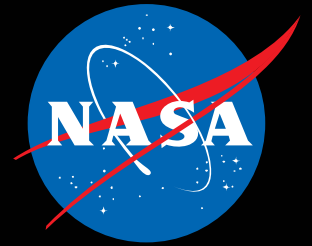


National Aeronautics and
Space Administration



Tutorial

Current Status and Future Challenges in Risk-Based Radiation Engineering

Jonathan A. Pellish

*NASA Goddard Space Flight Center
Greenbelt, MD USA*

October 2017

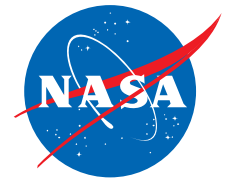
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www.nasa.gov

To be published on <https://cpaess.ucar.edu/>

Background image courtesy of NASA/SDO and the AIA, EVE, and HMI science teams.

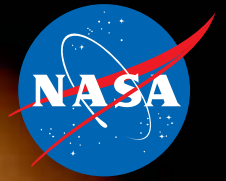
Acronyms



Acronym	Definition
AIA	Atmospheric Imaging Assembly
AIEE	American Institute of Electrical Engineers
CME	Coronal Mass Ejection
CMOS	Complementary Metal Oxide Semiconductor
COTS	Commercial Off the Shelf
DDD	Displacement Damage Dose
ELDRS	Enhanced Low Dose Rate Sensitivity
EVE	Extreme Ultraviolet Variability Experiment
FET	Field Effect Transistor
FPGA	Field Programmable Gate Array
GCR	Galactic Cosmic Ray
GSFC	Goddard Space Flight Center
HMI	Helioseismic and Magnetic Imager
IEEE	Institute of Electrical and Electronics Engineers
IRE	Institute of Radio Engineers
LASCO	Large Angle and Spectrometric Coronagraph
LED	Light-Emitting Diode
LEP	Low-Energy Proton
LET	Linear Energy Transfer
MBU	Multiple-Bit Upset
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NASA	National Aeronautics and Space Administration

Acronym	Definition
NIEL	Non-Ionizing Energy Loss
NSREC	Nuclear and Space Radiation Effects Conference
PKA	Primary Knock-on Atom
RAM	Random Access Memory
RHA	Radiation Hardness Assurance
SAA	South Atlantic Anomaly
SAMPEX	Solar Anomalous Magnetospheric Explorer
SBU	Single-Bit Upset
SDO	Solar Dynamics Observatory
SDRAM	Synchronous Dynamic RAM
SEB	Single-Event Burnout
SEE	Single-Event Effects
SEFI	Single-Event Functional Interrupt
SEGR	Single-Event Gate Rupture
SEL	Single-Event Latchup
SET	Single-Event Transient
SEU	Single-Event Upset
SOHO	Solar & Heliospheric Observatory
SOI	Silicon-on-Insulator
TAMU	Texas A&M University
TID	Total Ionizing Dose
TNID	Total Non-Ionizing Dose

Operation vs. Design – Dual Focus



- 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]

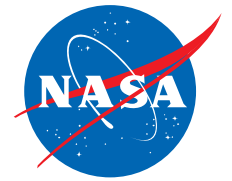
“Space weather” refers to the dynamic conditions of the space environment that arise from emissions from the Sun, which include solar flares, solar energetic particles, and coronal mass ejections.

These emissions can interact with Earth and its surrounding space, including the Earth’s magnetic field, potentially disrupting [...] technologies and infrastructures.

*National Space Weather Strategy,
Office of Science and Technology
Policy, October 2015*

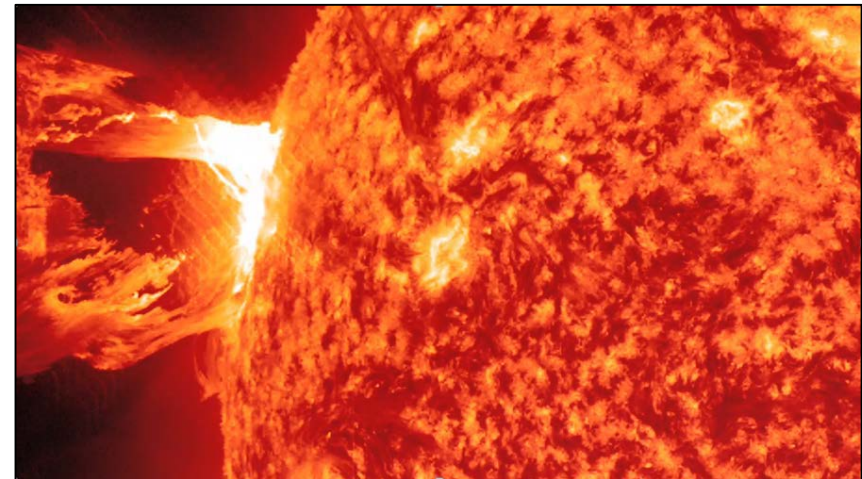
Chart adapted from content developed by M. Xapsos, NASA/GSFC

Outline



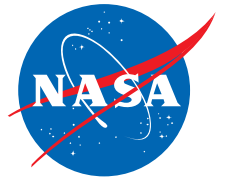
- Basis and challenges for radiation effects in electronics
- 3 main types of radiation effects in electronics
 - Total ionizing dose (TID)
 - Total non-ionizing dose (TNID), displacement damage dose (DDD)
 - Single-event effect (SEE)
- Relevant examples of effects, current concerns, and possible environmental model-driven solutions

Coronal mass ejection shot off the east limb (left side) of the Sun on April 16, 2012



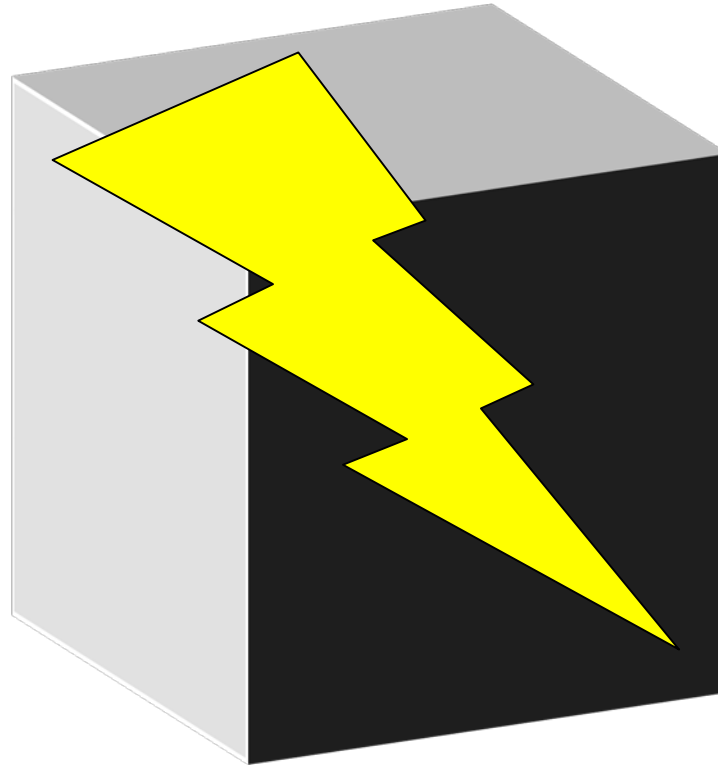
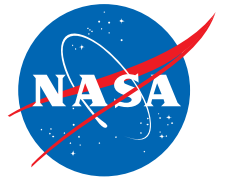
NASA/Goddard Space Flight Center/SDO

What makes radiation effects so challenging?

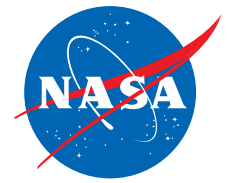


- Field is still evolving as are the technologies we want to use
- A problem of dynamic range
 - Length: 10^{16} m \rightarrow 10^{-15} m (1 light year, 1 fm)
 - » 10^{31}
 - Energy: 10^{19} eV \rightarrow 1 eV (extreme energy cosmic ray, silicon band gap)
 - » 10^{19}
 - Those are just two dimensions; there are many others.
 - » Radiation sources, electronic technologies, etc.
- Variability and knowledge of the environment

What are radiation effects?



- Energy deposition rate in a “box”
- Source of energy and how it’s absorbed control the observed effects



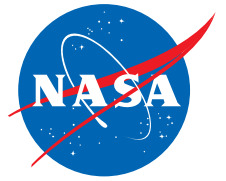
What is total ionizing dose?

- Total ionizing dose (TID) is the **absorbed dose** in a given material resulting from the **energy deposition of ionizing radiation**.
- TID results in **cumulative parametric degradation** that can lead to **functional failure**.
- In space, caused mainly by **protons** and **electrons**.

Examples

Metal Oxide Semiconductors Devices	Bipolar Devices
Threshold voltage shifts	Excess base current
Increased off-state leakage	Changes to recombination behavior

What is displacement damage?

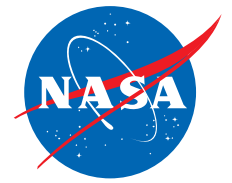


- Displacement damage dose (DDD) is the **non-ionizing energy loss (NIEL)** in a given material resulting from a portion of **energy deposition by impinging radiation**.
- DDD is **cumulative parametric degradation** that can lead to **functional failure**.
- In space, caused mainly by **protons** and **electrons**.

DDD Effects

Degraded minority carrier lifetime (e.g., gain reductions, effects in LEDs and optical sensors, etc.)

Changes to mobility and carrier concentrations



What are single-event effects?

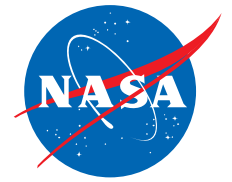
- A single-event effect (SEE) is a **disturbance** to the normal operation of a circuit caused by the passage of a **single ion** (*typically* a proton or heavy ion) through or near a sensitive node in a **circuit**.
- SEEs can be either **destructive** or **non-destructive**.

Examples

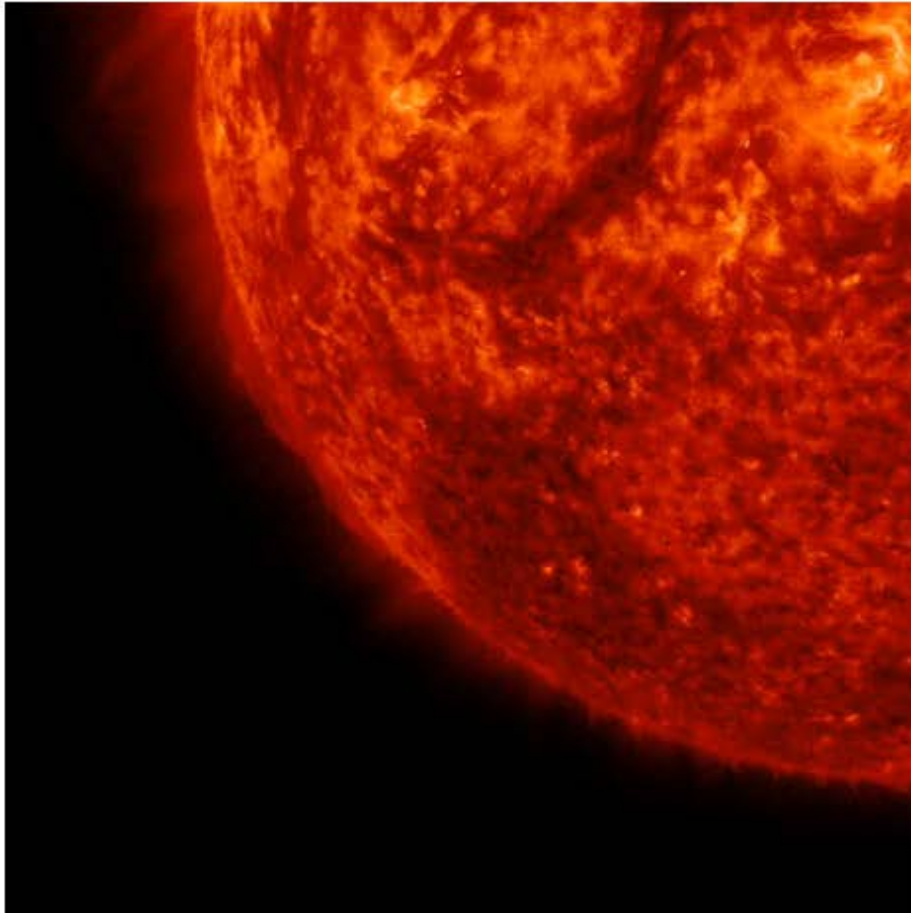
Non-Destructive	Destructive
Single-Event Upset (SEU)	Single-Event Latchup (SEL)
Multiple-Bit Upset (MBU)	Single-Event Burnout (SEB)
Single-Event Transient (SET)	Single-Event Gate Rupture (SEGR)
Single-Event Functional Interrupt (SEFI)	

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

Space Weather-Driven SEE

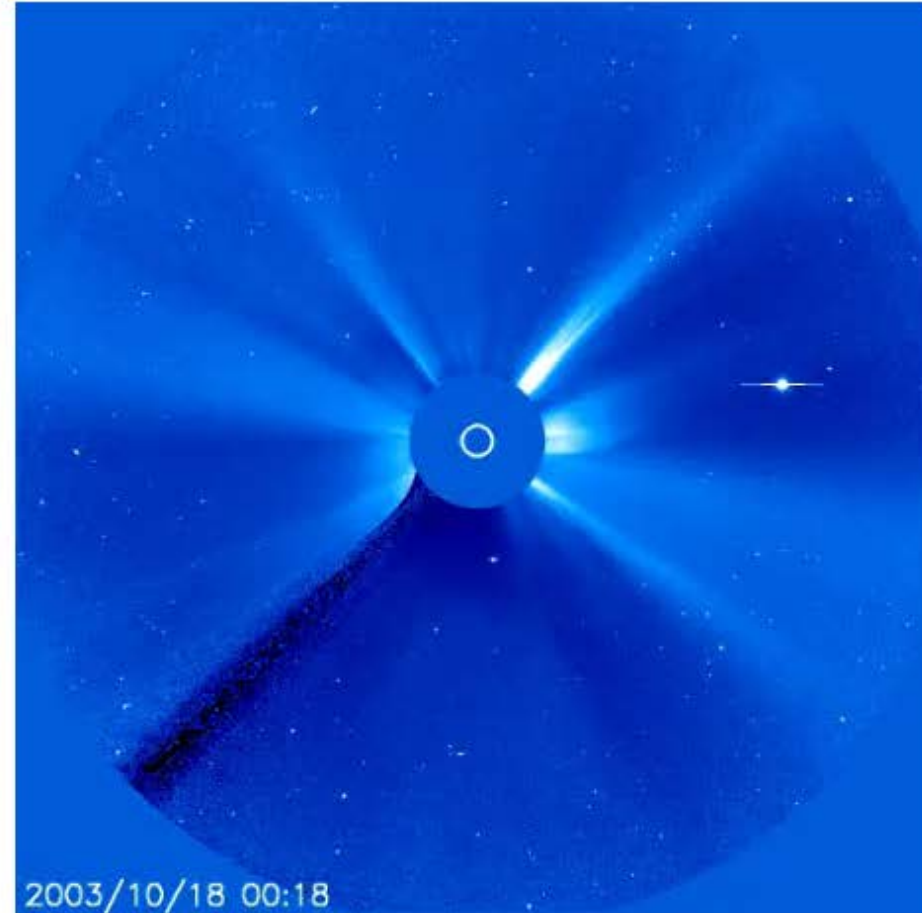


Coronal Mass Ejection and Filament (Feb. 24, 2015)



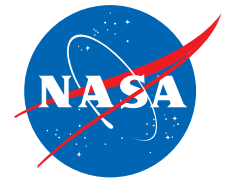
Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams.

Halloween Storms (Oct. 18 - Nov. 7 2003)



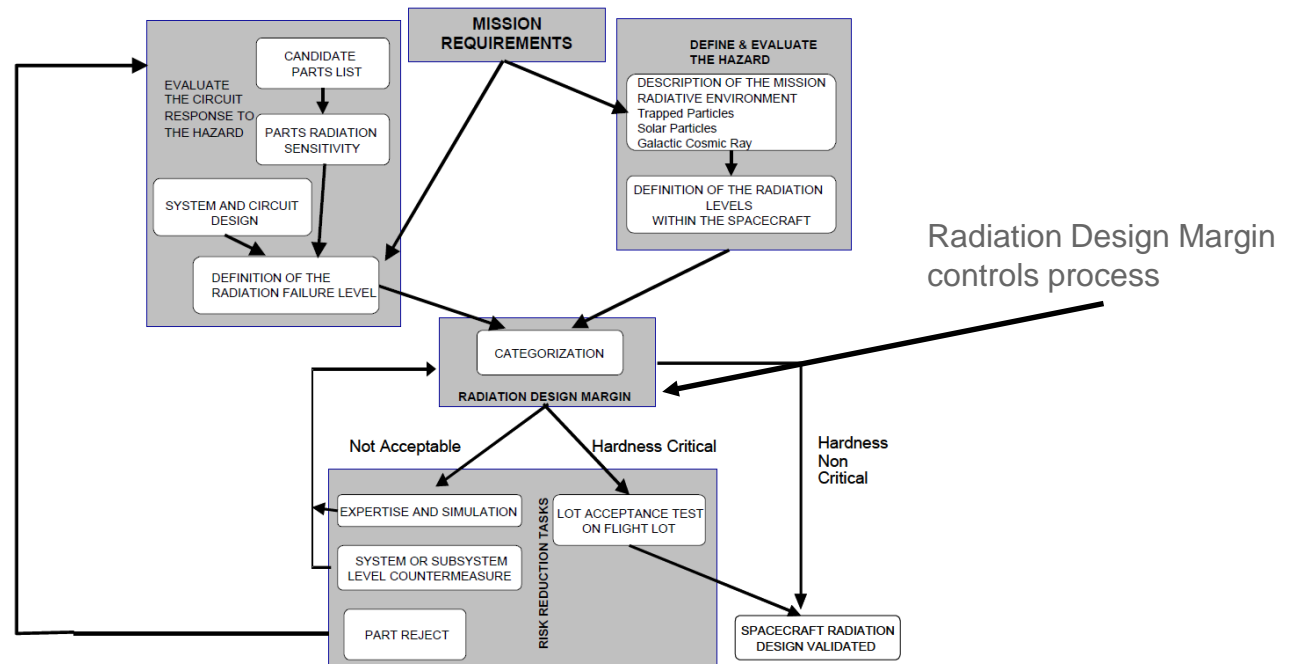
Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA.

Hardness Assurance (HA)



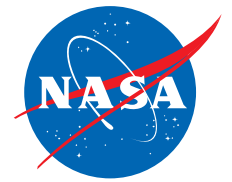
- HA defines the methods used to assure that microelectronic piece-parts meet specified requirements for system operation at specified radiation levels for a given probability of survival (P_s) and level of confidence (C).

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



Overview of the radiation hardness assurance process

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

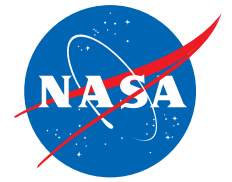


Additional HA Details

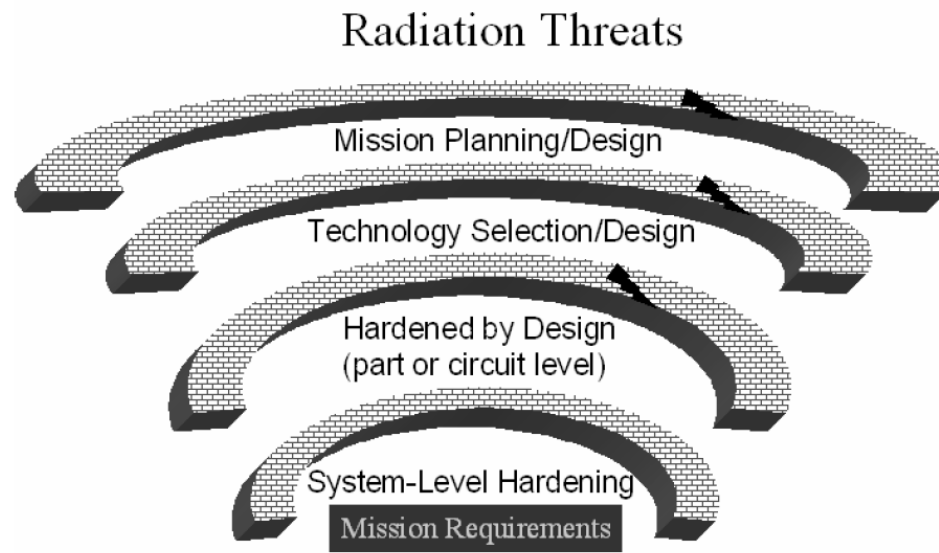
- HA applies to both single-particle and cumulative degradation mechanisms.
 - Total ionizing dose (TID),
 - Total non-ionizing dose (TNID) / displacement damage dose (DDD), and
 - Single-event effects (SEE) – both destructive and non-destructive.
- Historically, HA tends to be dominated by large design margins and risk avoidance – some of which is driven by environmental uncertainty.

Traditional approach may not be valid for all scenarios in modern systems

System Level HA

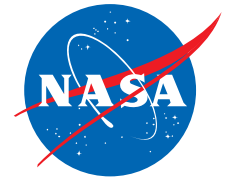


- Always faced with conflicting demands between “Just Make It Work” (designer) and “Just Make It Cheap” (program).
- Many system-level strategies pre-date the space age (e.g., communications, fault-tolerant computing, etc.).
- Tiered approach to validation of mission requirements.

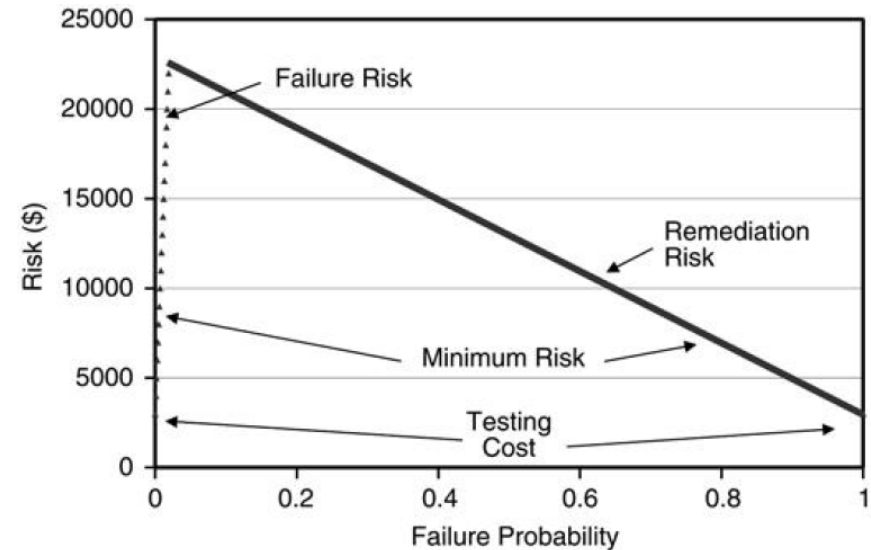


R. Ladbury, *IEEE NSREC Short Course*, “Radiation Hardening at the System Level,” Honolulu, July 2007.

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 (environment contributes here).



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

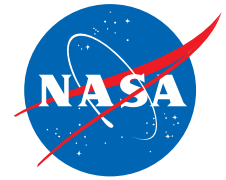
Costs for:

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

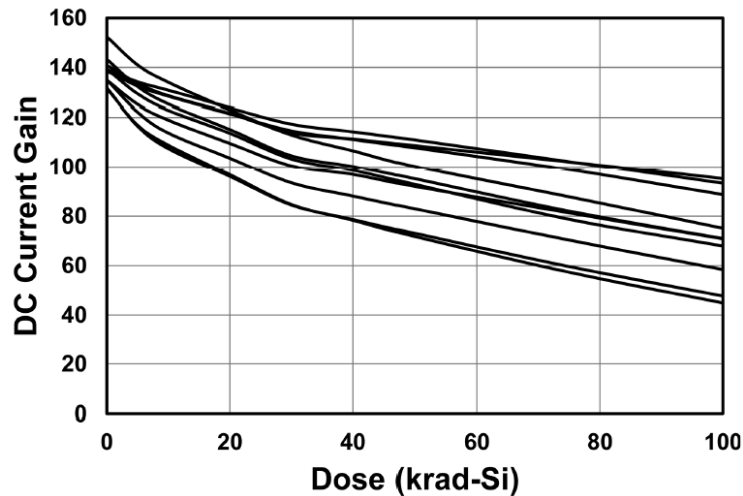
Two cases:

- 1) Fly “as-is” when risk is too high
- 2) Remediate when risk is acceptable

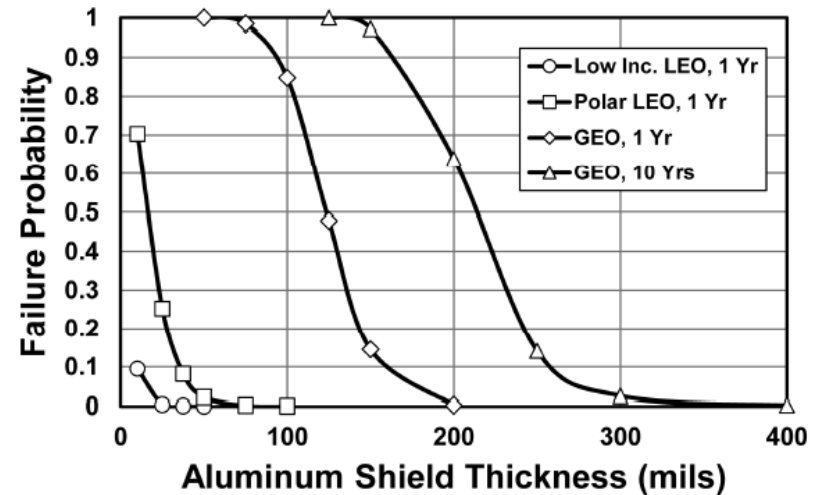
Possible Solution Strategy for TID/TNID Risk Mitigation



Gamma Ray TID Data on 2N2907 Bipolar Transistor

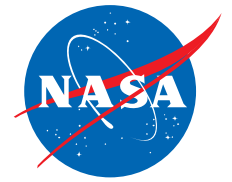


Environment Variability



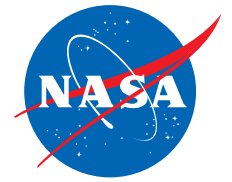
- AP-9/AE-9 trapped particle models are probabilistic and permit full Monte Carlo calculations for evaluating environment dynamics.
 - Outputs parameters are similar to solar proton fluence models, though derivation process is different.
- For applicable missions, combined environment modeling capability allows us to replace radiation design margin with failure probability.
 - M. A. Xapsos, *et al.*, "Inclusion of Radiation Environment Variability in Total Dose Hardness Assurance Methodology," *IEEE TNS*, vol. 64, Jan 2017.

Where we are going...



<u>THEN</u>	<u>NOW</u>
Magnetic core memory	NAND flash, resistive random access memory (RAM), magnetic RAM, phase-change RAM, programmable metallization cell RAM, and double-data rate (DDR) synchronous dynamic RAM (SDRAM)
Single-bit upsets (SBUs) and single-event transients (SETs)	Multiple-bit upset (MBU), block errors, single-event functional interrupts (SEFIs), frequency-dependence, etc.
Heavy ions and high-energy protons	Heavy ions, high- and low-energy protons, high-energy electrons, ???
Radiation hardness assurance (RHA)	RHA what?

Where we are going...



THEN

NOW

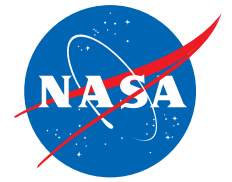


Increases in capability introduce additional evaluation challenges

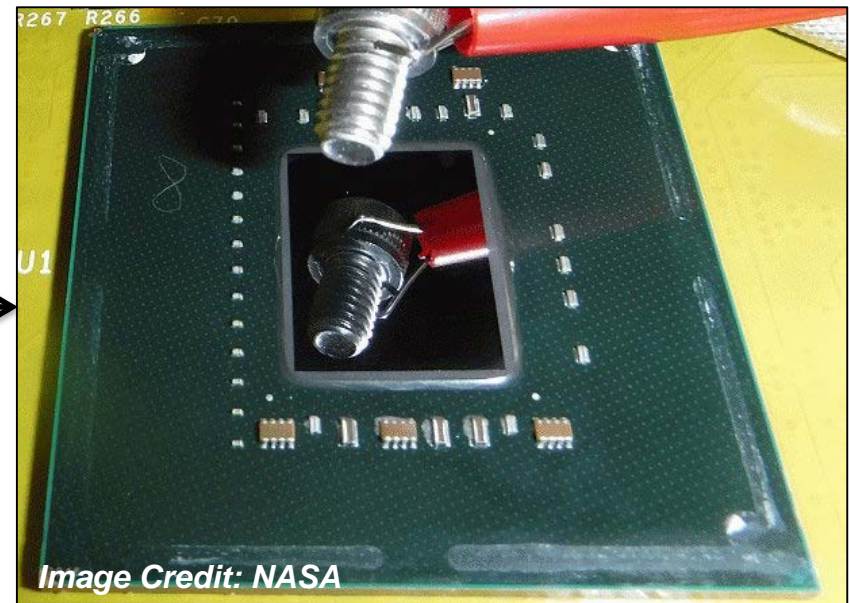
- FinFETs/Tri-gate devices
- Nanowire MOSFETs
- Organic transistors
- Ultra-thin body SOI
- Ge MOSFETs
- III-V MOSFETs
- Carbon nanotube FETs
- GaN, SiC,...

Risk Assessment & Disposition

Electronics for Space Use

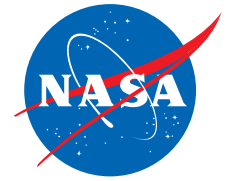


- Commercial Off the Shelf (COTS) – including automotive-grade
 - Designed with no attempt to mitigate radiation effects. COTS can refer to commodity devices or to application-specific integrated circuits (ASICs) designed using a commercially available design system.
- Radiation-Tolerant
 - Designed explicitly to account for and mitigate radiation effects by process and/or design



Xilinx Virtex-7 (28 nm CMOS) thinned in preparation for SEE testing

Policies to Mitigate Space Weather Hazards



National Space Weather Strategy
National Space Weather Action Plan
National Science and Technology Council, October 2015

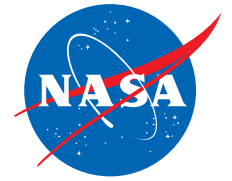
Coordinating Efforts to Prepare the Nation for Space Weather Events
Executive Order 13744, October 2016



Many other departments, agencies, and service branches involved

Restart vs. Rebound

Summary



- Radiation effects are challenging due to:
 - Space environment knowledge,
 - Number/type of physical processes involved, and
 - Rapid evolution of technology.
- Effects split into cumulative and single-particle varieties
- Radiation effects community is aggressively pursuing advanced technologies (e.g., CMOS \leq 32 nm, SiC, automotive electronics, etc.), which is increasing the need for evolutions in test techniques, data analysis, and environment knowledge