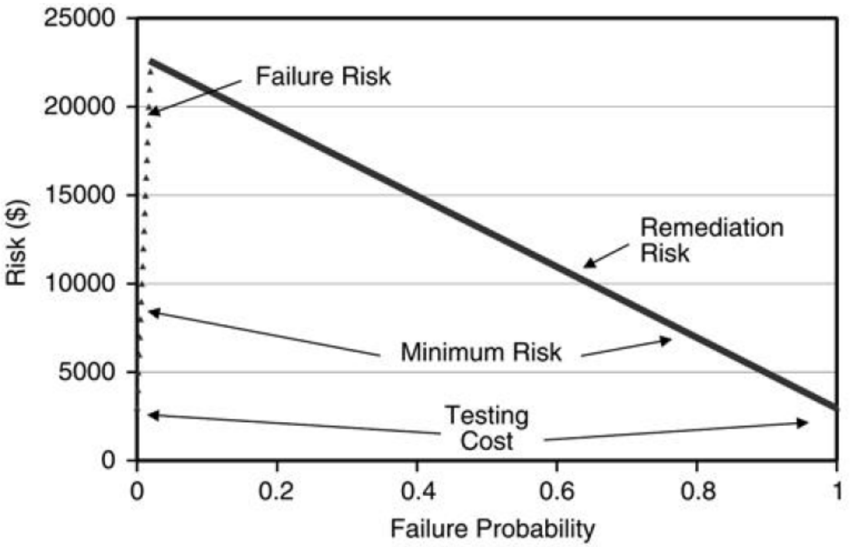
- Always faced with conflicting demands between “Just Make It Work” (designer) and “Just Make It Cheap” (program).
- Many system-level strategies pre-date the space age (e.g., communications, fault-tolerant computing, etc.).
- Tiered approach to validation of mission requirements.



R. Ladbury, *IEEE NSREC Short Course*, “Radiation Hardening at the System Level,” Honolulu, July 2007.

Why Are We So Risk Averse?

- HA, in general, relies on statistical inference to quantitatively reduce risk.
  - 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.



R. Ladbury, *et al.*, "A Bayesian Treatment of Risk for Radiation Hardness Assurance," *RADECS Conf.*, Cap D'Agde, France, September 2005.

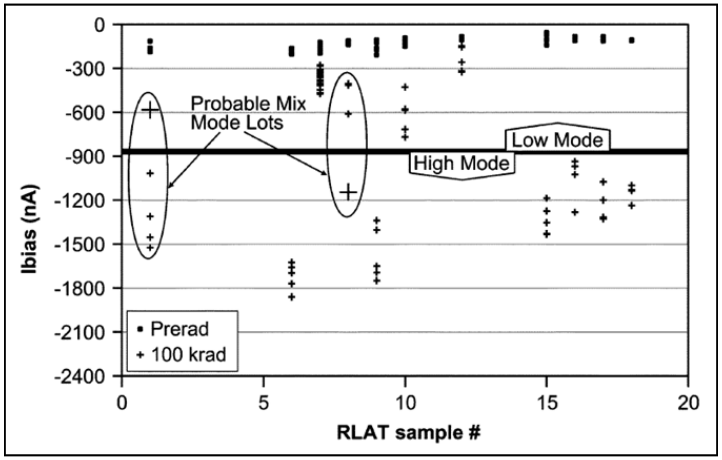
Costs for:
- Testing (C_t),
- Remediation (C_r), and
- Failure (C_f).

Two cases:
1) Fly "as-is" when risk is too high
2) Remediate when risk is acceptable

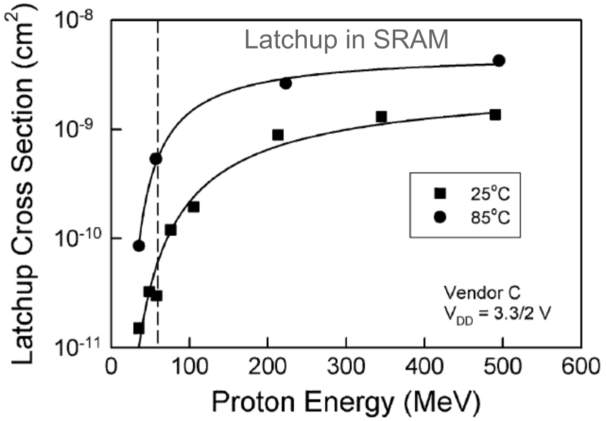
Sources of Radiation Effects Uncertainty

- 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

OP484 Quad Op Amp at 100 krad(SiO_2)



R. Ladbury, *et al.*, *IEEE TNS*, 2005.



Effect of temperature on SEE sensitivity

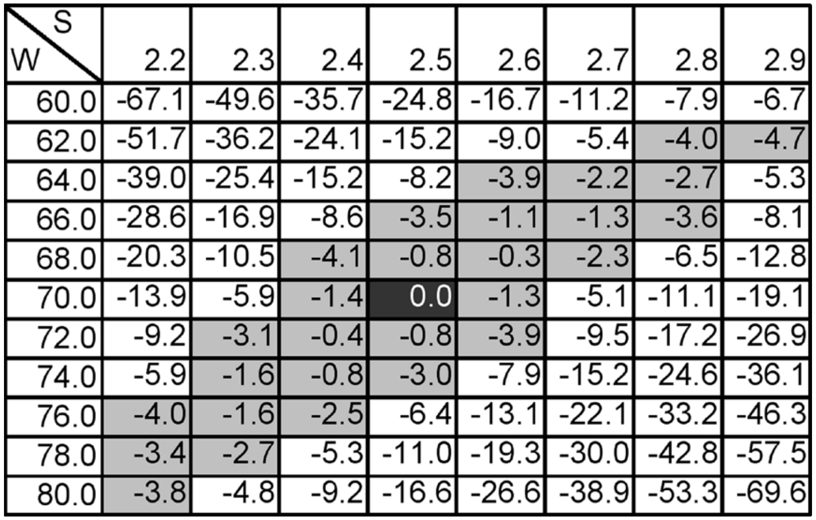
J. R. Schwank, *et al.*, *IEEE TNS*, 2005.

R. Ladbury, *et al.*, "A Bayesian Treatment of Risk for Radiation Hardness Assurance," *RADECS Conf.*, Cap D'Agde, France, September 2005.

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).
    - For example: R. Ladbury, “Statistical Properties of SEE Rate Calculation in the Limits of Large and Small Event Counts,” in *IEEE TNS*, Dec. 2007.
    - Potentially solves traditional test method data analysis gaps (e.g., JESD57) for small event counts – particularly important for destructive events.

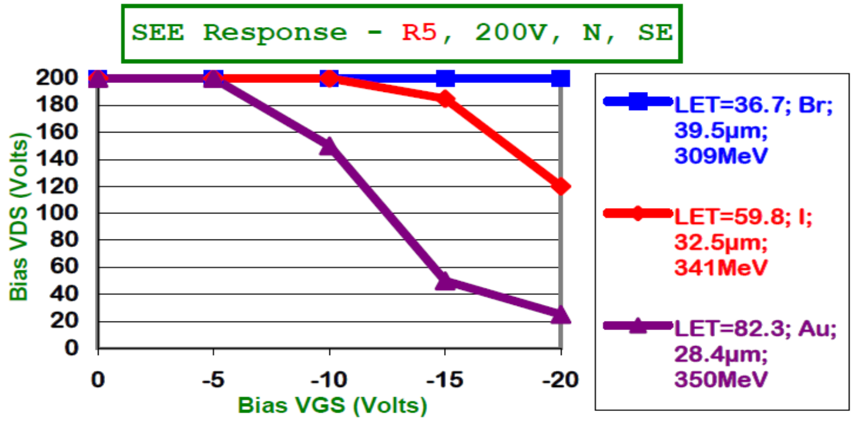
Effective LET	Cross Section	Events Observed	Effective Fluence
7.80	0.00×10^{0}	0	1.00×10^{7}
11.03	0.00×10^{0}	0	1.00×10^{7}
15.60	0.00×10^{0}	0	1.00×10^{7}
28.80	1.00×10^{-7}	1	9.99×10^{6}
40.73	6.29×10^{-6}	50	7.95×10^{6}
53.10	2.79×10^{-5}	100	3.59×10^{6}
57.60	4.01×10^{-5}	100	2.50×10^{6}
75.09	1.06×10^{-4}	100	9.46×10^{5}
106.20	2.36×10^{-4}	100	4.23×10^{5}



S W	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9
60.0	-67.1	-49.6	-35.7	-24.8	-16.7	-11.2	-7.9	-6.7
62.0	-51.7	-36.2	-24.1	-15.2	-9.0	-5.4	-4.0	-4.7
64.0	-39.0	-25.4	-15.2	-8.2	-3.9	-2.2	-2.7	-5.3
66.0	-28.6	-16.9	-8.6	-3.5	-1.1	-1.3	-3.6	-8.1
68.0	-20.3	-10.5	-4.1	-0.8	-0.3	-2.3	-6.5	-12.8
70.0	-13.9	-5.9	-1.4	0.0	-1.3	-5.1	-11.1	-19.1
72.0	-9.2	-3.1	-0.4	-0.8	-3.9	-9.5	-17.2	-26.9
74.0	-5.9	-1.6	-0.8	-3.0	-7.9	-15.2	-24.6	-36.1
76.0	-4.0	-1.6	-2.5	-6.4	-13.1	-22.1	-33.2	-46.3
78.0	-3.4	-2.7	-5.3	-11.0	-19.3	-30.0	-42.8	-57.5
80.0	-3.8	-4.8	-9.2	-16.6	-26.6	-38.9	-53.3	-69.6

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.

Solution Strategies for SEE Risk Mitigation

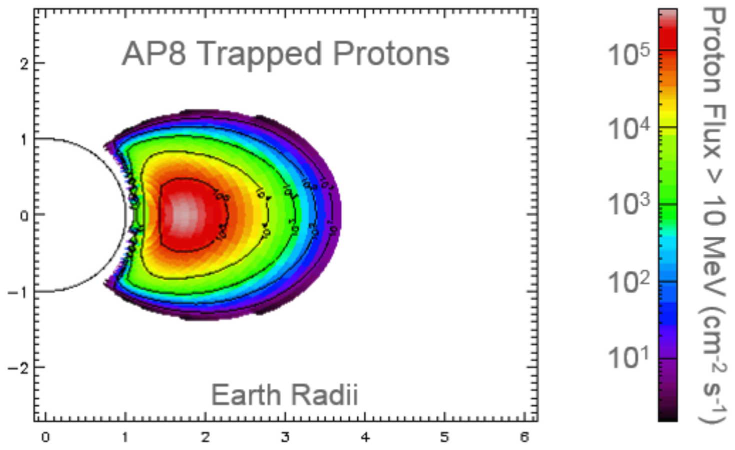


http://www.irf.com/product-info/hi-rel/reports/gssee_572x0se.pdf

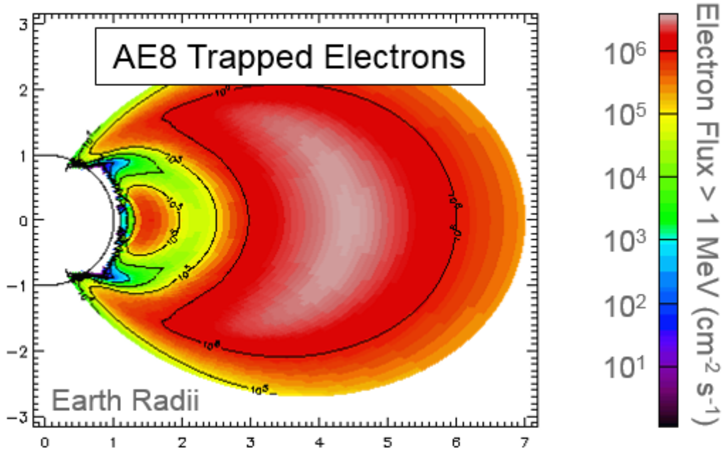
Infineon / International Rectifier
Gen5 MOSFET
Safe Operating Area (SOA)

- 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.
  - For example: J. M. Lauenstein, et al., “Interpreting Space-Mission LET Requirements for SEGR in Power MOSFETs,” in *IEEE TNS*, 2010.

Solution Strategies for TID/TNID Risk Mitigation



SPENVIS, http://www.spenvis.oma.be/, v4.6.5

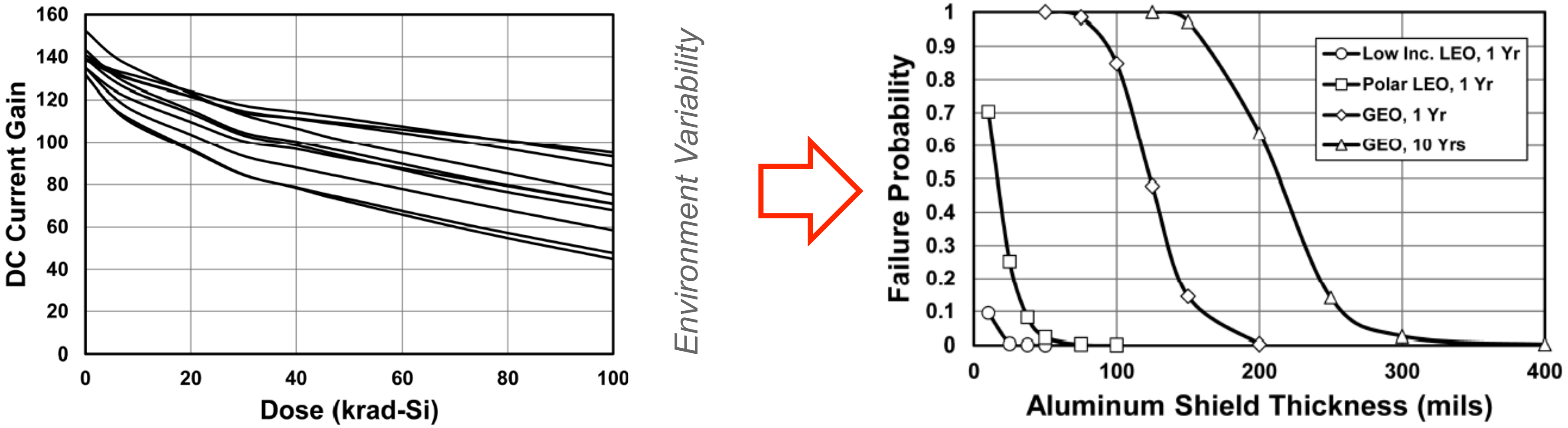


SPENVIS, http://www.spenvis.oma.be/, v4.6.5

- 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

Gamma Ray TID Data on 2N2907 Bipolar Transistor



- 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.
  - M. A. Xapsos, *et al.*, “Inclusion of Radiation Environment Variability in Total Dose Hardness Assurance Methodology,” in *IEEE TNS*, in press.

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.

Acronyms

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