

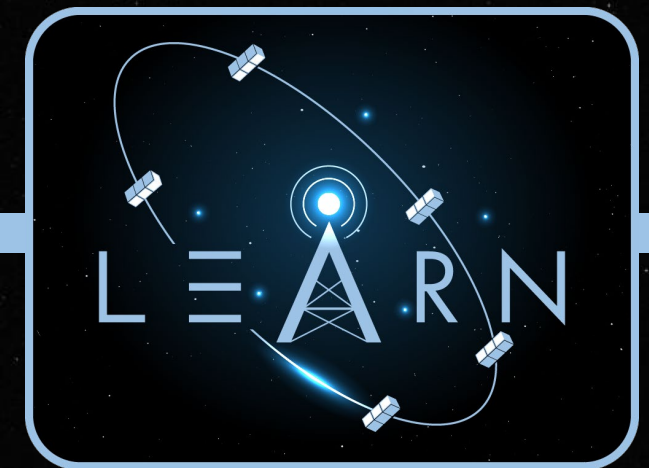


Radiation Effects & EEE Parts Selection

Michael Campola NASA GSFC

Radiation Effects and Analysis Group (Code 561)

National Aeronautics and Space Administration Small Satellite Learning from Experience, Achievements and Resolution Navigation Forum





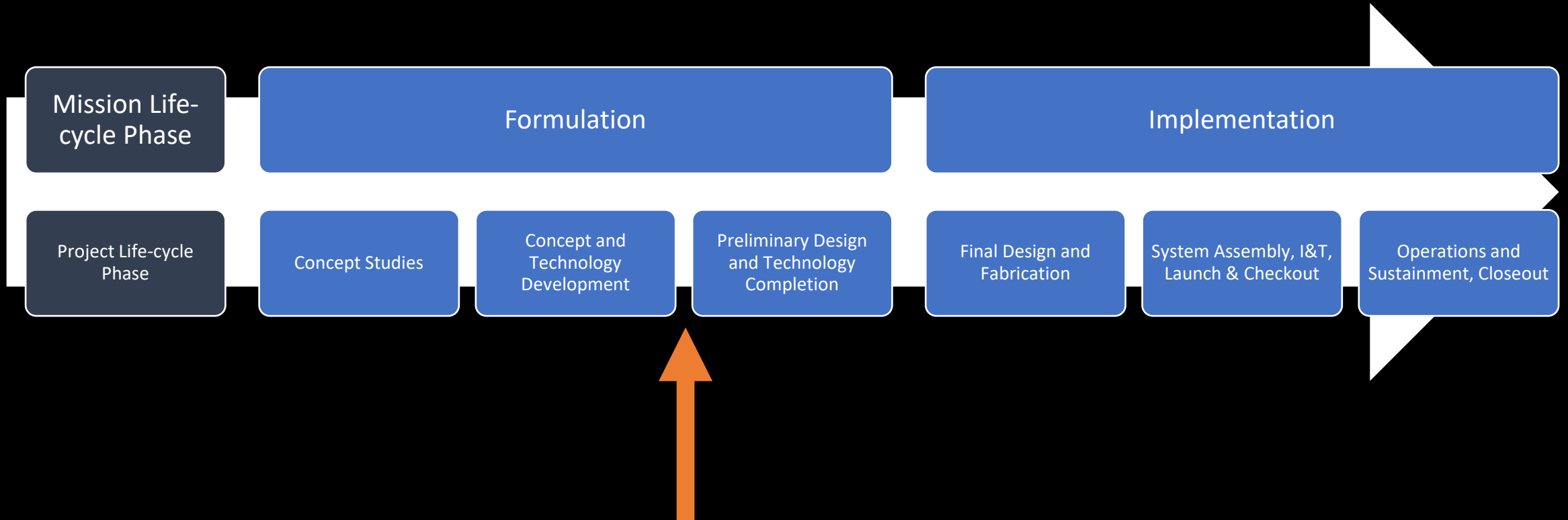
Acronyms and Abbreviations



- CL: Confidence Level
- CMOS: Complementary metal-oxide semiconductor
- ConOps: Concept of Operations
- COTS: Commercial Off The Shelf
- DDD: Displacement Damage Dose
- EDAC: Error Detection and Correction
- EEE: Electrical, Electronic, and Electromechanical
- EEEE: Electrical, Electronic, Electromechanical, and Electro-optical
- EMI: ElectroMagnetic Interference
- FET: Field-Effect Transistor
- FPGA: Field Programable Gate Array
- GSN: Goal Structuring Notation
- Hi-Rel: High Reliability
- IC: Integrated Circuit
- LET: Linear Energy Transfer
- MBU: Multi-Bit Upset
- MOSFET: Metal-on-Silicon Field Effect Transistor
- NESC: NASA Engineering and Safety Center
- RDM: Radiation Design Margin
- R-GENTIC: Radiation Guidelines for Notional Threat Identification and Classification
- RHA: Radiation Hardness Assurance
- SEAM: System Engineering and Assurance Modeling
- SEB: Single-Event Burnout
- SEE: Single Event Effects
- SEECA: Single Event Effects Criticality Assessment
- SEFI: Single-Event Functional Interrupt
- SEGR: Single-Event Gate Rupture
- SEL: Single-Event Latch-up
- SET: Single-Event Transient
- SEU: Single-Event Upset
- STTR: Small Business Technology Transfer
- TID: Total Ionizing Dose
- TMR: Triple Modular Redundancy
- TNID: Total Non-Ionizing Dose



Timing is everything



Last Call for Radiation Tests



Agency level support



Contacts:

Pete Majewicz – PM

Susana Douglas - Deputy



Office of the
Chief Engineer



NASA Engineering
and Safety Center

Communities of Practice:

Bob Hodson – Avionics

Ray Ladbury – Radiation

Yuan Chen – EEE Parts

Joe Minow – Space Environments

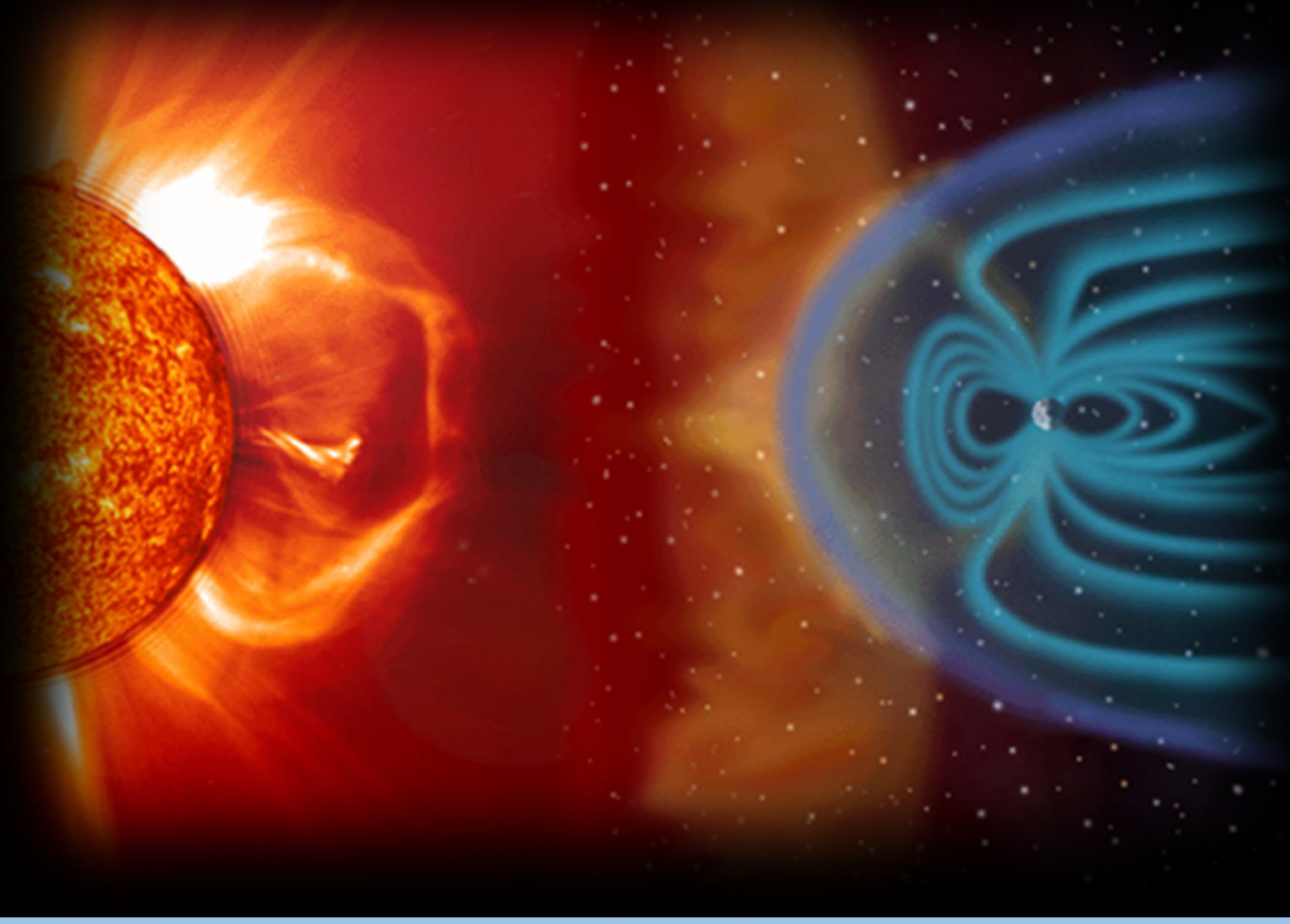


Natural space radiation environment overview



This is a *dynamic* system governed by the heliomagnetosphere

- Solar Maximum / Minimum
- Solar Flares
- Coronal Mass Ejections

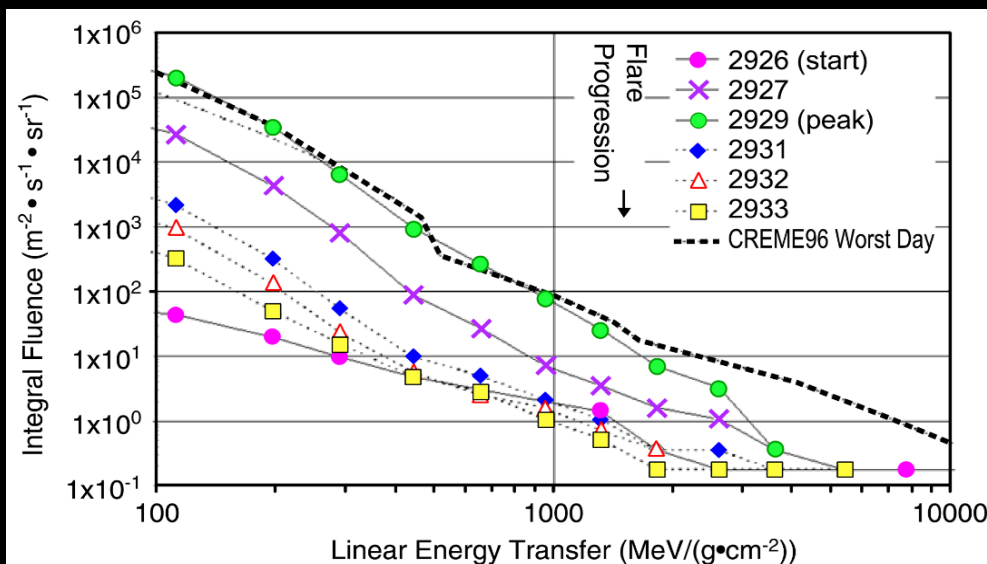


- Radiation Belts
- Geomagnetic Storms
- Galactic Cosmic Rays



What a CME/Flare looks like when it shows up

- Halloween Storms (Oct. 18 - Nov. 7 2003)
 - Noise on detector
 - Lots of deposited charge
 - Lots of coverage, lots of secondaries



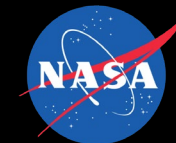
C.S. Dyer et al., IEEE TNS, Dec. 2002



Courtesy of SOHO/LASCO consortium. SOHO is a project of international cooperation between ESA and NASA. (Mercury transit in background)

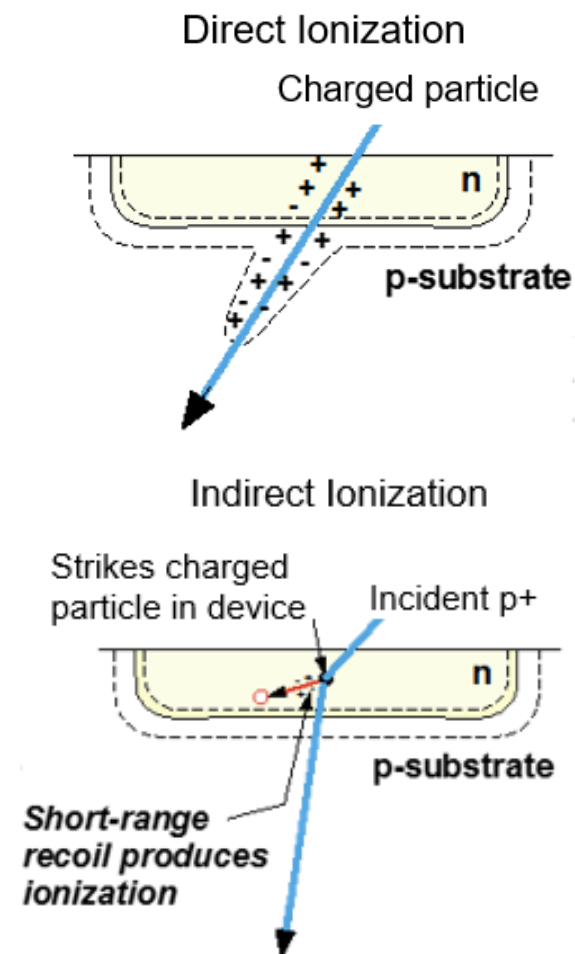
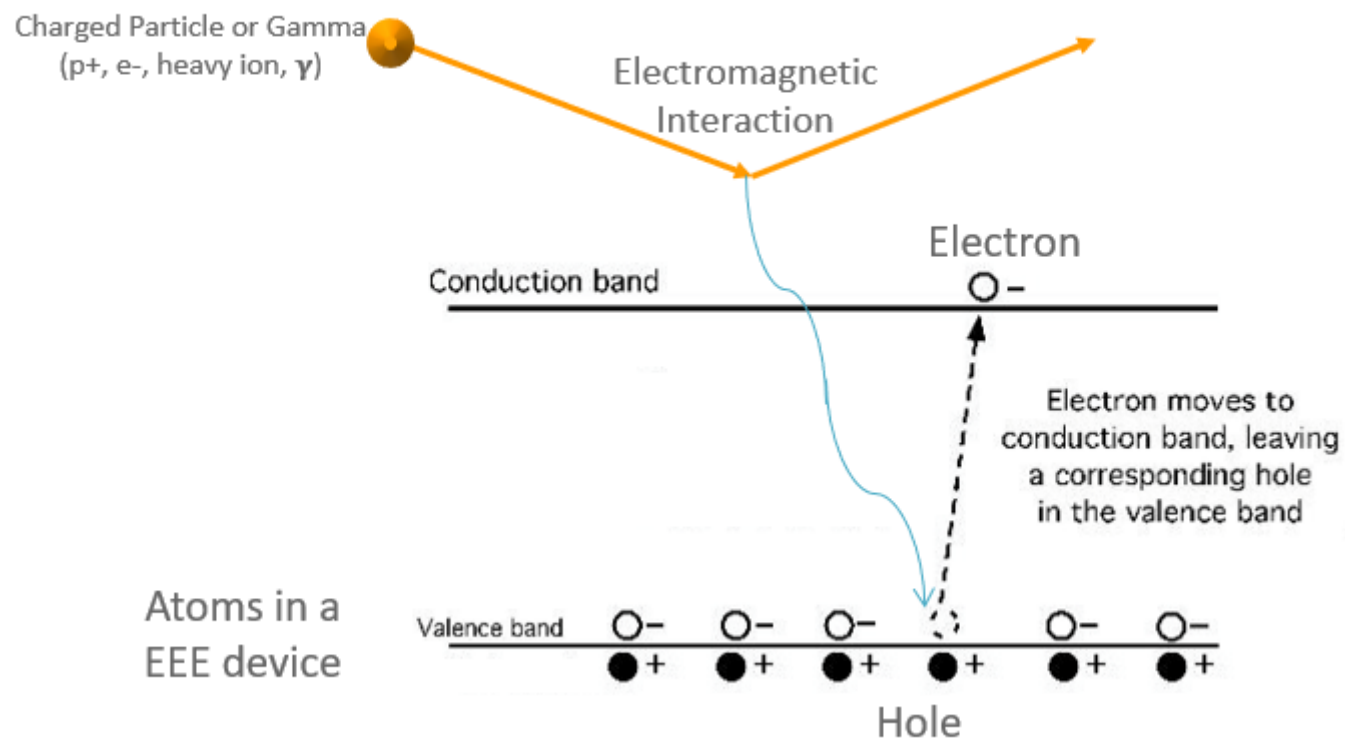


Outline

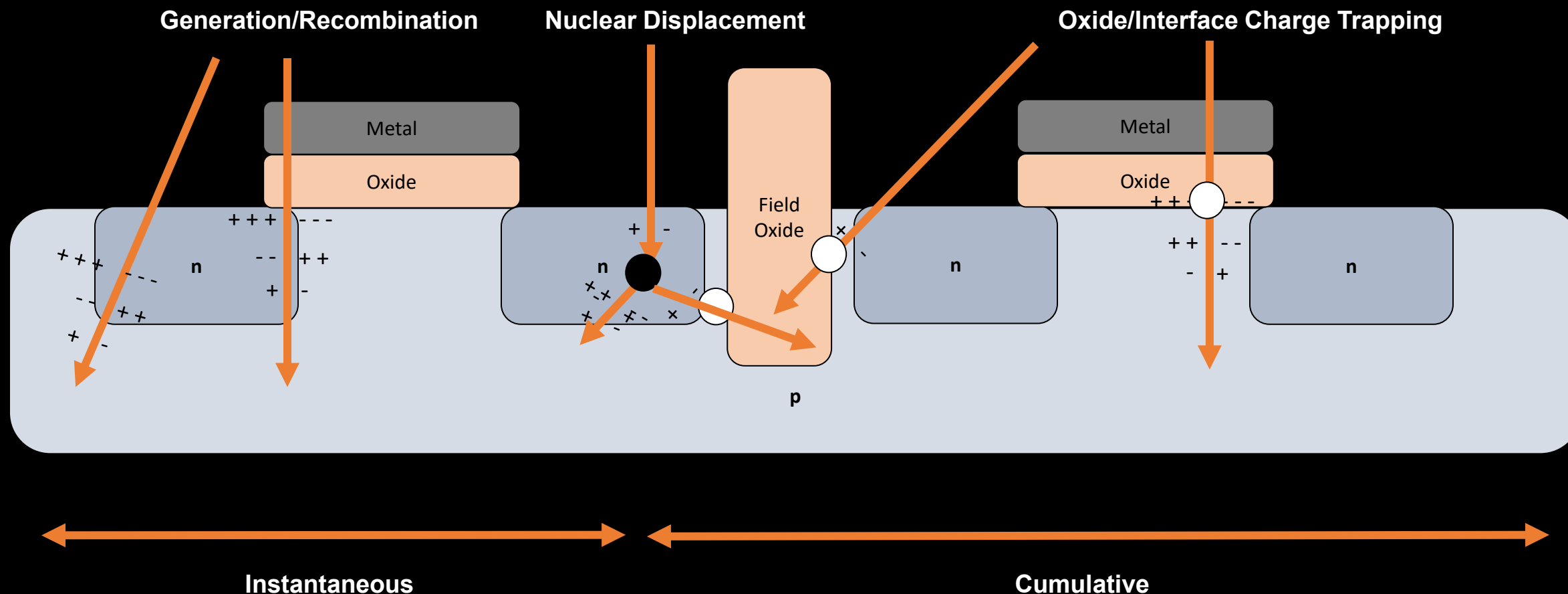


- **How radiation damage semiconductor devices**
 - Cumulative effects: ionizing and non-ionizing dose
 - Single particle effects
 - Examples of failures
- **Methods of analysis and test**
 - Environment modeling and transport
 - Correlation
 - Radiation testing
- **Key parameters to consider when selecting parts**
 - Process / semiconductor layout / application
 - Ways system architecture can be used to help mitigate radiation effects
 - Part database resources and how to use them wisely
- **Common pitfalls, lessons learned**
- **Radiation tools / resources / acronyms**

Ionization Overview



Damage in parts overview – location matters



Brock J. LaMeres, Colin Delaney, Matt Johnson, Connor Julien, Kevin Zack, Ben Cunningham Todd Kaiser, Larry Springer, David Klumpar, "Next on the Pad: RadSat – A Radiation Tolerant Computer System," Proceedings of the 31st Annual AIAA/USU Conference on Small Satellites, Logan UT, USA, Aug. 5-10, 2017, paper: SSC17-III-11, URL: <http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3618&context=smallsat>

Ionizing Radiation Effects

Total Ionizing
Dose (TID)

Total
Non-Ionizing
Dose (TNID)

Single-Event Effects (SEE)

Primarily high-energy protons and heavy ions

Non-Destructive

Destructive

Breaking down the different types of effects

Ionizing Radiation Effects

Total Absorbed dose –
rad in material
(RAD)

Absorbed dose –
rad in material

Total particles per unit area –
fluence
(FNID)

Total particles per unit area –
fluence

Single-Event Effects (SEE)

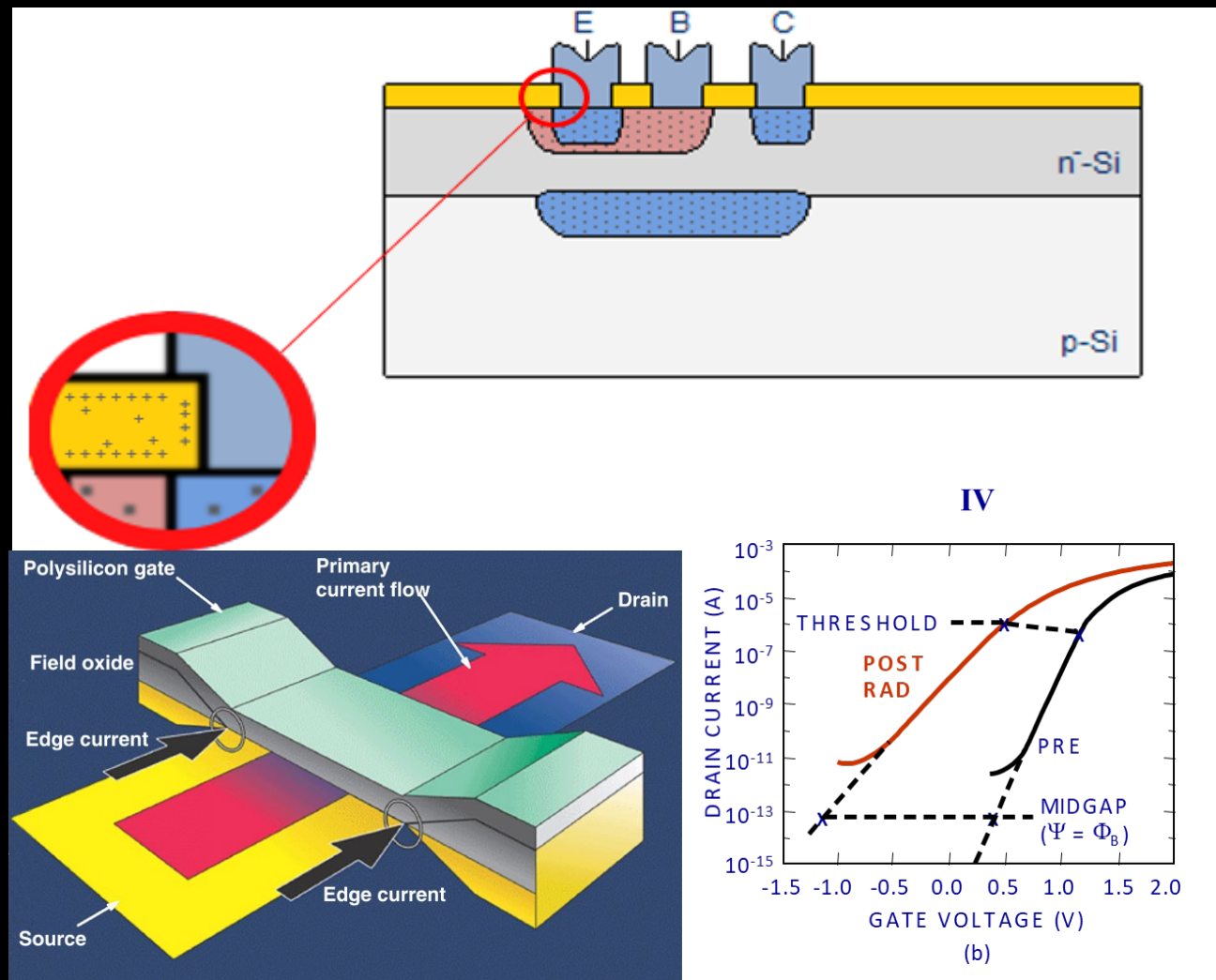
Energy deposition –
linear energy transfer (LET)

Non-Destructive

Destructive

Primarily high-energy protons and heavy ions

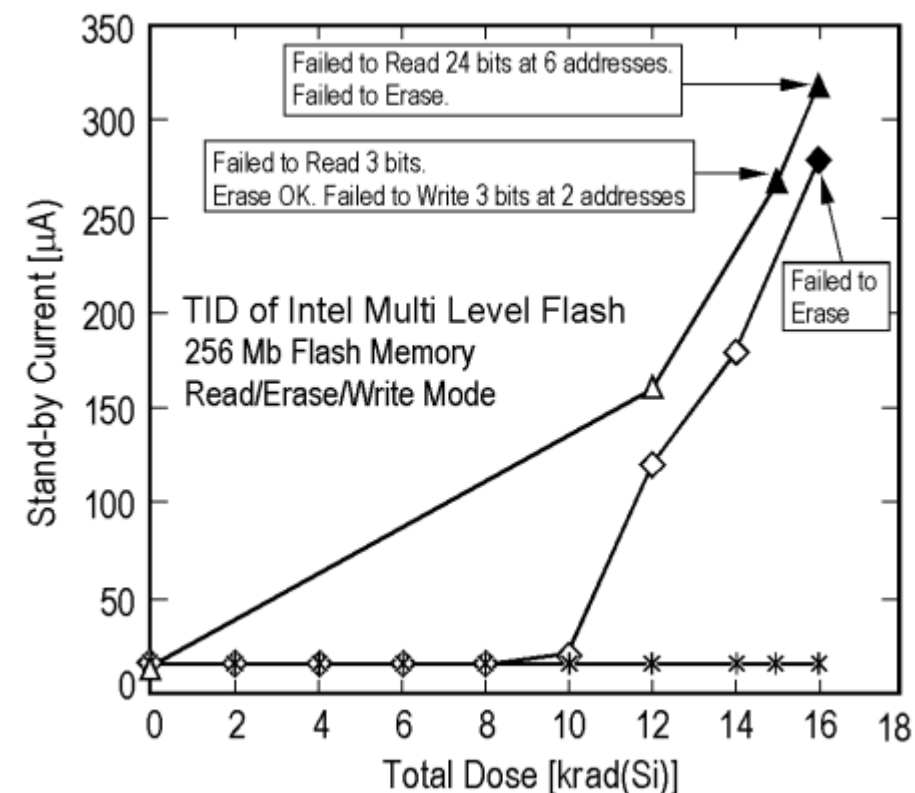
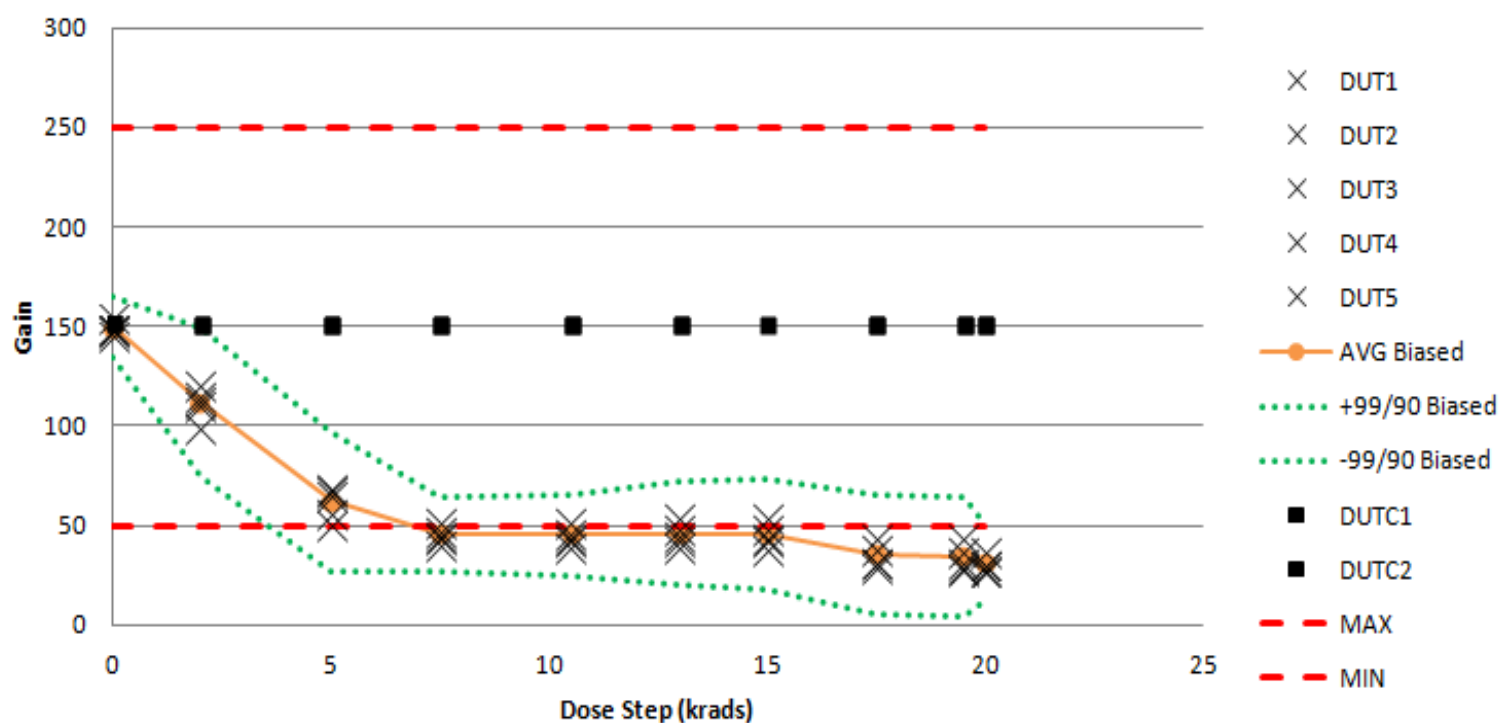
- Cumulative effect
 - Electron-hole pair creation and collection
 - Interface traps and oxide traps collect charge permanently
 - More imperfections result in easier charge trapping
 - Residual shift in static operation
 - Electric field impacts drift and diffusion
 - Oxide thickness and manufacturing plays a role in technology response
 - This is “TID damage”. Eventually the device will fail to operate.



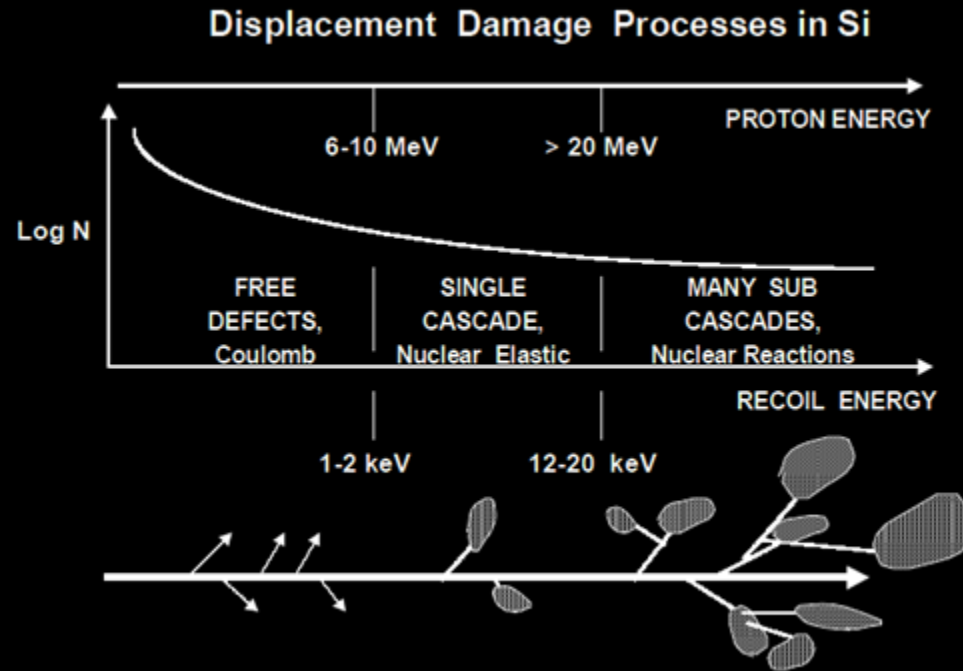
Examples of TID device failures

- Gain degradation, and drop of function... anything goes

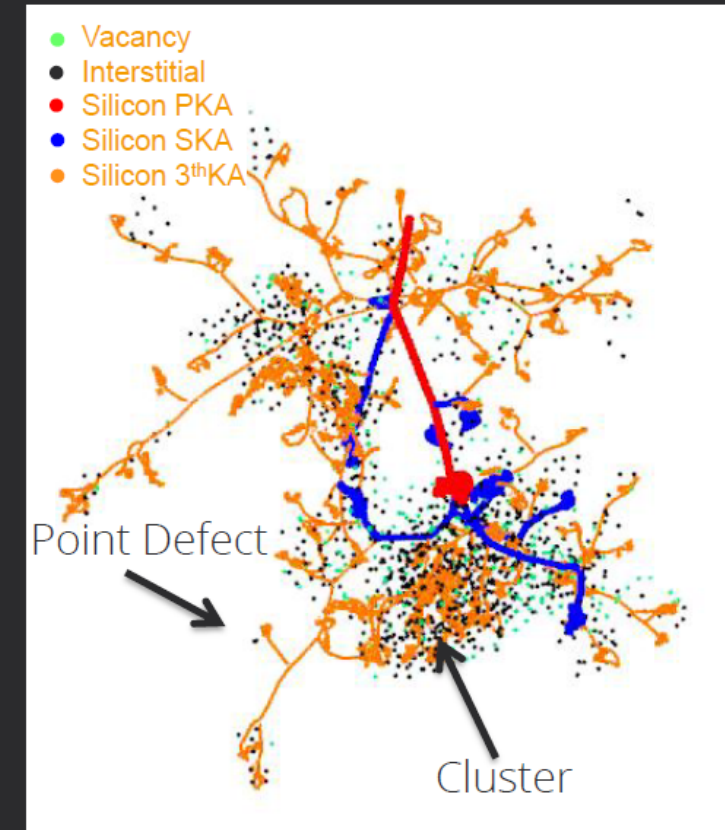
Microsemi 2N2222 hFE @ .1 mA Biased



- Cumulative effect
 - Primary knock-on atoms displace lattice and leave damage clusters
 - Changing fundamental properties like carrier mobility means that opto-electronics are the most susceptible
 - Some damage sites are so great that can lead to one hit failures within component functions (RTS, hot pixels, etc.)



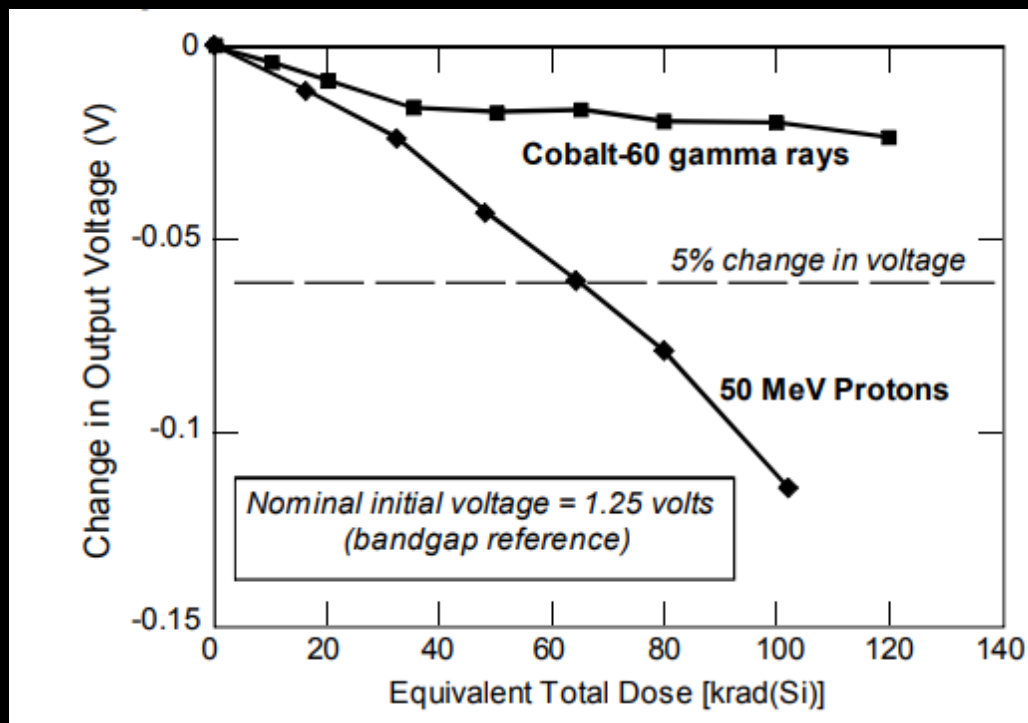
After C. J. Marshall, 1999 IEEE NSREC Short Course.



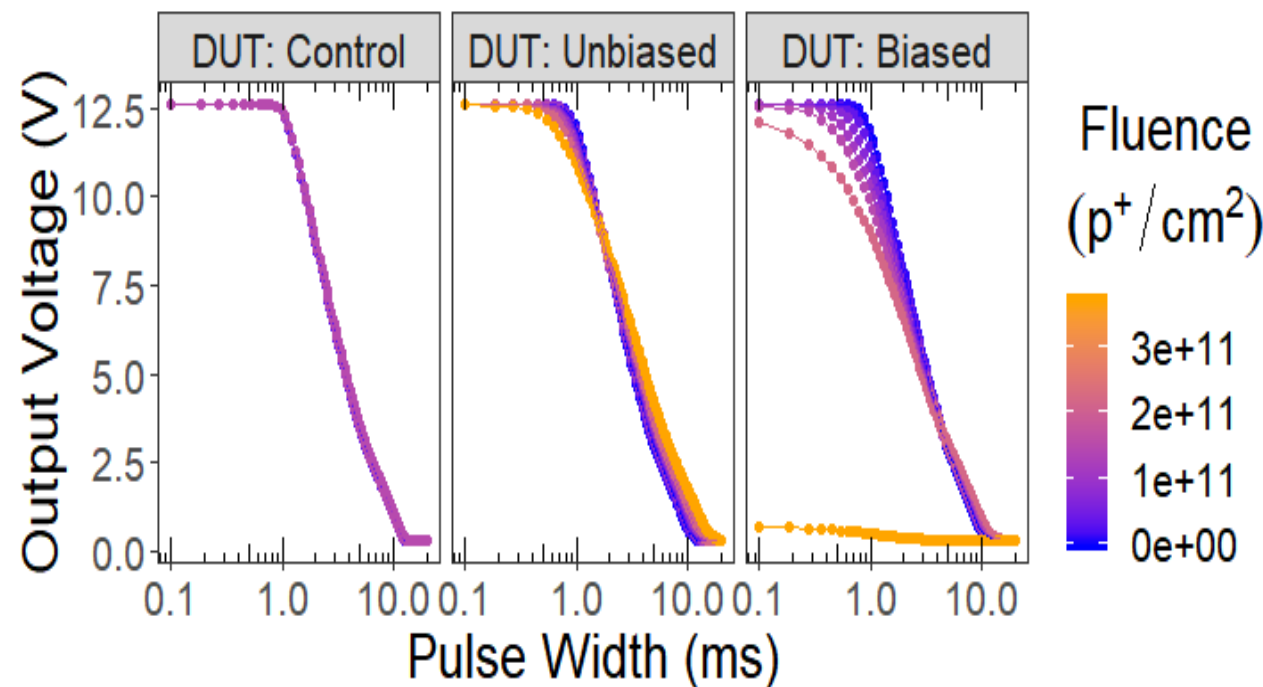
A. Jay et al., "Simulation of Single-Particle Displacement Damage in Silicon—Part III: First Principle Characterization of Defect Properties," in IEEE Transactions on Nuclear Science, vol. 65, no. 2, pp. 724-731, Feb. 2018, doi: 10.1109/TNS.2018.2790843.

Examples of TNID device failures

- Loss of function, permanent damage – need experts for detectors/cryo



Linear Bipolars that depend on bulk properties



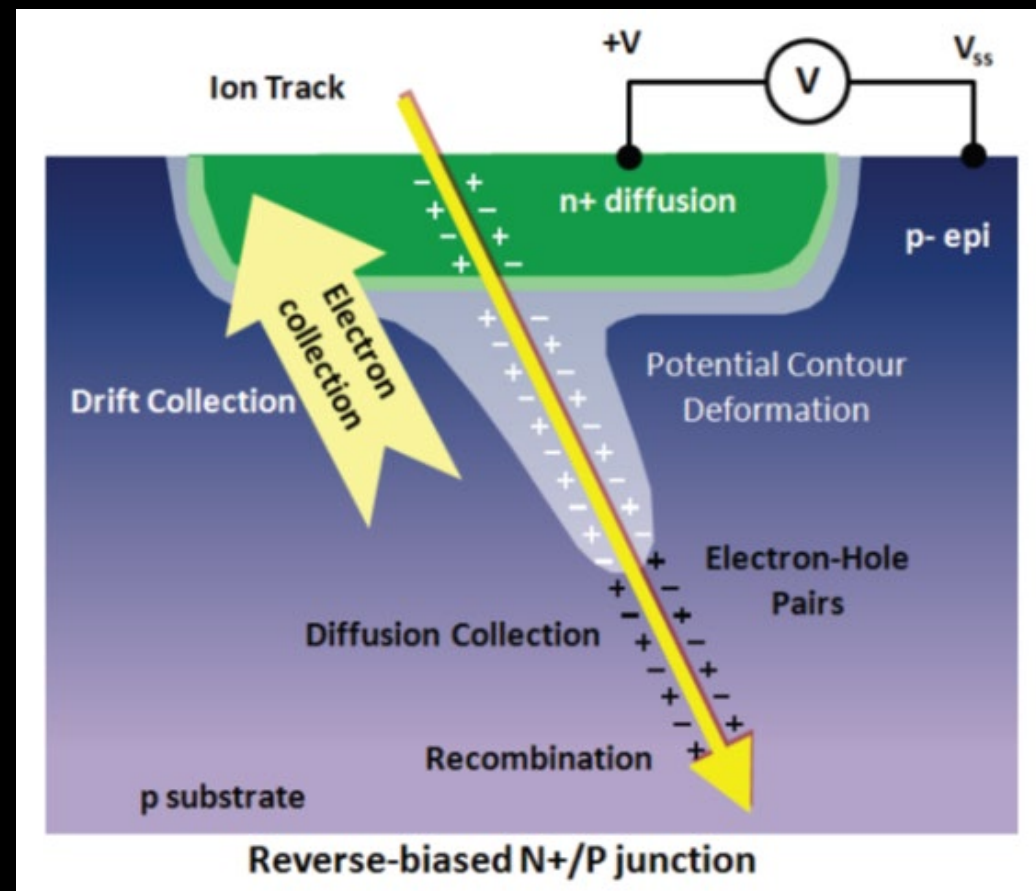
Optocouplers using highly efficient LEDs will be very soft

Comparing TID to TNID

(After Le Roch)	TID	Vs	TNID
Dose threshold	TID threshold		One displacement = high degradation
Hardening	Hardening by design or process ⁽¹⁾		Limited hardening technic possible ⁽²⁾
Shrinking electronic size	Thin oxide is less sensitive to TID ⁽³⁾		More elementary functions impacted
Degradation uniformity	Almost uniform degradation		High nonuniformity: Poisson law

Single Event Effects in a p-n junction

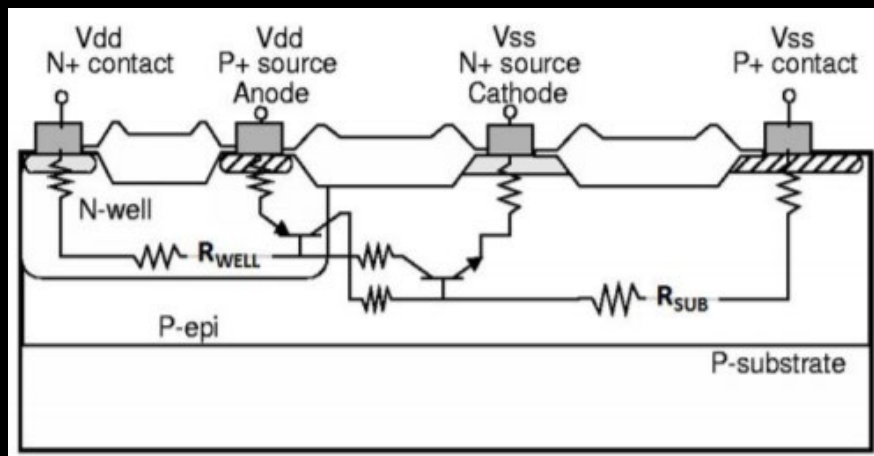
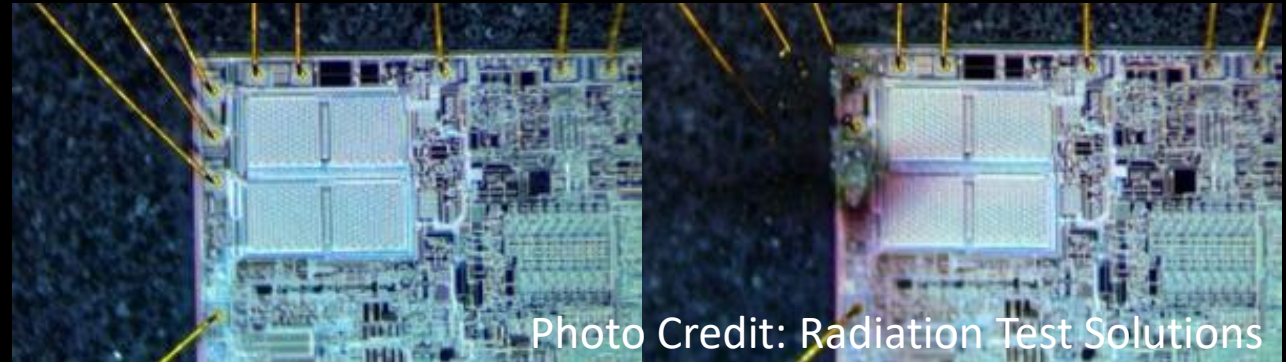
- Single Incoming Particle
 - Ions traverse device, depositing energy along their path
 - Electron-hole pairs produced
 - Deformation of the depletion region if a junction is hit
 - Recombination dominates
 - Diffusion and drift driven by electrostatics within device
 - Dimensions and materials of device are crucial in signature response



R.C. Baumann, 2013 NSREC Short Course

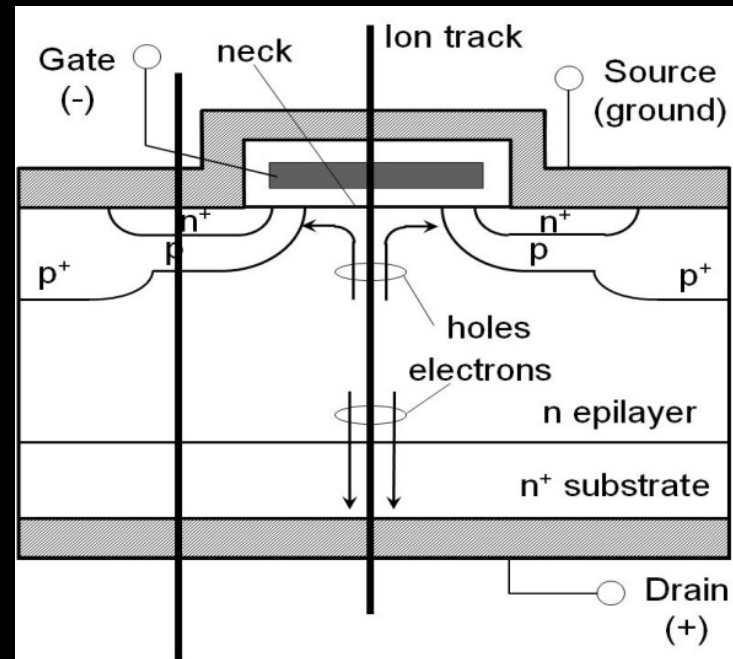
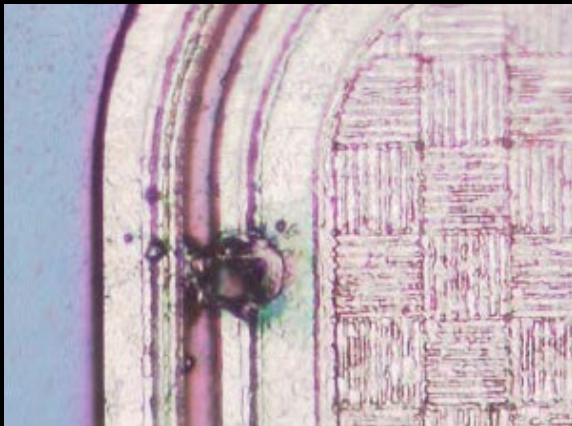
Types of radiation effects – Single Event Latchup (SEL)

- Instantaneously destructive
- SEL is a parasitic structure within the device being turned on, different than electrical latchup
- Even “non-destructive” has ramifications



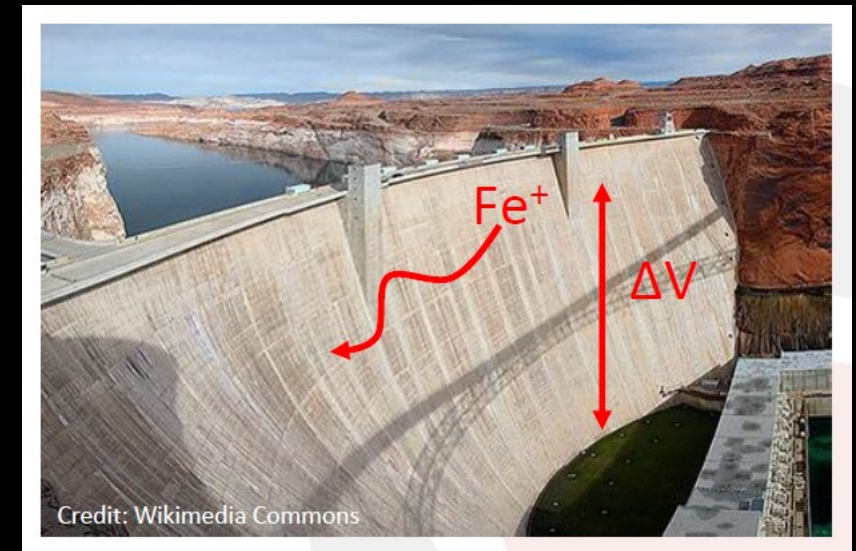
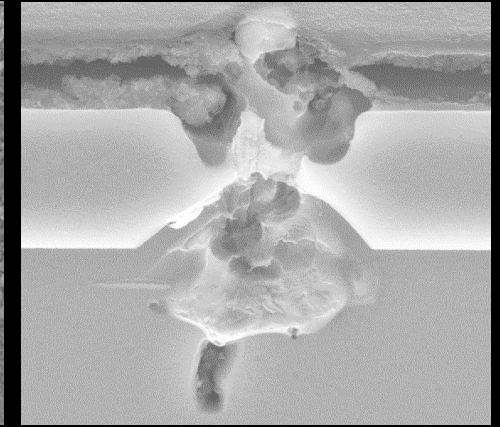
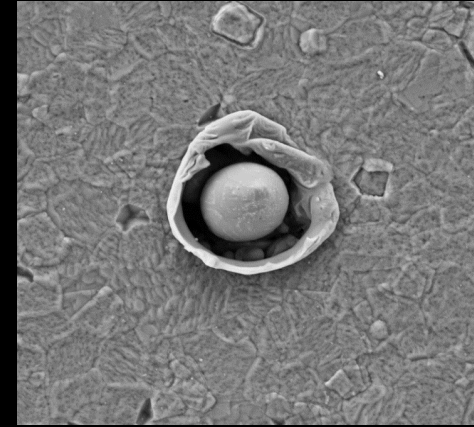
Types of Radiation Effects - SEB/SEGR/SEDR

- Gate/Dielectric Rupture is charge overwhelming the oxide
- Burnout is current in the bulk mat'l.



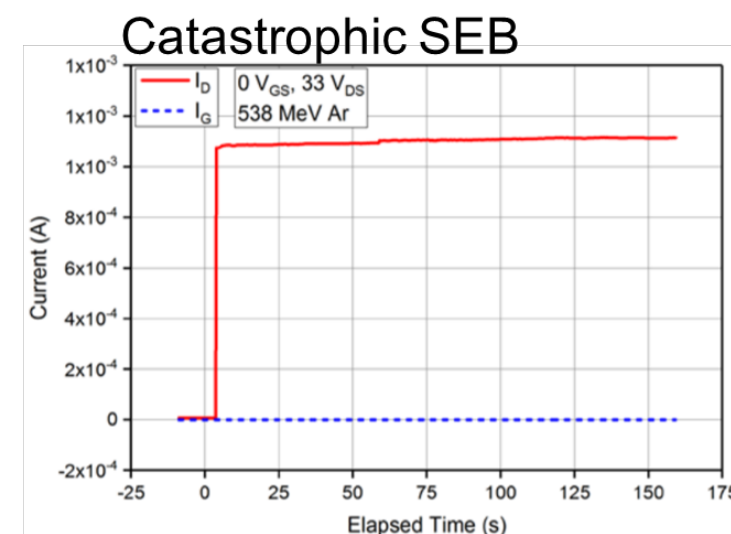
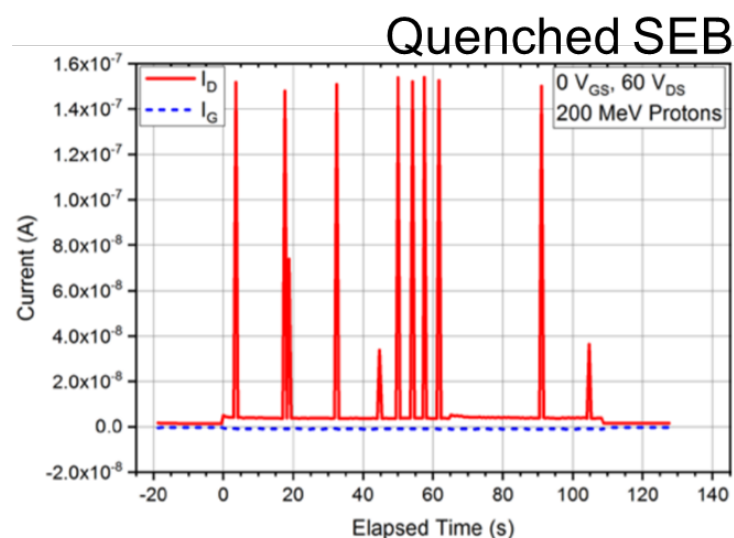
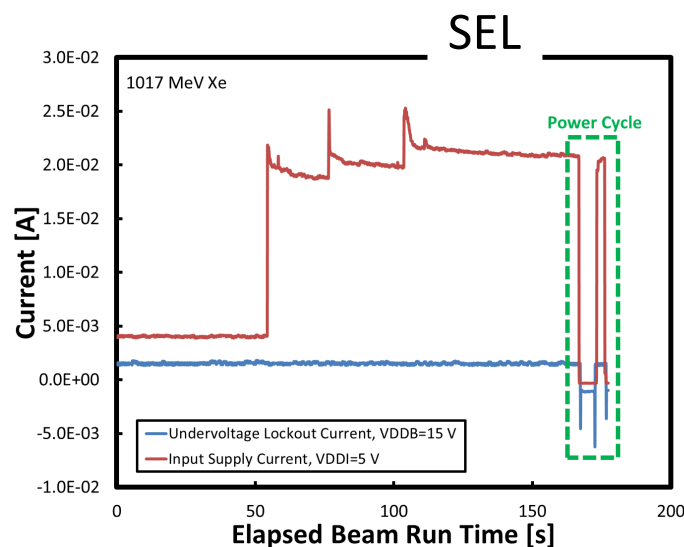
Single Event Burnout

Single Event Gate Rupture



Destructive effects, electrically speaking

- Current limiting is not foolproof, but can help in select applications

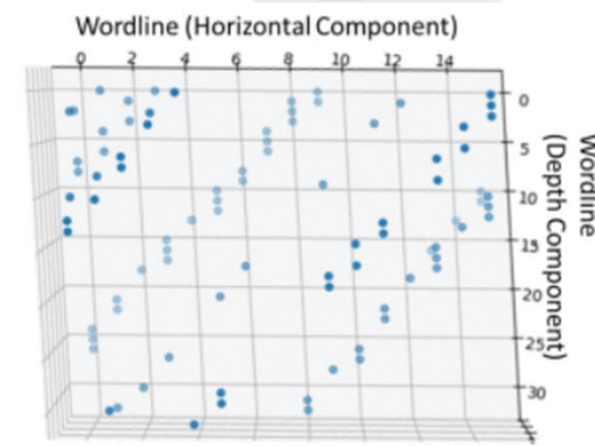
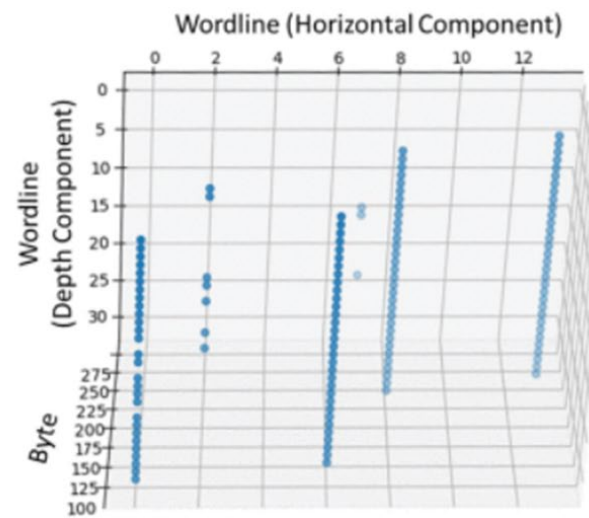
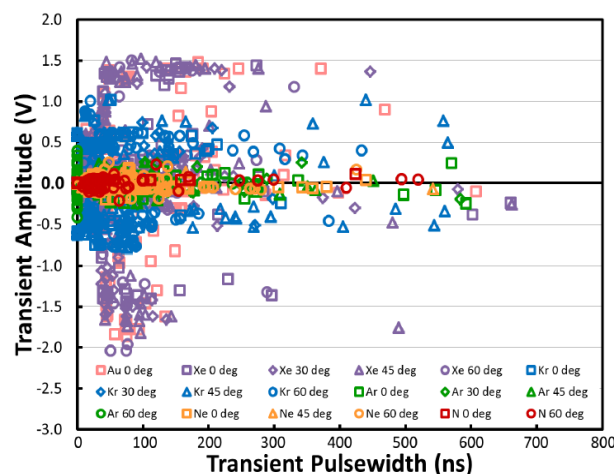
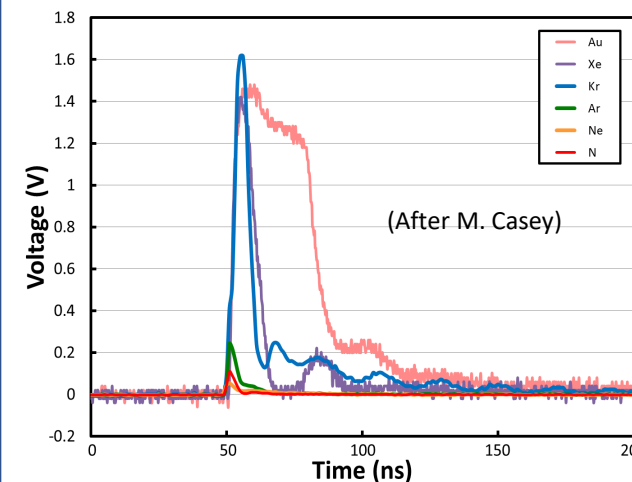
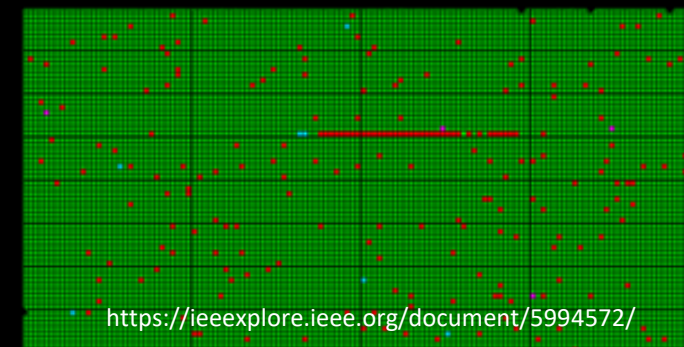


Figures from "Recent Radiation Test Results for Trench Power MOSFETs,"
<https://nepp.nasa.gov/files/28959/2017-Lauenstein-NSREC-Paper-DW-MOSFETs-TN44382.pdf>

- Failure can depend on the mechanism, range of particle, and even the species

Types of radiation effects – non-destructive SEE

- Individual errors persist and will accrue
- SET – happens in both analog/digital circuits
- SEU/MBU – feature size, physical layout
- Nuisances that must be planned for



E. P. Wilcox and M. J. Campola, "A TID and SEE Characterization of Multi-Terabit COTS 3D NAND Flash," 2019 IEEE Radiation Effects Data Workshop, San Antonio, TX, USA, 2019, pp. 1-7.

Single Event Functional Interrupt (SEFI)

- A soft error that causes the component to reset, lock-up, or otherwise malfunction in a detectable way, but does not result in permanent damage as in single event burnout (SEB) or single-event latch-up (SEL). These often require power cycling of the device (all pins) to restore operability, but sometimes can be cleared in less disruptive ways like reset/refresh.



Figures from "Heavy Ion Test Report for the AD9364 RF Transceiver,"
<https://nepp.nasa.gov/files/28554/NEPP-TR-2016-Chen-15-071-AD9364-T031716-TN44752.pdf>

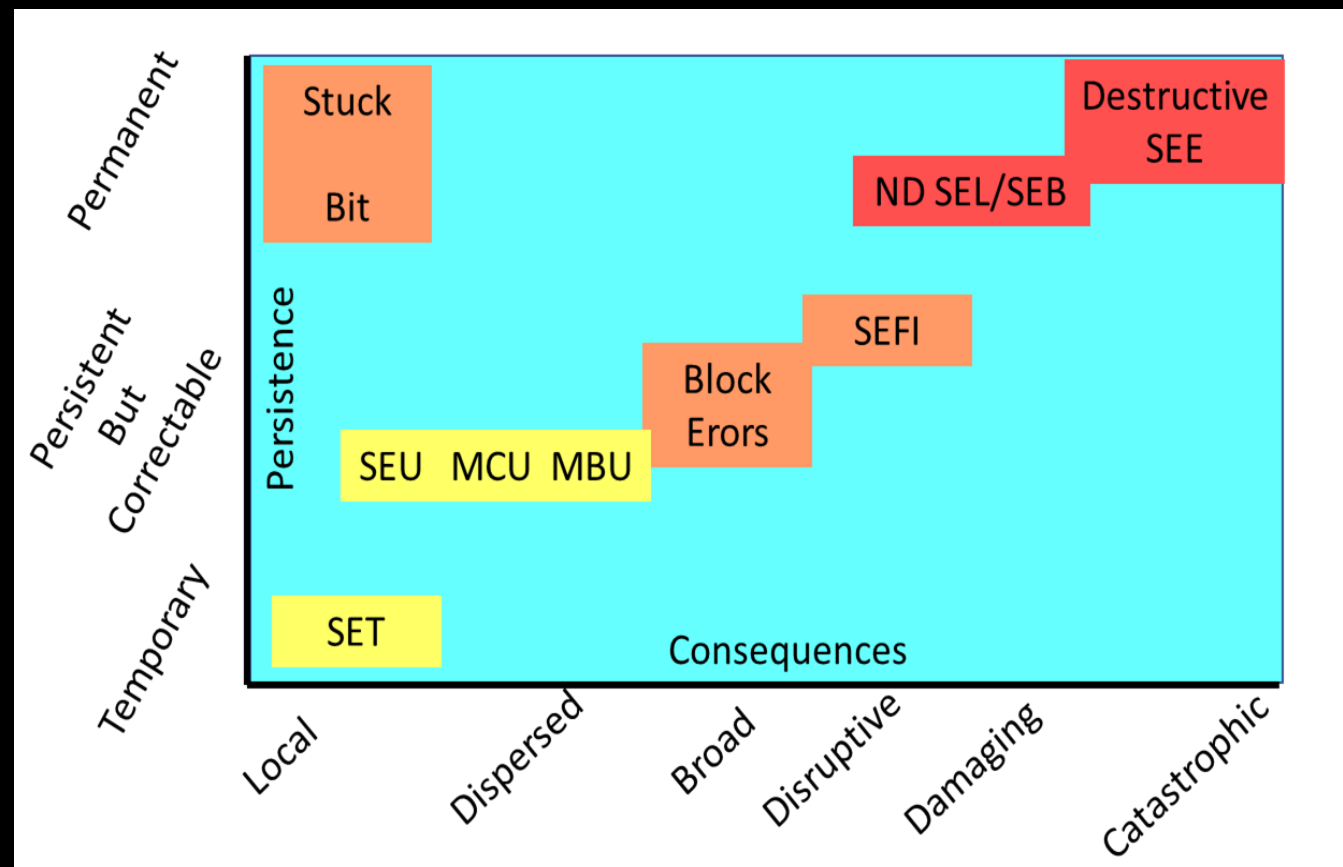
Types of radiation effects – Single Event Effects (SEE)

- Destructive

- SEL - Latchup
- SEB - Burnout
- SEGR – Gate Rupture
- SEDR – Dielectric Rupture
- *SEU – Upsets can become stuck bits*

- Non-destructive

- SET – Transients, can be analog and digital
- SEU – Upsets, can happen in multiple bits/cells – can be Multiple Bit Upsets (MBU) or Multiple Cell Upsets (MCU)
- SEFI – Functional Interrupts, for complex devices, typical category for response that needs refresh/reset/power-cycle to return to operation
- Non-destructive does not mean non-disruptive



(After Ladbury)



Which SEE?



- Concerns manifest differently by part type/technology
- This list is not exhaustive, and new technologies could fall into a family where new failure mechanisms are unknown
- Architecture and structures within are what create the threat

	Non-destructive SEEs			Destructive SEEs			
	SET	SEU	SEFI	SEL	SEB	SEGR	SEDR
Memories	✓	✓	✓	✓			
Logic (Latches)		✓					
Logic (Combinational)	✓		✓	✓			
Microprocessors		✓	✓	✓			
Analog or Mixed Signal Circuits	✓		✓	✓	✓		✓
Photonics	✓						
FPGAs		✓	✓	✓			✓
ASICs		✓	✓	✓			
Power MOSFETs					✓	✓	
Other Power Devices	✓			✓			✓
Converters	✓	✓	✓	✓	✓	✓	



Summary of risks to electronic parts

TID

- Increased leakage current, power consumption
- Threshold voltage shifts
- Stuck bits in memory cells
- Changes in timing
- Decreased functionality

TNID/DDD

- Decreased efficiency in optical devices
- Increased dark current in CCDs
- Degradation of CCD charge transfer efficiency
- Degradation of solar cells, optocouplers, linear bipolar devices

SEE

- Voltage/current spikes (SET)
- Bit-flips (SEU)
- Instantaneous high current states (SEL)
- Program crashes (SEFI)
- Catastrophic device failure in power devices (SEB, SEGR)

Charging:

- Electrostatic discharge
- Arcing
- Enhanced surface contamination
- Local dielectric breakdown

(After K. Ryder)

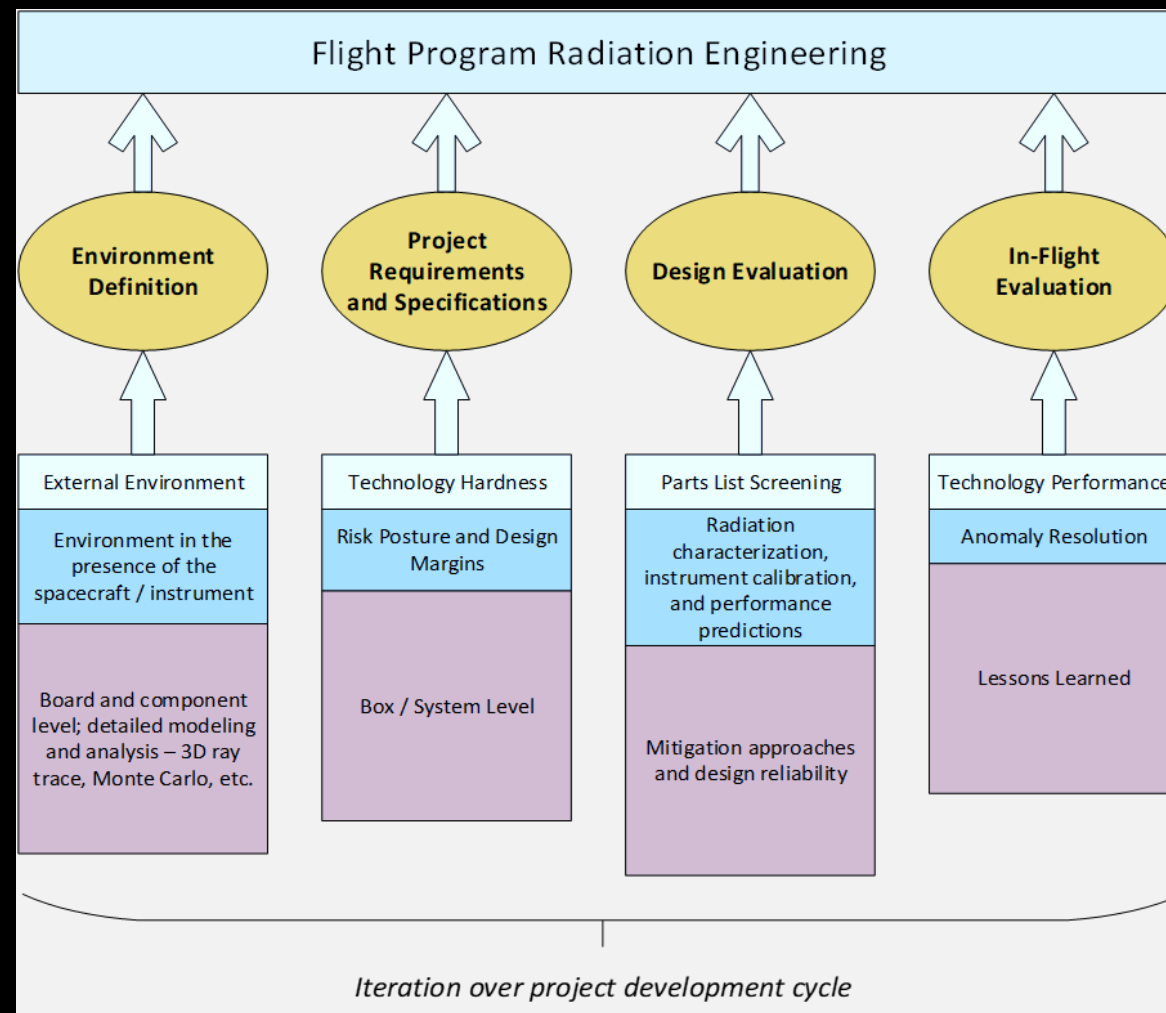
Radiation Hardness Assurance (RHA) overview

RHA consists of all activities undertaken to ensure that the electronics and materials of a space system perform to their *design* specifications throughout exposure to the mission space environment

(After Poivey 2007) ↑

(After LaBel 2004) →

As we go beyond low earth orbit with our SmallSats it's important to note that the challenges are not unique to the platform



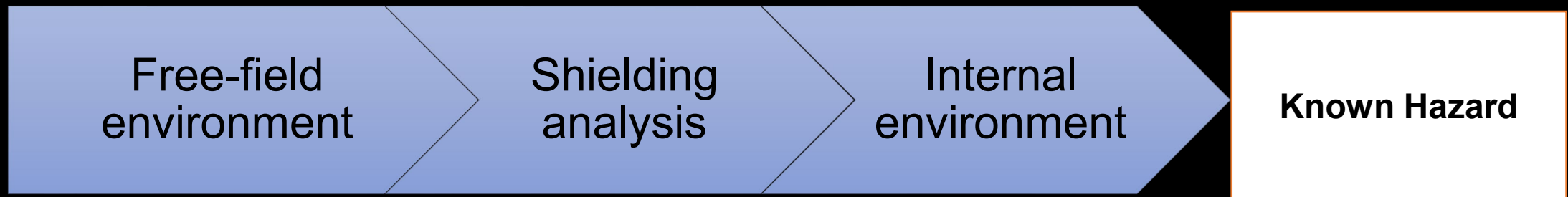


Methods of analysis



- Environment modeling and transport

Considers all contributors based on mission environment and lifetime



- Analysis and test correlation





Free-field environment



- Shielding and boxes also scatter the incoming particles
- CMEs/Flares present the worst case SEE environment and contribute to the dose of the mission



Space radiation is truly omnidirectional.

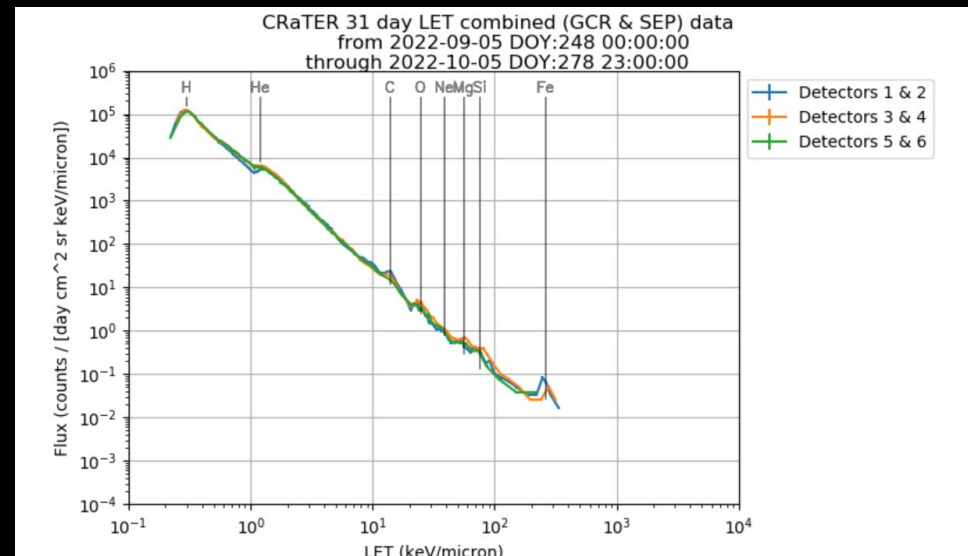
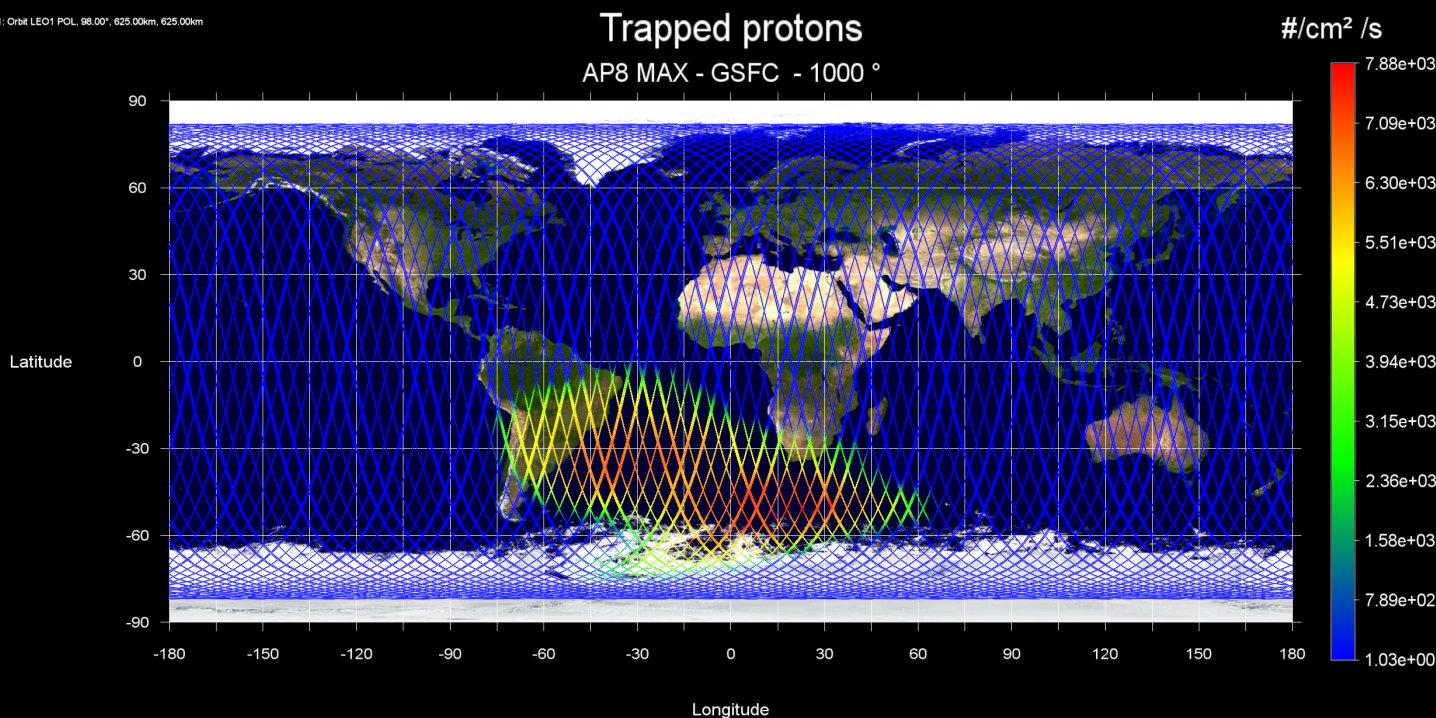


On-orbit data products are used to create environment models



- We benefit from the science data products that come from calibrated instruments to map to environment conditions that inform our tests

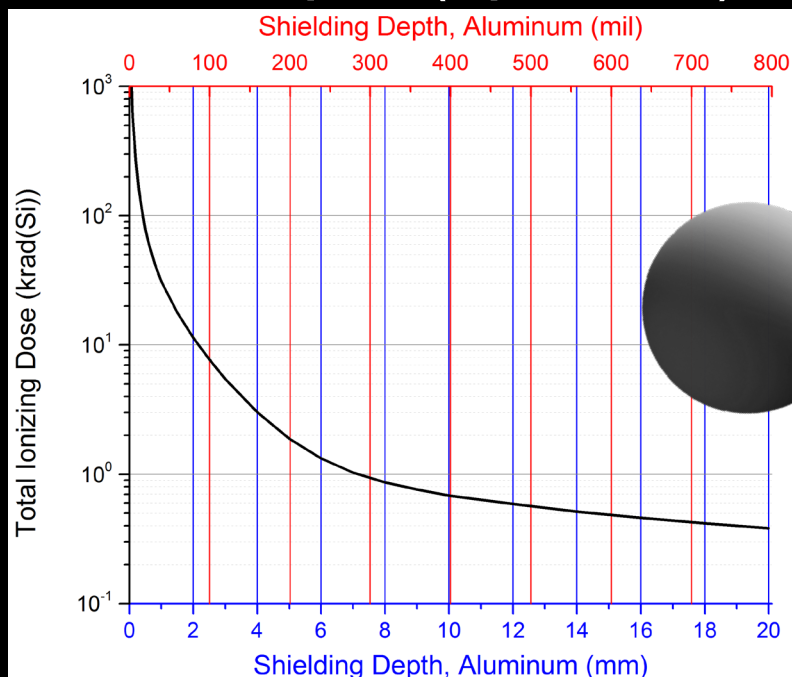
1: Orbit LEO1 POL, 98.00°, 625.00km



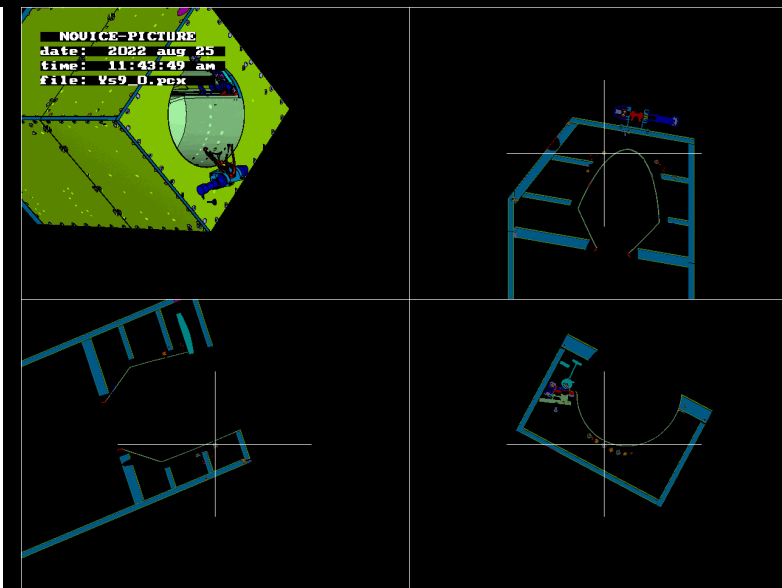
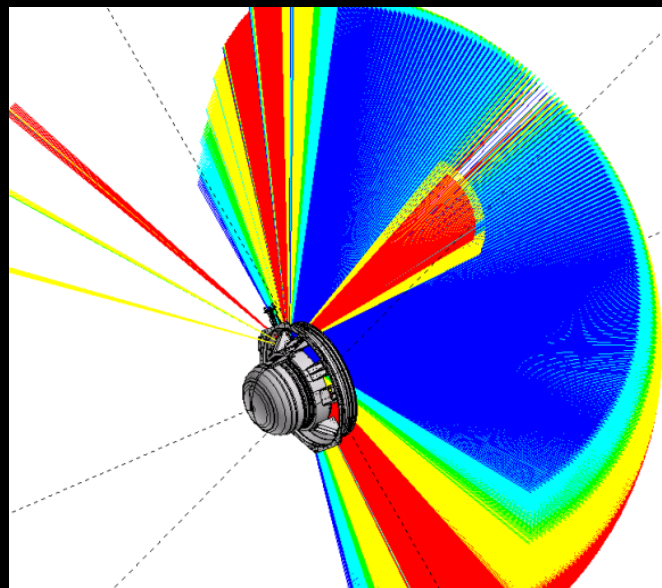
Transport and deposition of dose

- Outside environment can get transported in several ways
- Shielding might not be as easy to increase on a SmallSat

Simple (spheres)

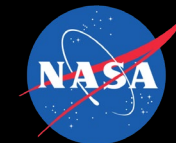


Complex (CAD models)

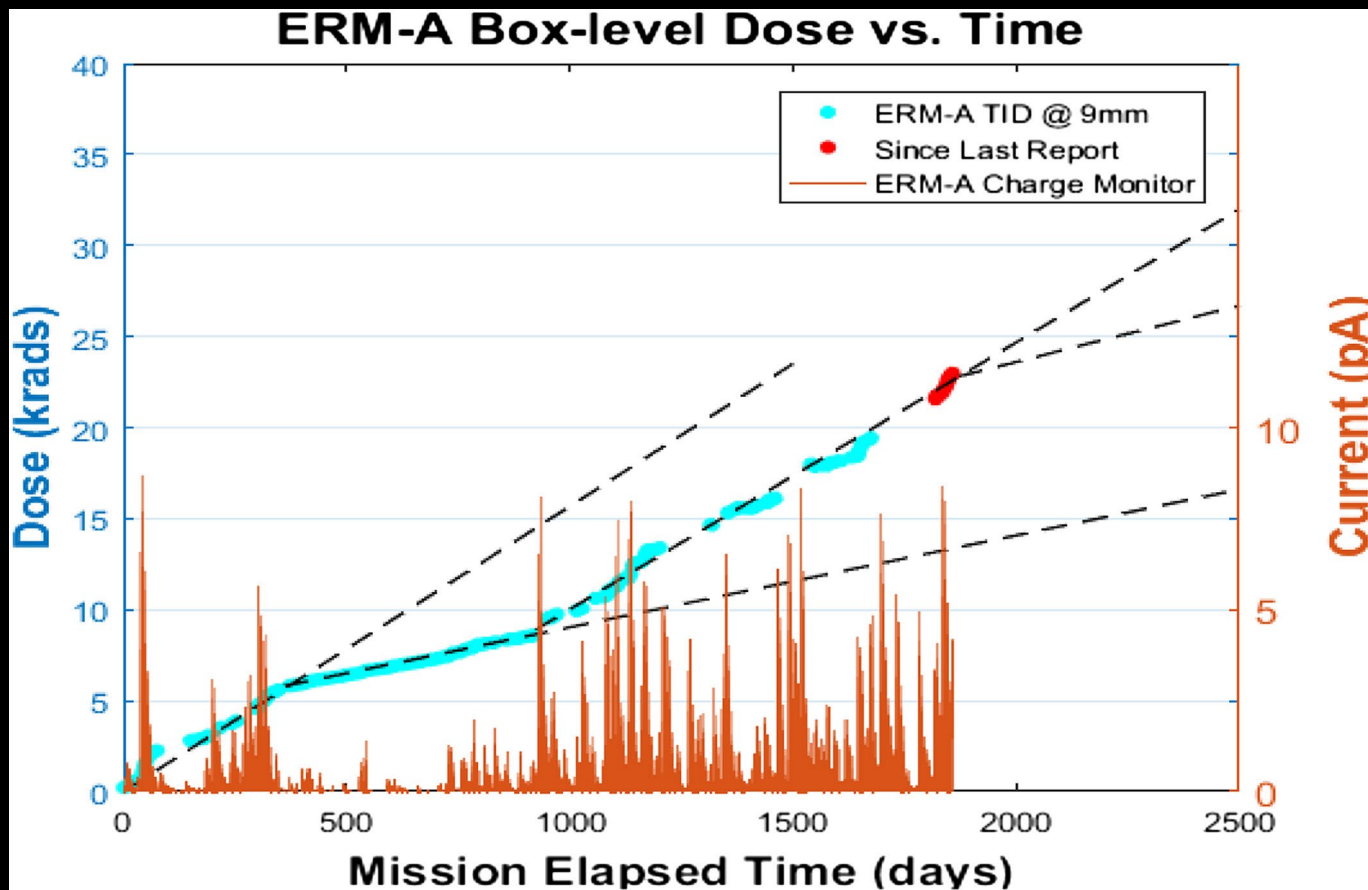




Environment correlation: Measured Dose



- On orbit dosimetry is straight forward: we have actual dose rates from dosimeters
- Ground based dose tests are accelerated life tests with special considerations: annealing, ELDRS, etc.

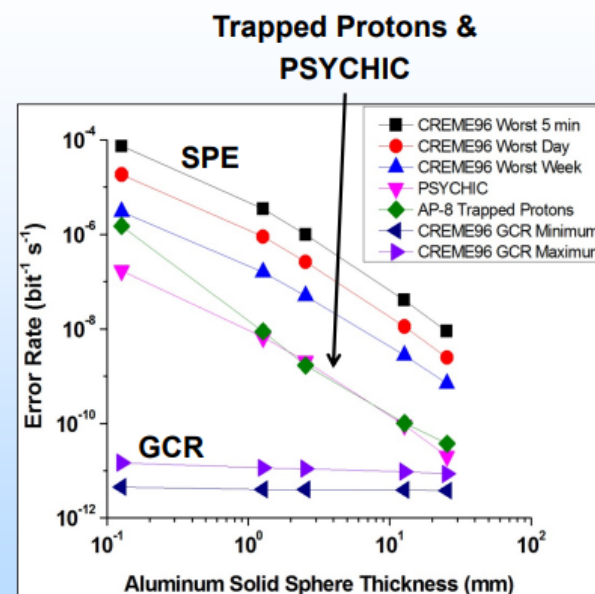


Space Weather, Volume: 16, Issue: 10, Pages: 1561-1569, First published: 24 September 2018, DOI: (10.1029/2018SW001910)

45 nm SOI SRAM Soft Error Rates



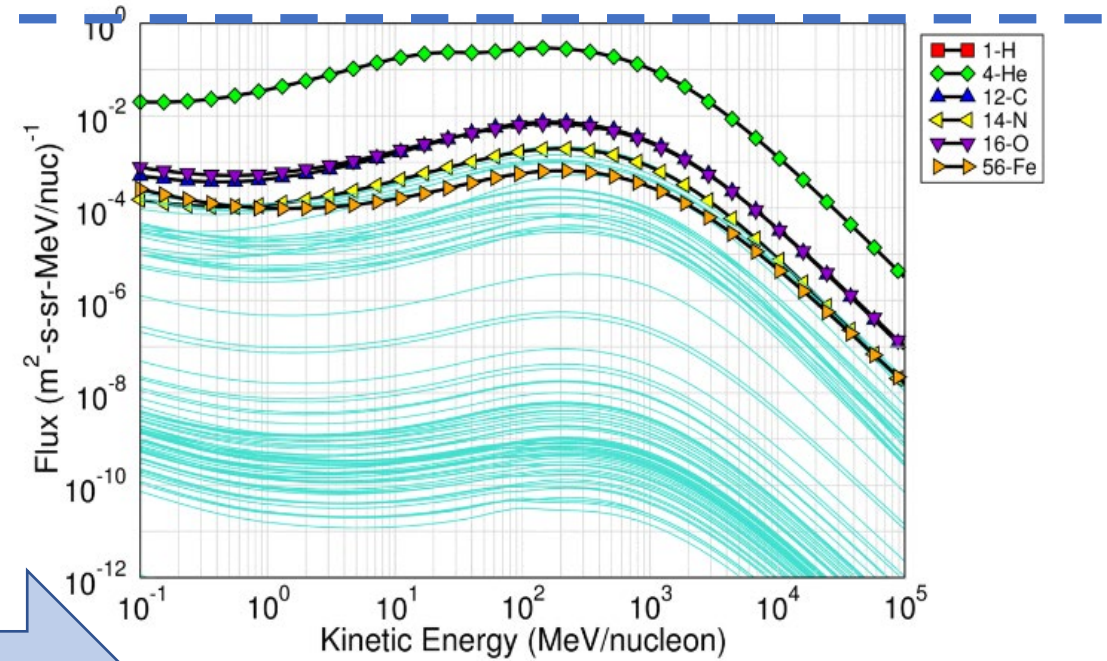
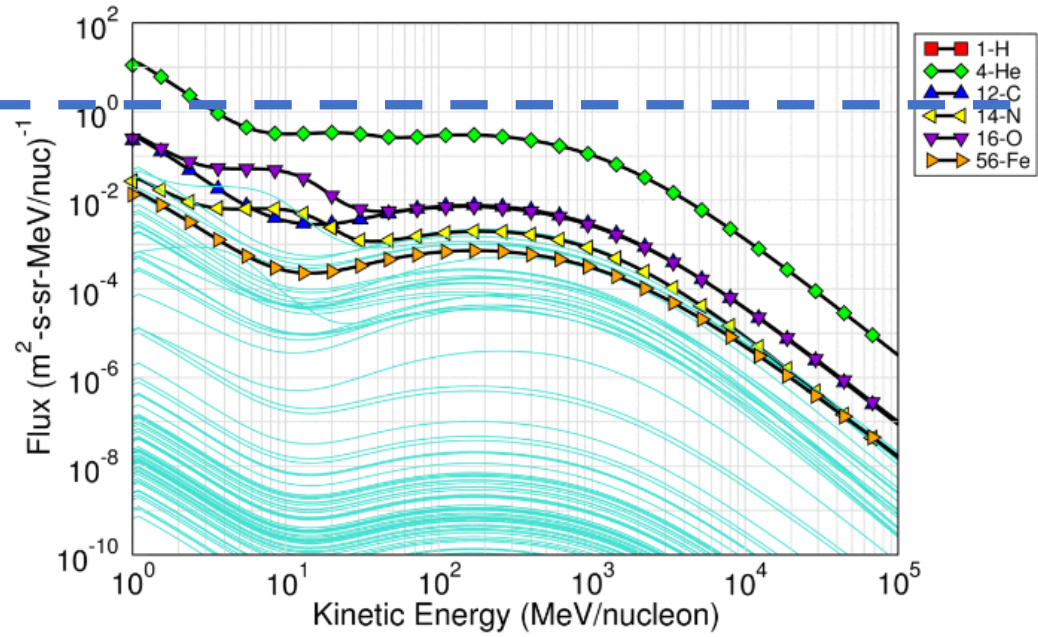
- Shielding has significant impact on both solar event radiation (SPE and PSYCHIC) and trapped protons, but not GCR



Trapped proton environment dominates error rate under ambient conditions

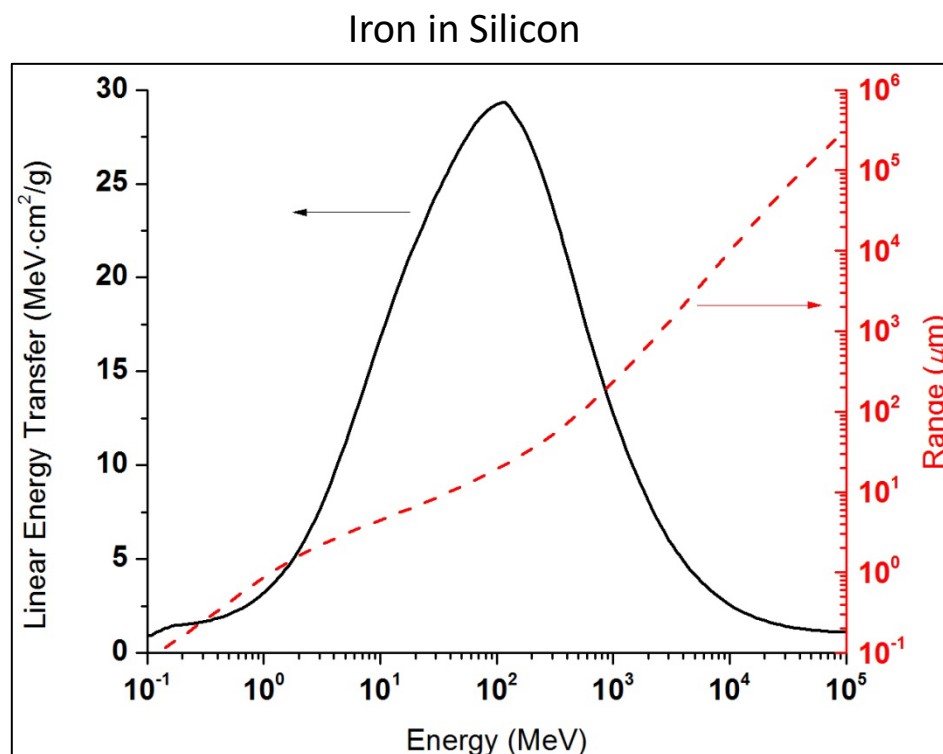
Presented by J. A. Pellish at the 2010 Nuclear and Space Radiation Effects Conference (NSREC), Denver, CO USA 19-23 July 2010 and published on <http://radhome.gsfc.nasa.gov/> and <http://www.nepp.gov/>.

9

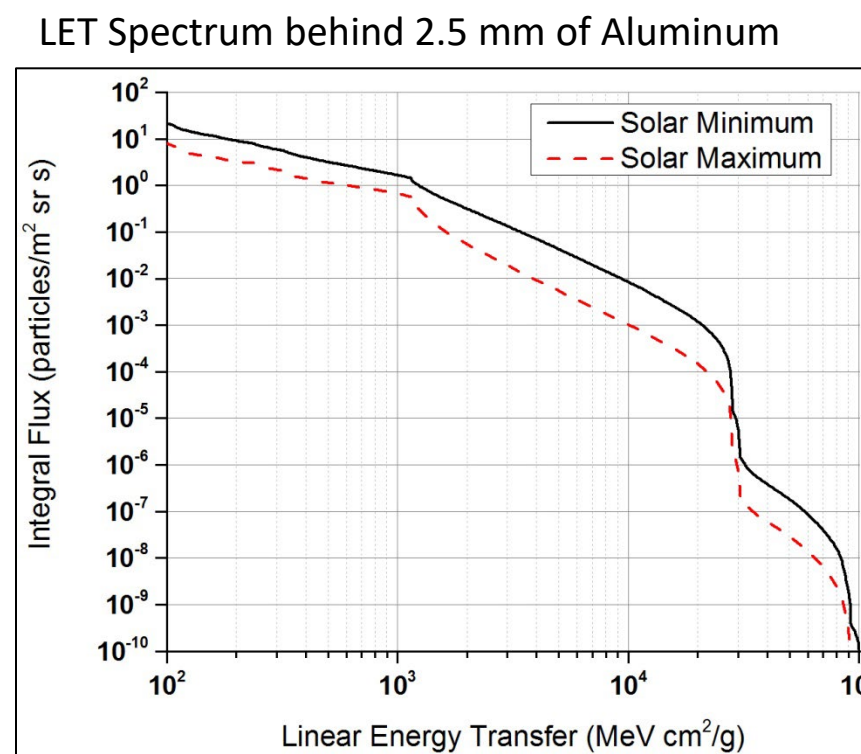


100mils

Using the Linear Energy Transfer (LET) metric



Generated with SRIM-2008



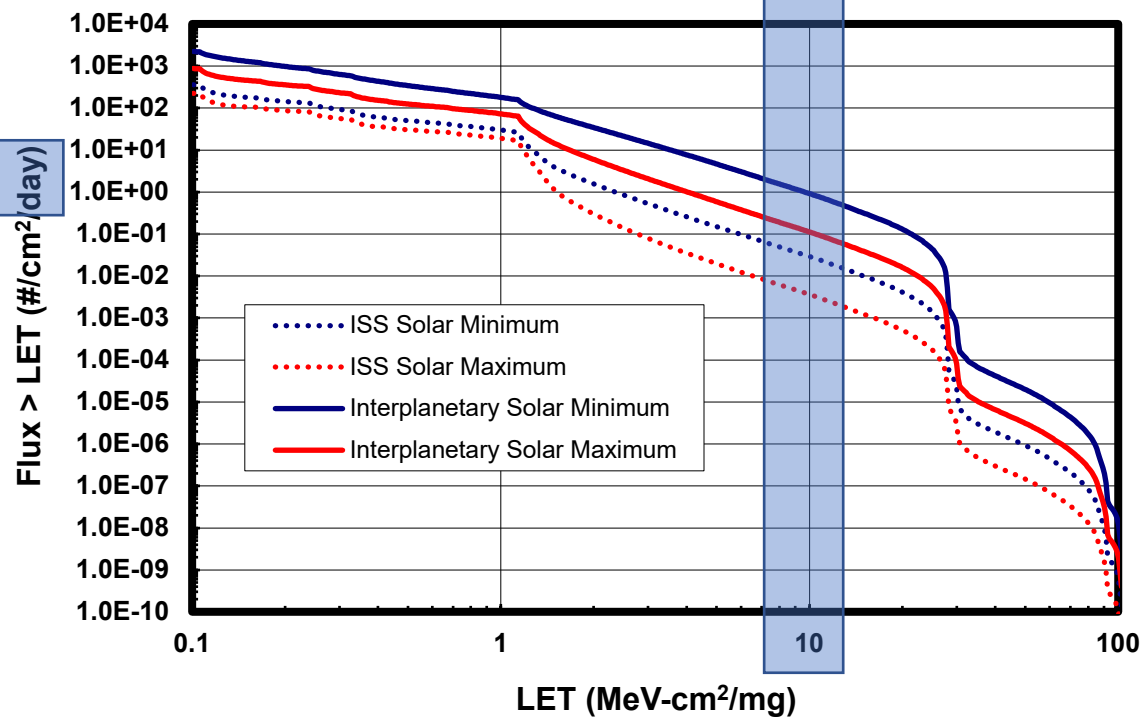
Generated with CREME96

$$S = -\frac{dE}{dx} \Rightarrow \text{LET} = -\frac{1}{\rho} \frac{dE}{dx}$$

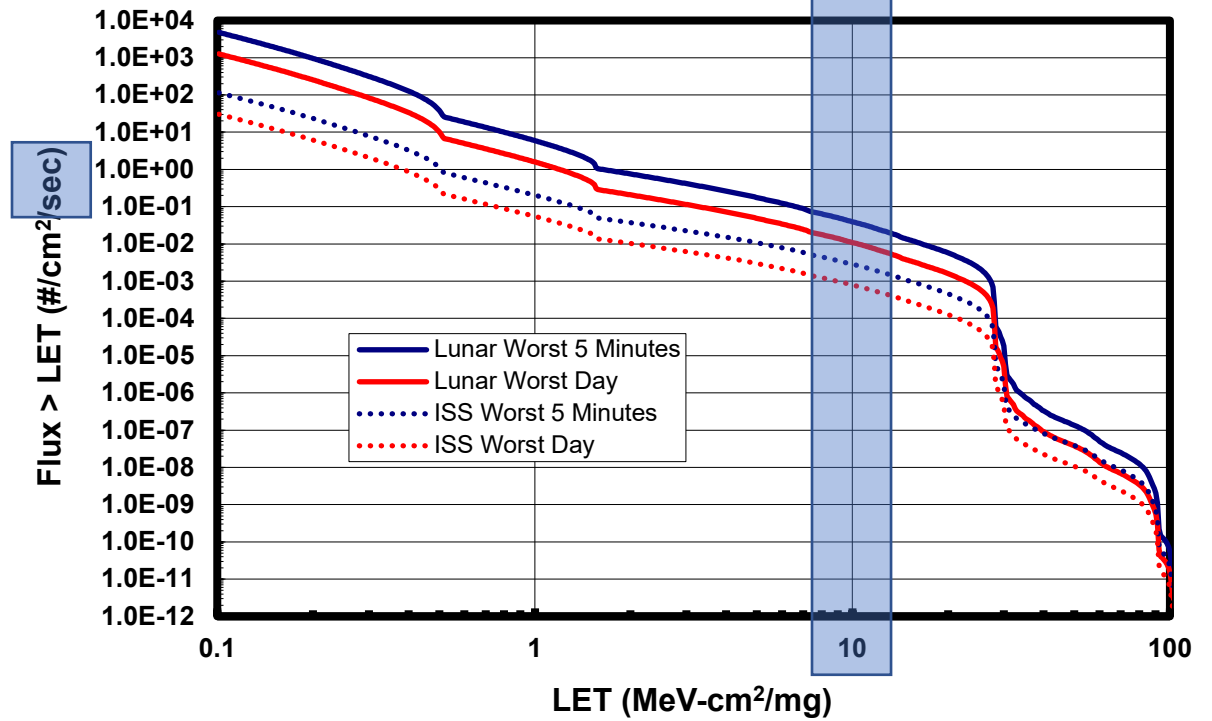
Stopping power (S), depends on target material; LET does not

Considering the different environments

Galactic Cosmic Ray LET Spectra



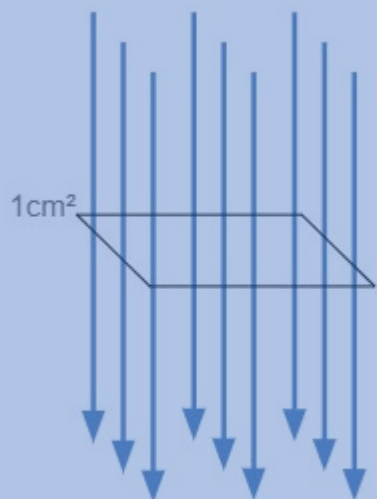
Worst Case Solar Particle Event Spectra



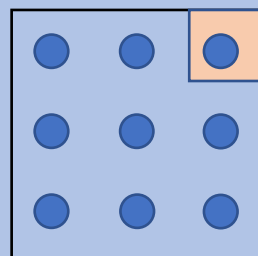
Just LET = 10 MeV·cm²/mg

1 full year background at ISS

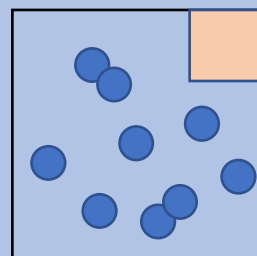
Flux = 0.025 /cm²·day



Fluence = 9 /cm²



A



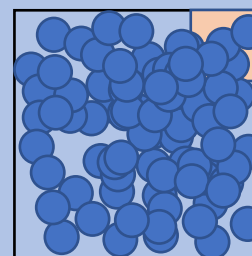
B



Latchup Structure

Flare at ISS

Flux = 0.005 /cm²·sec

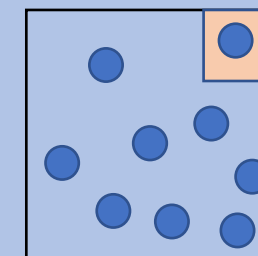


C

Fluence = 86 /cm²

Lunar Background

Flux = 1 /cm²·day



D

Fluence = 9 /cm²

Mission A – Device latches up catastrophically

Mission B – Same duration as mission A, but no effect seen

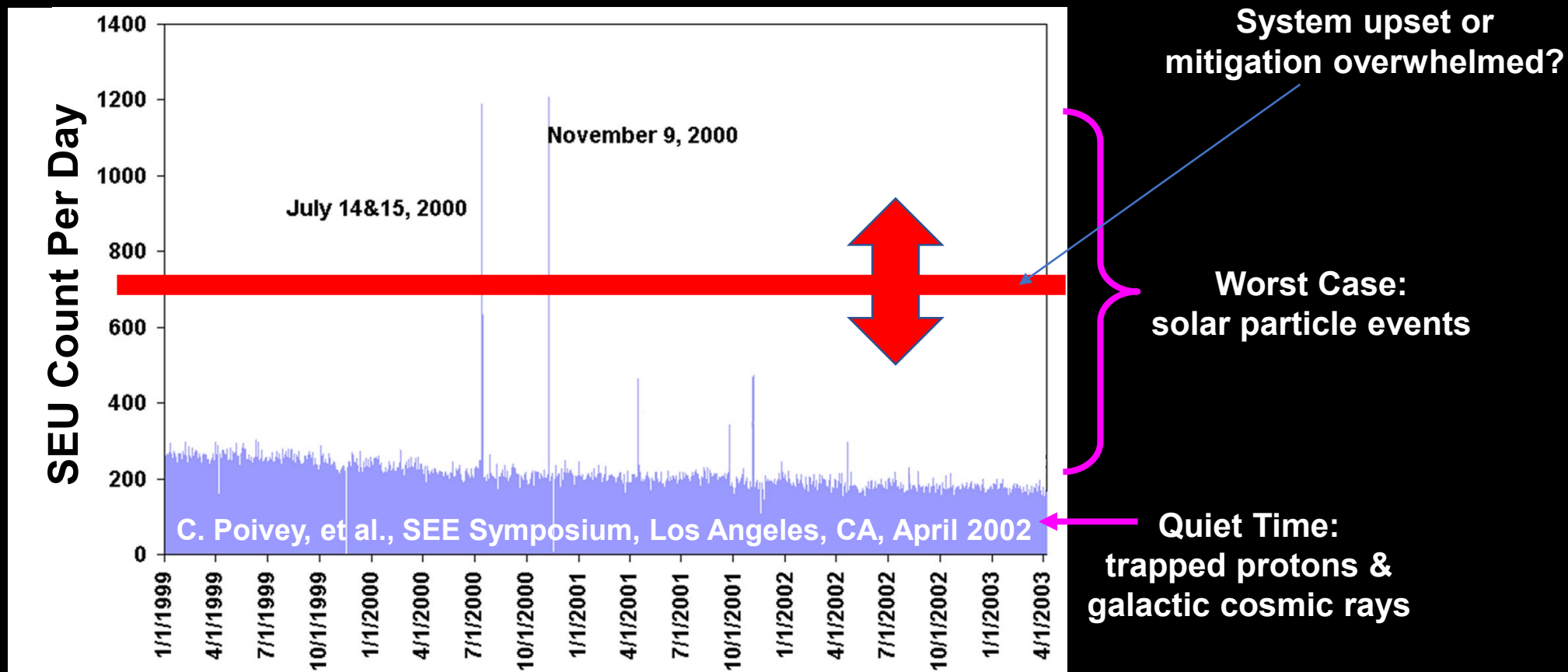
Mission C – 1 day solar flare

Mission D – Lunar orbit for 9 days

This is for one LET, and ignores directional effects and is meant to be a simple example of why on-orbit heritage does not work for DSEE



Environment Correlation: Measured Single Event Upsets



Without testing the flight design, we don't know if we are in or out of bounds



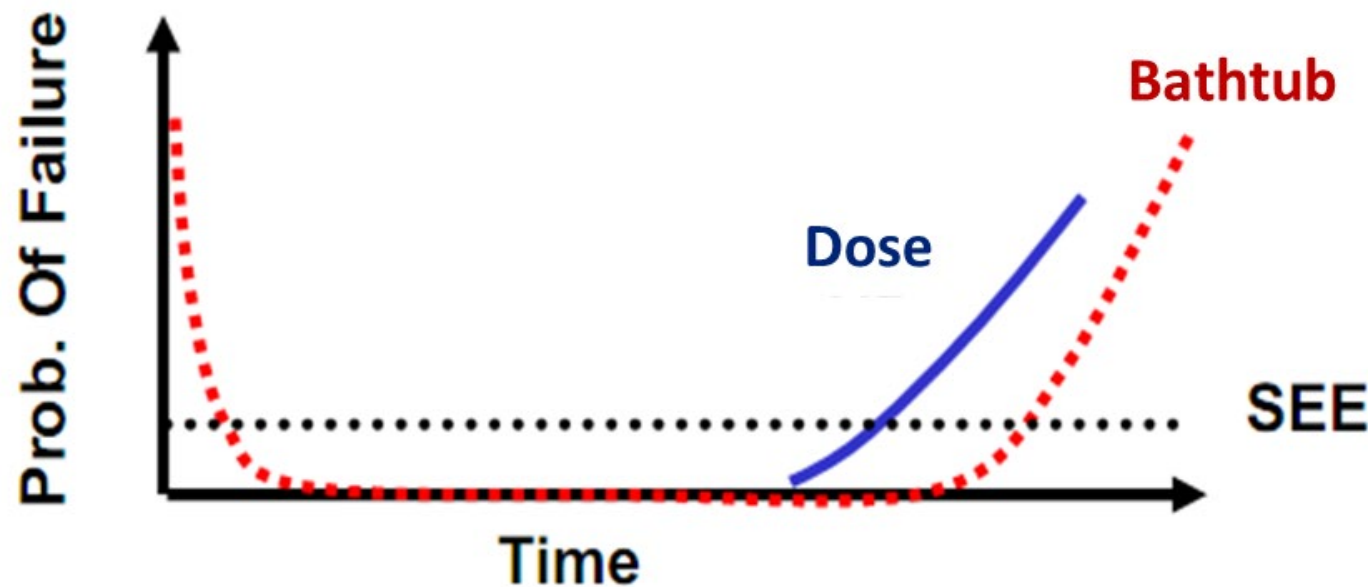
Parts Selection Questions



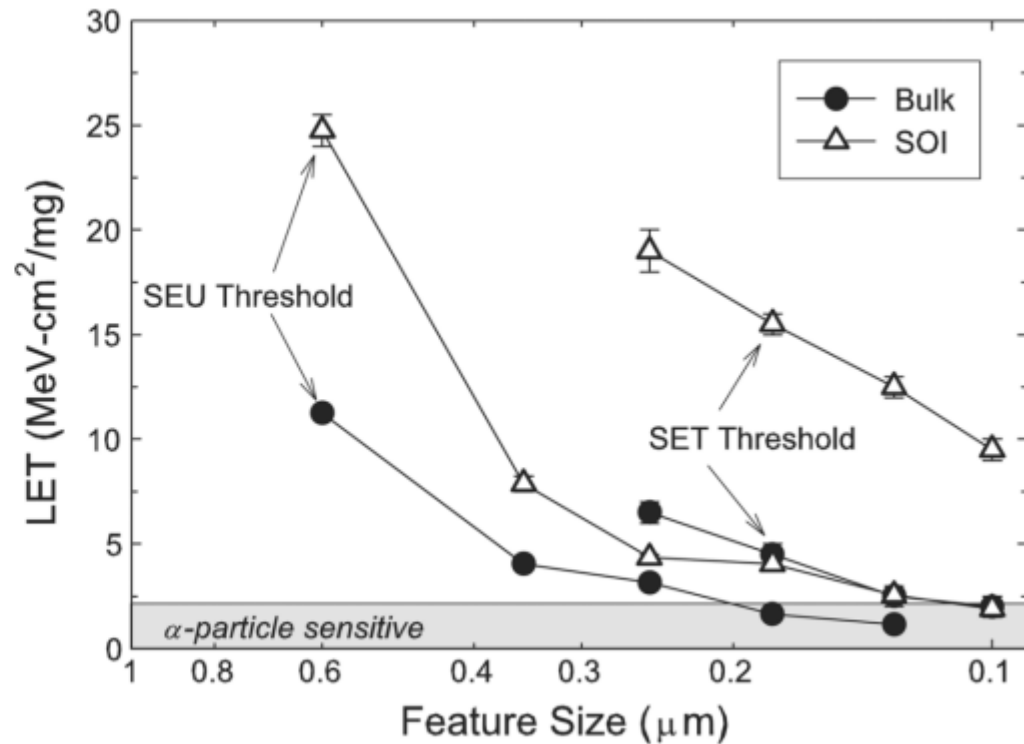
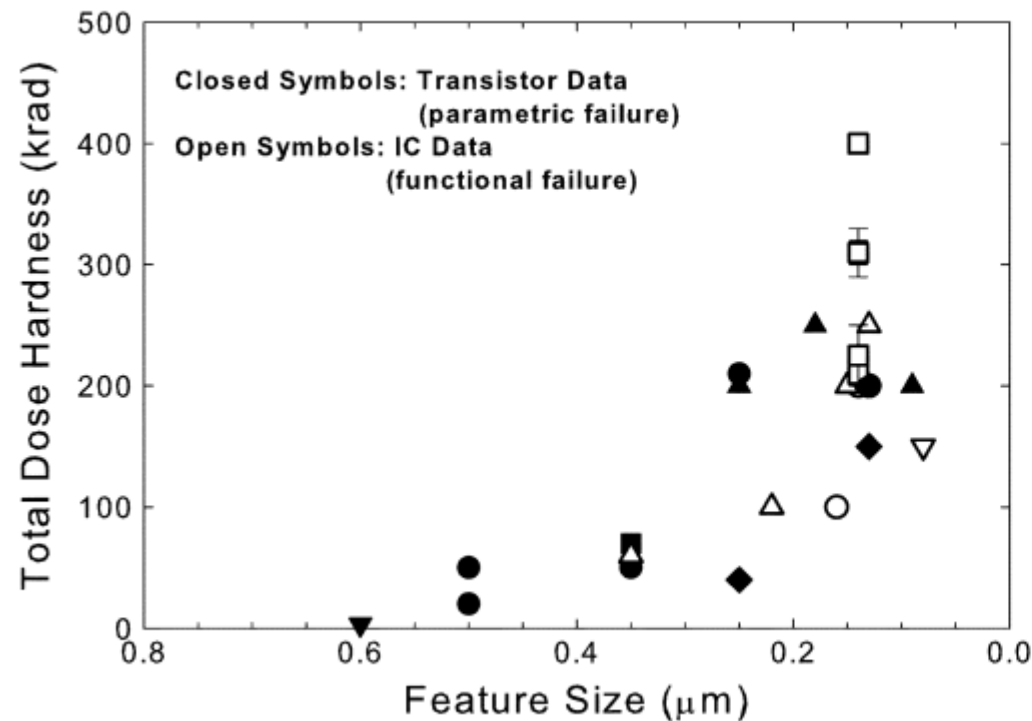
- What technology – semiconductor materials – make up your part?
- What functions do you need it to provide? How Critical?
- Could there be destructive SEE? Is there evidence to suggest that there aren't?
- Could non-destructive SEE interrupt your critical operations? Does the system have a way to accommodate them or return to safe operation?
- Will the parts survive the full mission when considering dose? Both Ionizing and Non-Ionizing?

Damage is a two-fold problem

- Dose shows up as you'd expect: wear-out mechanism (cumulative) – many damage sites or trapped charges accrue over time
- Single events show up as random failures-in-time (instantaneous) – one particle with sufficient energy deposition in the right location



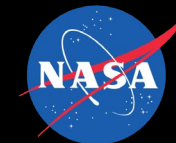
For CMOS in general, the scaling of feature size is increasing resilience with respect to dose and **increasing the susceptibility** to single event effects.



P. E. Dodd, M. R. Shaneyfelt, J. R. Schwank and J. A. Felix, "Current and Future Challenges in Radiation Effects on CMOS Electronics," in IEEE Transactions on Nuclear Science, vol. 57, no. 4, pp. 1747-1763, Aug. 2010, doi: 10.1109/TNS.2010.2042613.



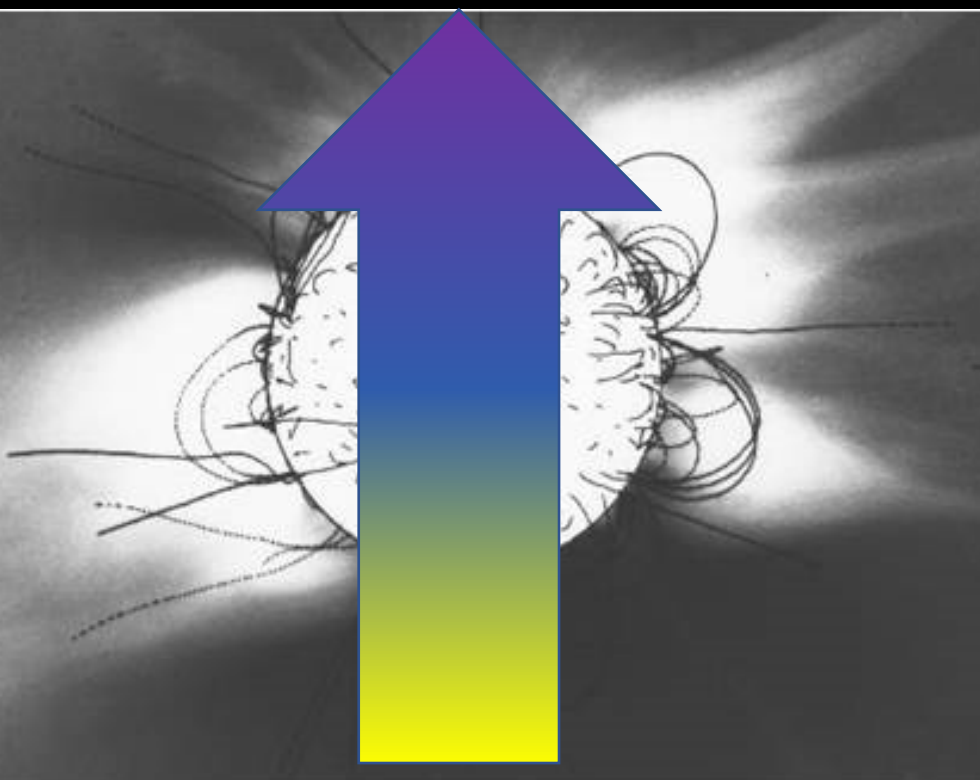
Part guidance diatribe: "IT DEPENDS"



- Power is always critical
 - Derating vs. Efficiency
- Process trends
 - CMOS shrinking
 - FinFETs
 - Gate All Around (GAA)FETs
 - GaN, SiC, GaO_x for Power
 - 3D Memory stacks
- Mixed Signal and System on a Chip
 - Always going to be performance driven usage of new components
- FPGA types
 - Flash
 - SRAM
 - Antifuse
- Memories
 - Flash, MRAM, FRAM, SDRAM

Notional dose factors to keep in mind for parts

Inherently difficult to expect nominal operation in radiation environment

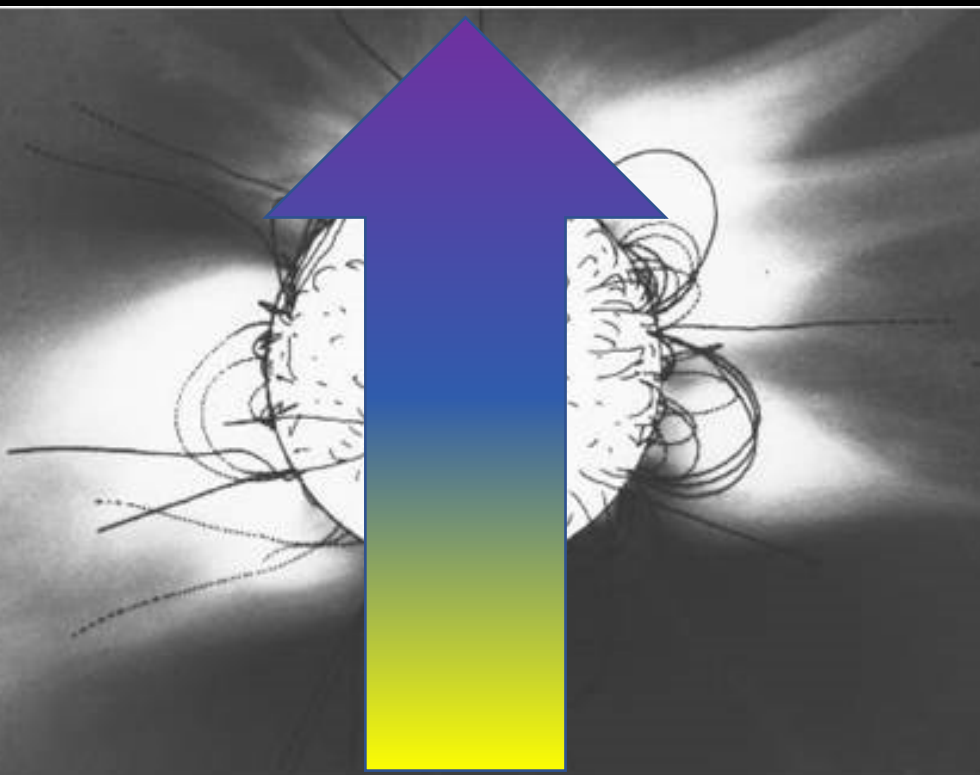


Dose signature predictable

Environment Contributors	Technology	Device Complexity
<i>Long Mission, Radiation Belts, High inclination</i>	Bipolar, Power, Hybrid, Multi-process, opto-electronics	Memories, Processors, FPGAs
<i>Solar Wind / Particle Events</i>	CMOS (to an extent)	ICs, FETs
<i>Galactic Cosmic Rays</i>	Hardened Devices	Discrete

Notional SEE risk factors to keep in mind

Inherently difficult to expect nominal operation in radiation environment



SEE signature less disruptive to functions

SEE Types	SEE in Technology	Device Complexity
Destructive SEE, Non-destructive SEL/SEB	Highly Scaled, Hybrid, Multi-process	Memories, Processors, FPGAs
Stuck bits, block errors, SEFI, MBU	Power, CMOS	ICs, FETs
SET, SEU	Bipolar, Hardened Devices	Discrete

Mitigation techniques

Mitigation Techniques	TID	DDD	SEE	Charging
Part Selection	X	X	X	
Material Selection				X
Shielding	X	X	(X)	X
Operating Parameters	X	X	(X)	
CONOPS	X	X	X	X
Circuit Design	X	X	X	
EMI Design				X
TMR			X	
EDAC			X	
Watchdog			X	
Cold Spare	(X)	(X)	(X)	

Adoption of mitigation techniques occur throughout the lifetime of the satellite

Deciding if you need to mitigate at all

Error-Functional

- High number of SEE signature allowable
- Design may inherently be indifferent to SEE signature with mitigation in place or robust design practices
- Nuisance or manageable function impacts (e.g. filtered transients, error detection and correction on memories) beyond part responses
- No action needed

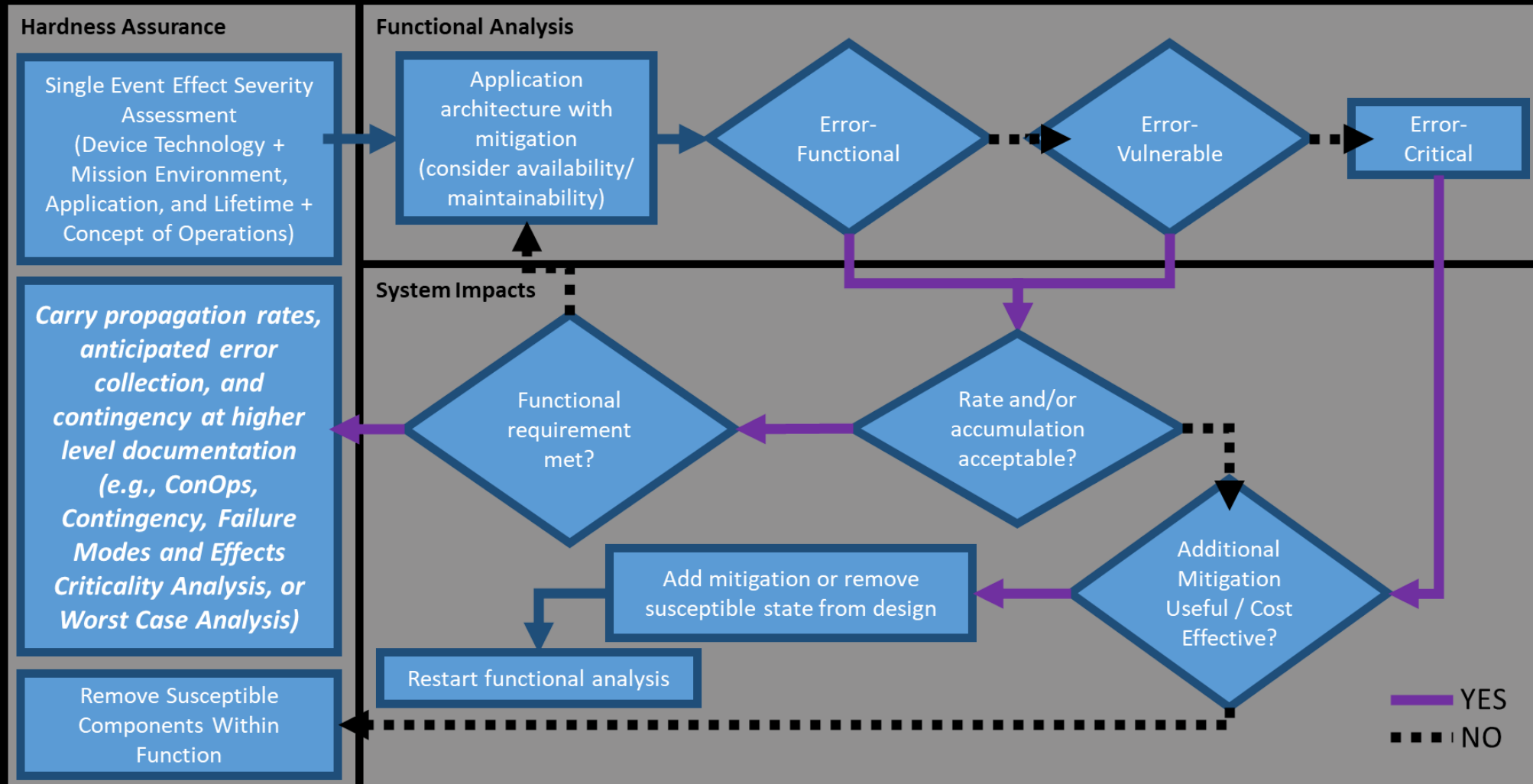
Error-Vulnerable

- Low number of SEE signature tolerable
- Design may require function for small window of availability or spend very little time in the susceptible state
- Mitigation needed in order to be reclassified as error-functional (e.g. SEFI of Flash, Multi-bit upsets)
- Ground or autonomous operations must be anticipated

Error-Critical

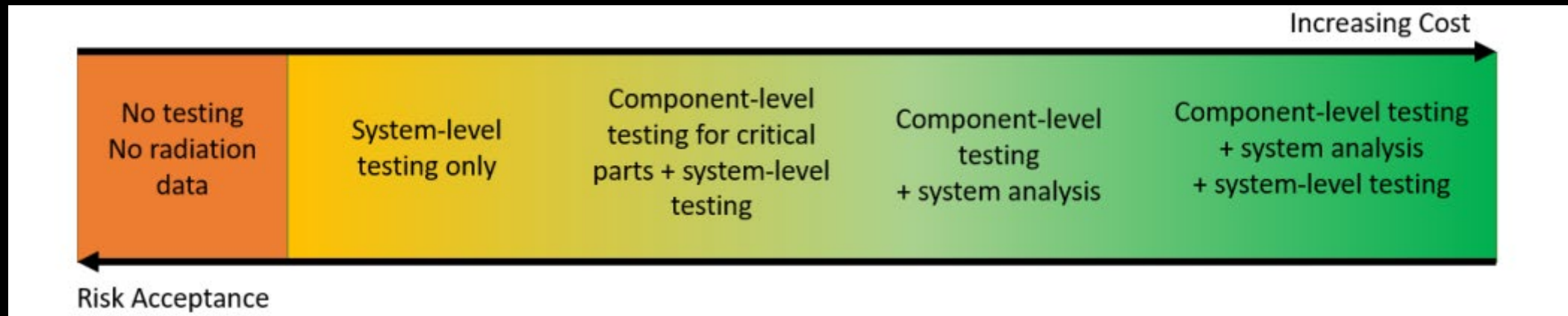
- SEE signature not allowable
- Disruption of function identified as single point of failure or design cannot continue to perform after SEE
- Mitigation needed in order to be reclassified as error-vulnerable (e.g. destructive SEL, many error accumulation, boot image corrupted due to error accumulation, SEFI that requires ground intervention or box level reset waiting on ground)
- Anomaly review needed or loss of mission

Mitigating with system architecture



Based on original SEECA (Gates, LaBel)

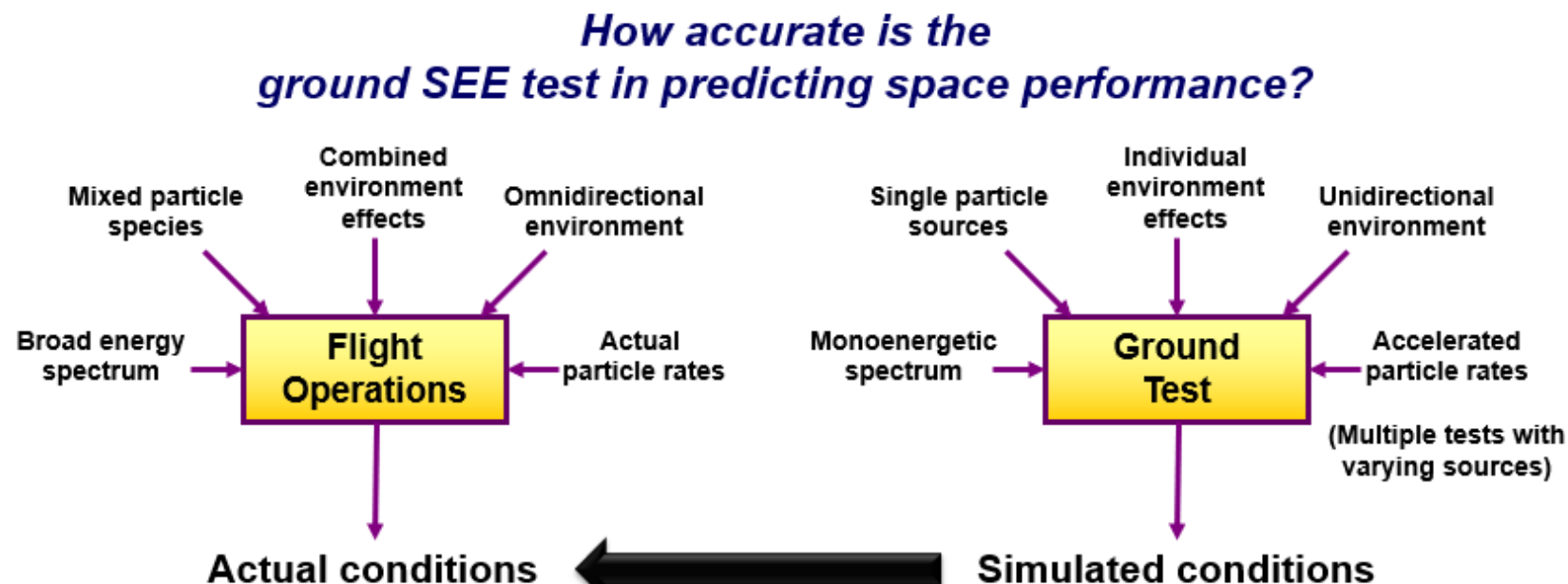
Radiation Testing



(After A. Coronetti)

- For TID we use energetic photons, typically gamma rays
 - They can be imparted uniformly and have good charge yield
- For TNID we use energetic protons or neutrons avoiding coulombic interactions
 - Can use mono-energetic fluences to represent full damage predicted in environment if the material follows Non-ionizing Energy Loss (NIEL) principles
- For SEE we use heavy ions, protons (mostly secondaries), secondaries of neutrons, and sometimes pulsed laser
 - We try to know the amount of charge creation, so that we can estimate rates on-orbit

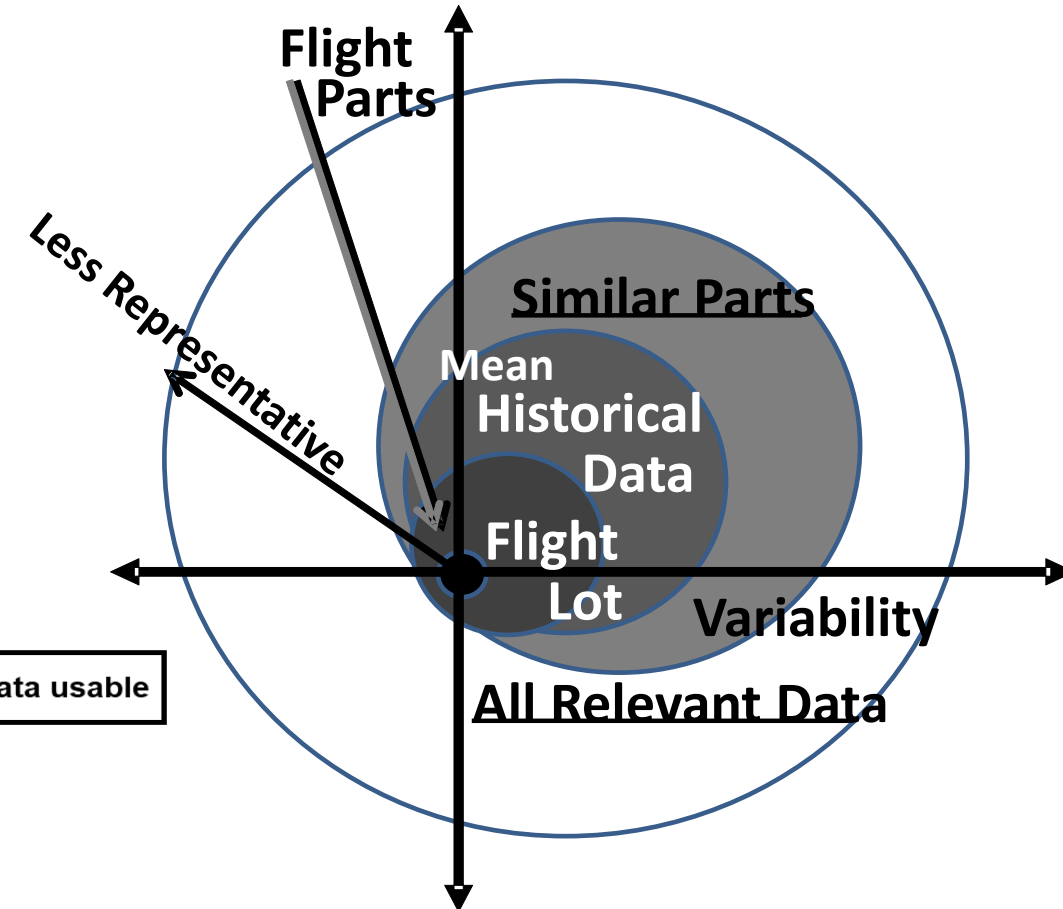
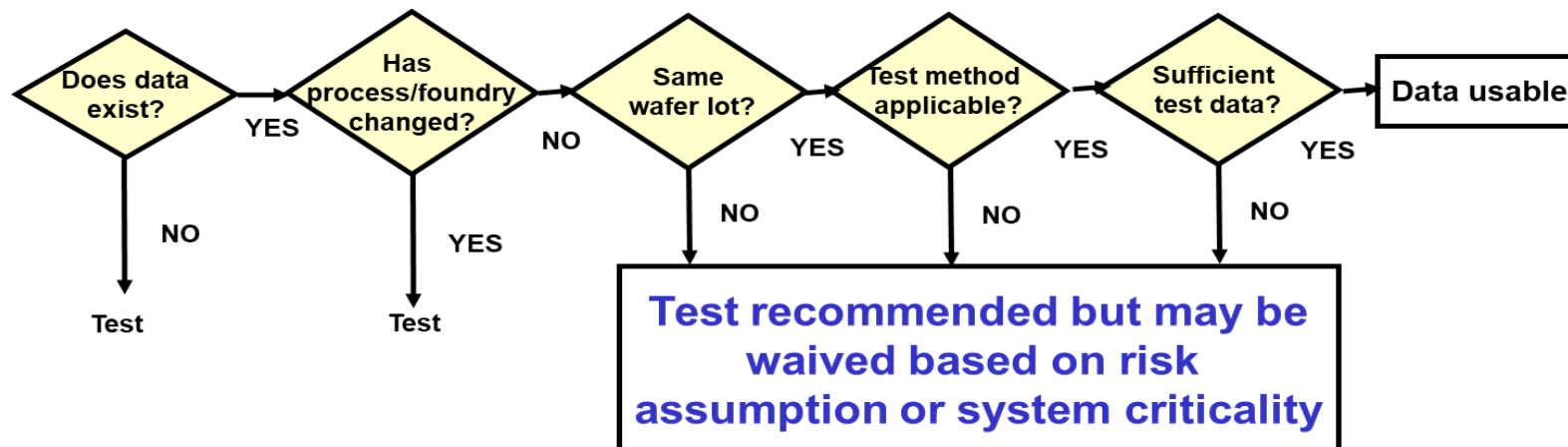
- Testing is tailored to characterizing mechanism for analysis in any environment
- Most times it takes multiple tests to okay a part for a given environment



Graphic prepared by K. A. LaBel, NASA GSFC, 2008.

Ground $\neq$ space – as radiation effects practitioners, we need to understand and account for the differences.

- Focus on application driven risks
- Mil-Aero vs. COTS vs. something else
- Is the data applicable?
 - Has the part changed? New foundry, new layout / tape-out / passivation?
 - Does the test condition address your application?
 - Is the source used sufficient to close all risks for your environment?



Ray Ladbury, NSREC2017 SC,

<https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170006865.pdf>



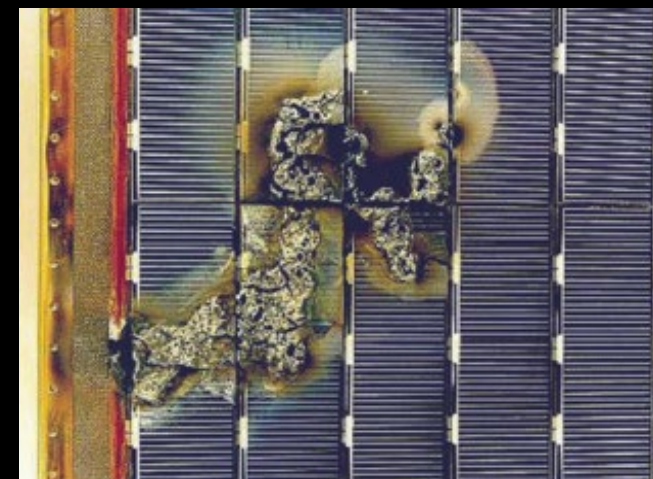
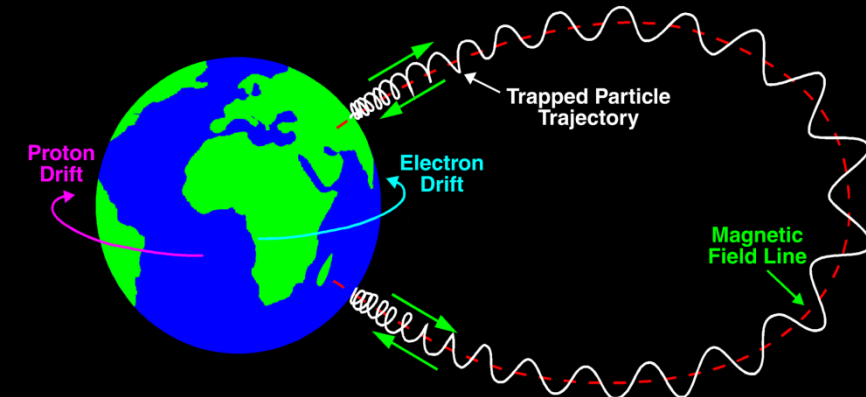
Databases and information



- Radhome – radhome.gsfc.nasa.gov – radiation test reports for flight projects and NEPP
- PMPedia – pmpedia.space – part data and reports
- NEPP – nepp.nasa.gov – publications/reports on technology trends
- S3VI – s3vi.ndc.nasa.gov
- NTRS – ntrs.nasa.gov – all REAG publications and presentations that are cleared for public consumption
- IEEE Xplore – one stop shop for radiation peer reviewed journal entries (TNS), data workshops, emerging methodologies, etc.
- CCMC - [Home | CCMC \(nasa.gov\)](http://www.ccmc.nasa.gov)
- Others to come ESA, JPL, SRHEC/DoD

Common pitfalls, lessons learned

- Thinking radiation is one number to meet
 - Dose profile behind different amounts of shielding also depends on the type of incident radiation
 - SEE that have low LET susceptibilities can benefit from some shielding, higher LET will always be present
- Tight tolerance in application
 - Not considering the dynamic environmental conditions
 - Derating is your friend
- Overly complex mitigation doesn't solve the problem
 - Verification of mitigation very well could require testing, and \$\$\$
 - Additional susceptibilities introduced into reliability overall
- Don't forget about other environment driven failures
 - Charging / Corrosion
 - Temperature
- Heritage? What heritage?
 - Part to part variation, lot to lot variation
 - Better predictor for dose performance if you have part fidelity



ESA EURECA satellite solar array sustained arc damage.
Credits: ESA



Big Takeaways



- Model your environment, it's free doesn't take a lot of effort and the simple approach is conservative as a starting point
- A little bit of shielding goes a long way! Not joking, Reynolds wrap if you have to
- If nothing else, due diligence is necessary for destructive SEE, either have evidence that they are not in your design, do a test, or design as if they exist
- Telemetry like dosimeters or memory upset counts can help with anomaly resolution



Radiation tools out there (free)

- SmallSat / System Architecture
 - R-Gentic – <https://vanguard.isde.vanderbilt.edu/RGentic/>
 - SEAM – <https://modelbasedassurance.org/>
- Environments and Transport
 - Spenvis – <https://www.spenvis.oma.be/>
 - OMERE – <http://www.trad.fr/en/space/omere-software/>
 - OLTARIS – <https://oltaris.nasa.gov>
 - SRIM – <http://www.srim.org/>
 - JPL NSET - [NSET Tools \(nasa.gov\)](https://nset.jpl.nasa.gov)
- Rate Calculations
 - CRÈME – <https://creme.isde.vanderbilt.edu/>



Recent NASA Guidelines



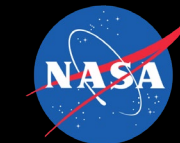
- *Avionics Radiation Hardness Assurance (RHA) Best Practices*

NESC-RP-19-01489

- TID, TNID, and SEE
 - Test and analysis
 - System level
-
- Application to COTS Electronics
 - Radiation effects issues with COTS parts are the same as with others
 - Guidance on robust methods to handle unit-to-unit variability
 - Guidance on test and evaluation to help address COTS testing challenges
 - Single-Event Effects Criticality Analysis



NASA RHA Standard in the works



- *RHA schedule of expectations*
- *Taxonomy*
- *Stems from findings on NESC avionics guidelines*
- *FY24 will see a review and feedback on drafted document*

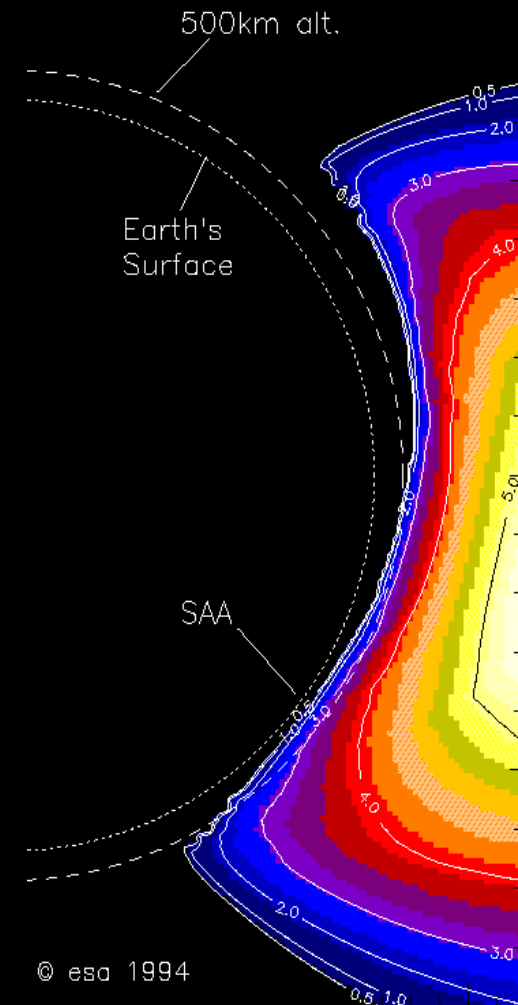
	Project Formulation				Project Implementation						Program
	Pre- Phase A	Phase A		Phase B	Phase C		Phase D		Phase E	Phase F	
	KDP A	KDP B		KDP C	KDP D		KDP E		KDP F		
Milestone	MCR	SRR ¹	SDR	PDR	CDR	SIR	ORR	FRR	DR	DRR	FRR
Assign RHA Lead	RAD3										
RHA Feasibility	RAD4	Update as necessary									
RHA Baseline		RAD5									
ERD/EDD	Preliminary estimates	Initial (RAD6)		Update	Final						
RHARD		Initial (RAD7, RAD8)		Update	Final						
Rad Analysis Reports				Initial (RAD9)	Mature (RAD10)	Update as necessary					Final (RAD11)
Parts List Rad Review		Critical Technologies		Initial	Update	Update as necessary					
Test Schedule Plan incl RLAT ²				Initial	Update	Update as necessary					
Subsystem Rad Req Allocations ³		Initial		Update	Final						
Radiation Risk	RAD2, then track to closure										
System-level Rad Analysis & Report ⁴					Inputs (RAD10)	Update as necessary					Final (RAD11)



Attribution for stolen content 😊



- A lot of this content has been previously put together
 - Radiation Effects & Analysis Group (REAG) members: Megan Casey, Ken LaBel, Ray Ladbury, Jonny Pellish, Ted Wilcox, Mike Xapsos, and others
 - Outside help: Jet Propulsion Lab (JPL), Radiation Test Solutions (RTS), Univ. Tennessee Chattanooga (UTC), and others
- You can find those resources readily in NASA Technical Reports Server (NTRS) by searching for:
 - Texas A&M University (TAMU) Cyclotron Facility Bootcamp
 - NASA Space Radiation Lab (NSRL) Radiation Test Workshop
 - NASA Electronic Parts and Packaging Electronics Technology Workshop (NEPP ETW)
- NASA Engineering & Safety Center (NESC) Academy – has video content of radiation 101



THANK YOU

michael.j.campola@nasa.gov

