National Aeronautics and
Space Administration

Radiation Effects & EEE Parts Selection

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Radiation Effects and Analysis Group (Code 561)

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

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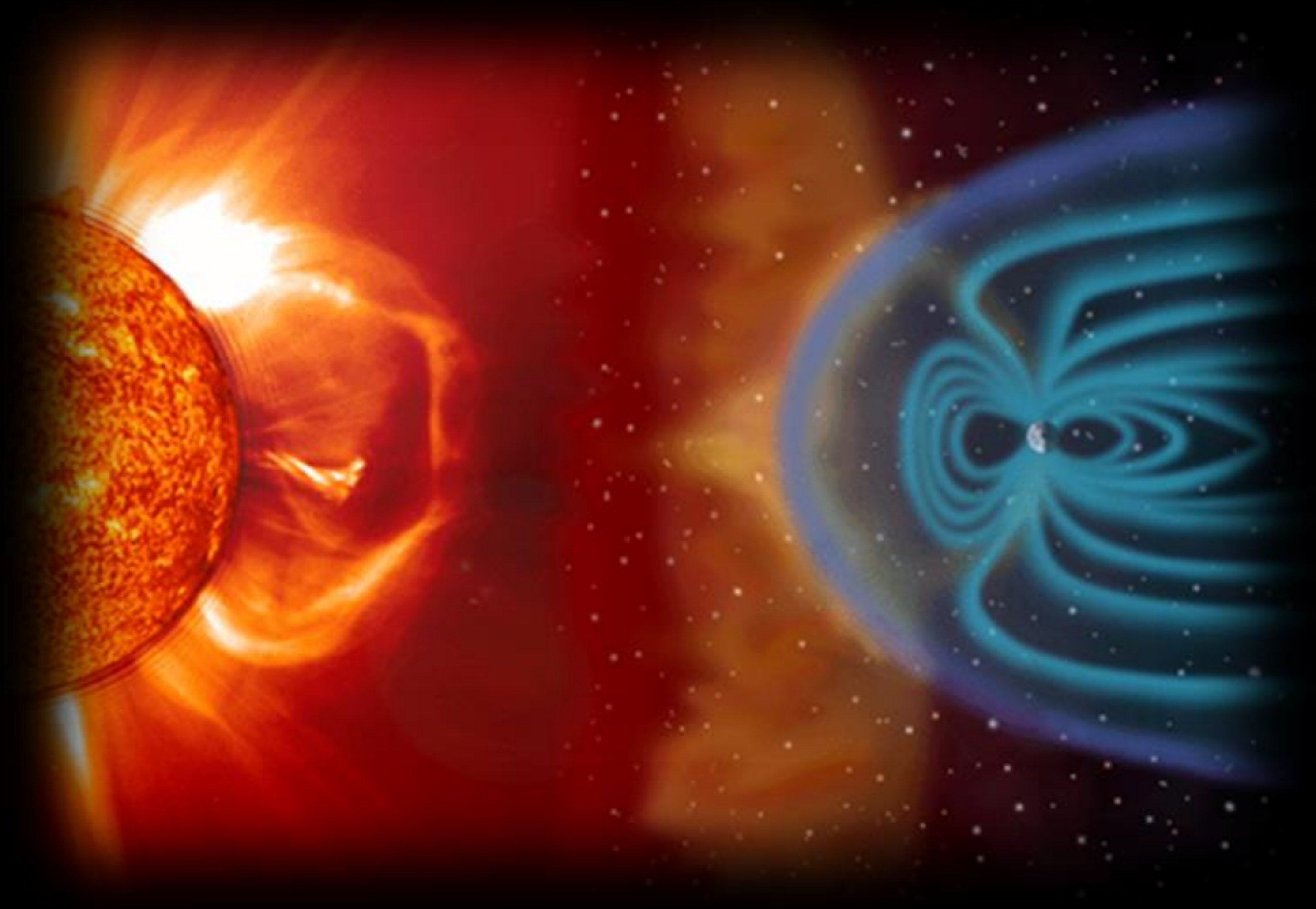
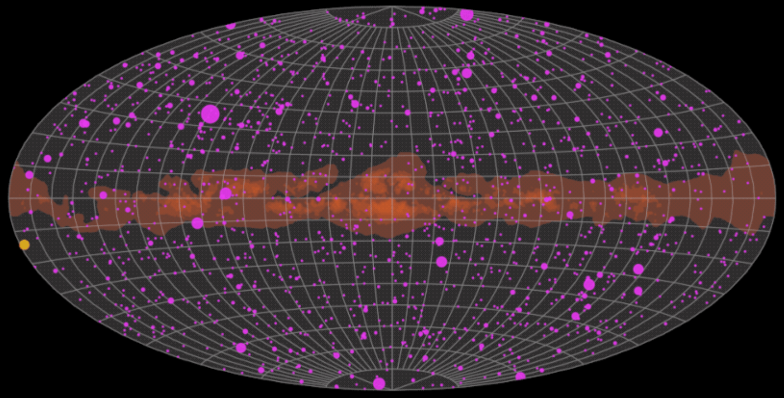
Outline

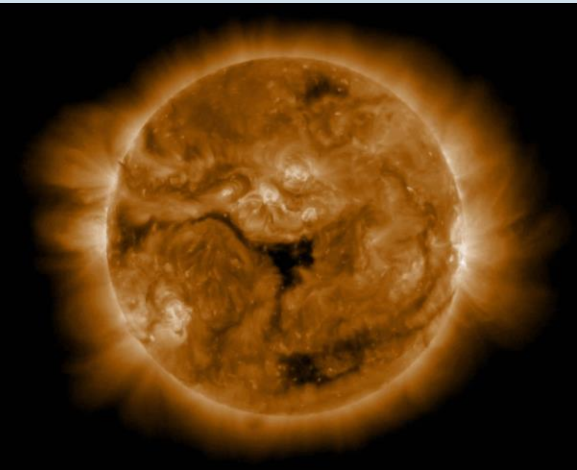
- Quick radiation effects summary
- Part selection
  - Radiation part categories
  - Notional challenges to keep in mind
- Finding and interpreting radiation data
- Mitigation strategies
- Common pitfalls
- Radiation tools and resources

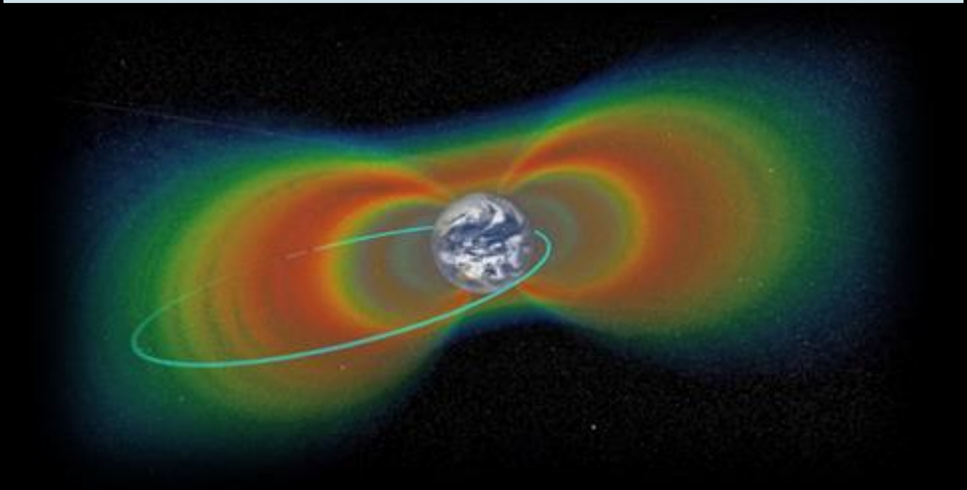


Natural space radiation environment

Galactic Cosmic Rays	Solar Activity	Trapped Particles in Planetary Magnetic Fields







Galactic Cosmic Rays

Energetic supernovae remnants
(~GeV, Z=1-92)
Originate outside of our solar system

Solar Activity

~11-year Solar Cycle
CMEs (proton rich)
Flares (heavy ion rich)
Solar Wind

Trapped Particles in Planetary Magnetic Fields

Fluctuate with Solar Activity and Events
Not a perfect dipole
Protons and Electrons trapped at different L-shell values and energies

These sources are **dynamic.**

Images from left to right – NASA FERMI X-ray telescope, Solar Dynamics Observatory, Janet Barth (radhome.gsfc.nasa.gov)

Breaking down radiation effects

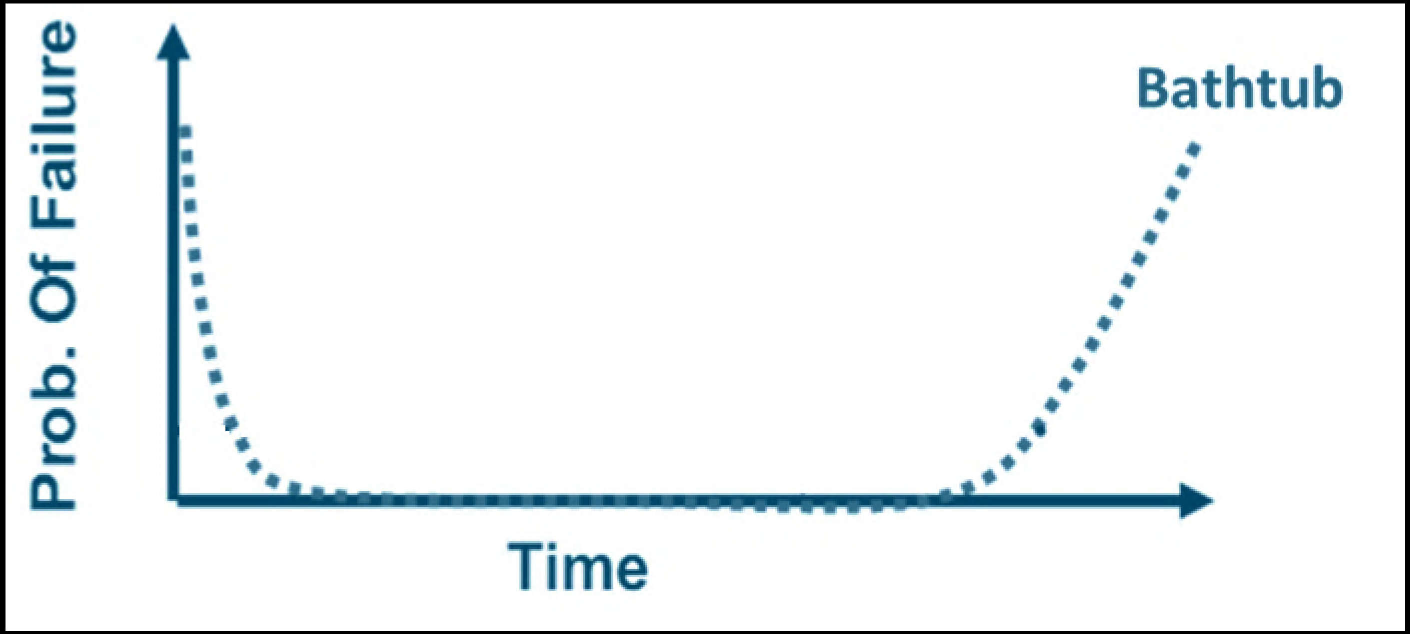
Ionizing Radiation Effects

- Total Ionizing Dose (TID)
- Total Non-Ionizing Dose (TNID)
- Single-Event Effects (SEE)
  - Non-Destructive
  - Destructive

Primarily high-energy protons and heavy ions

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



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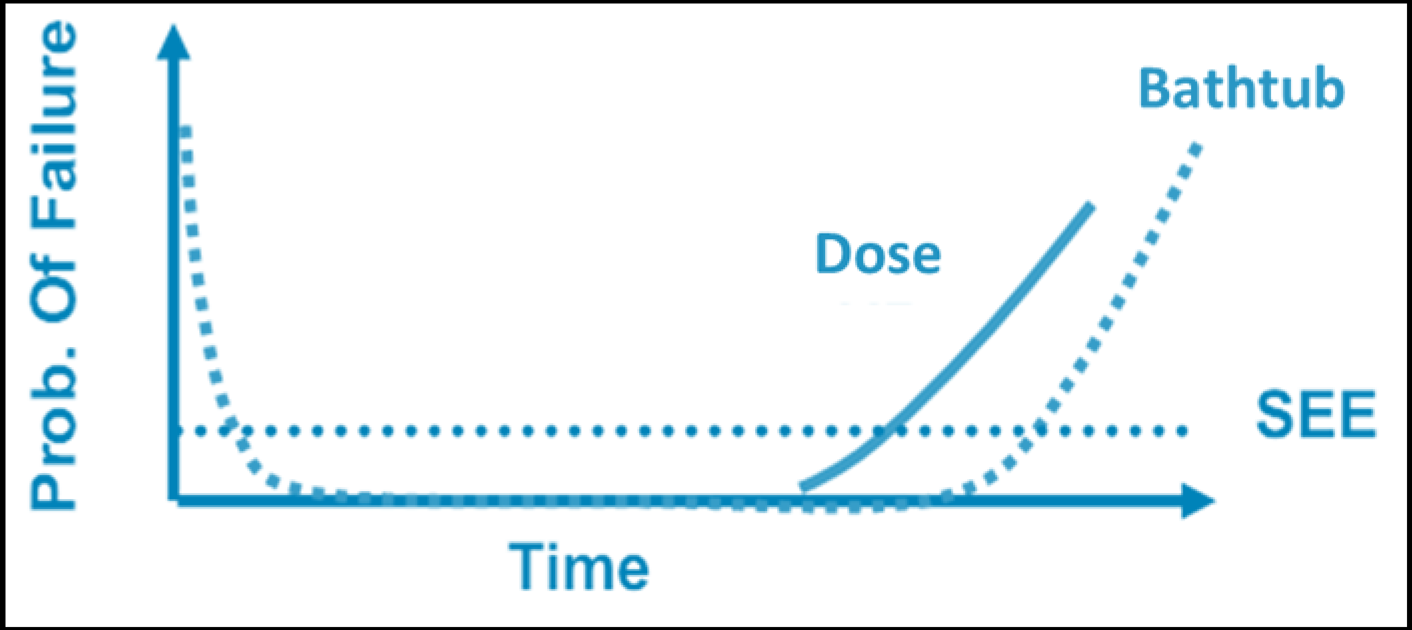
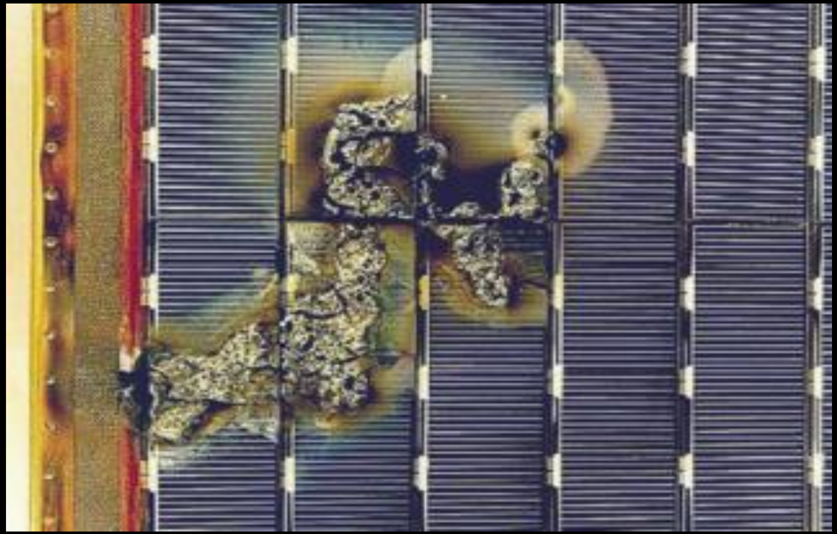
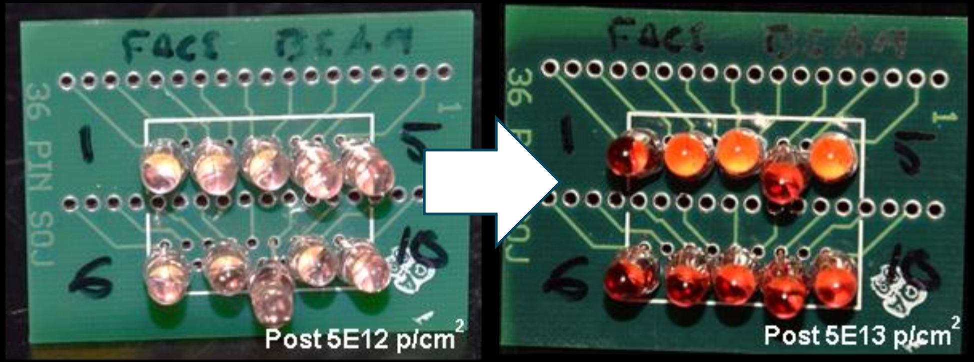


Parts don't like radiation

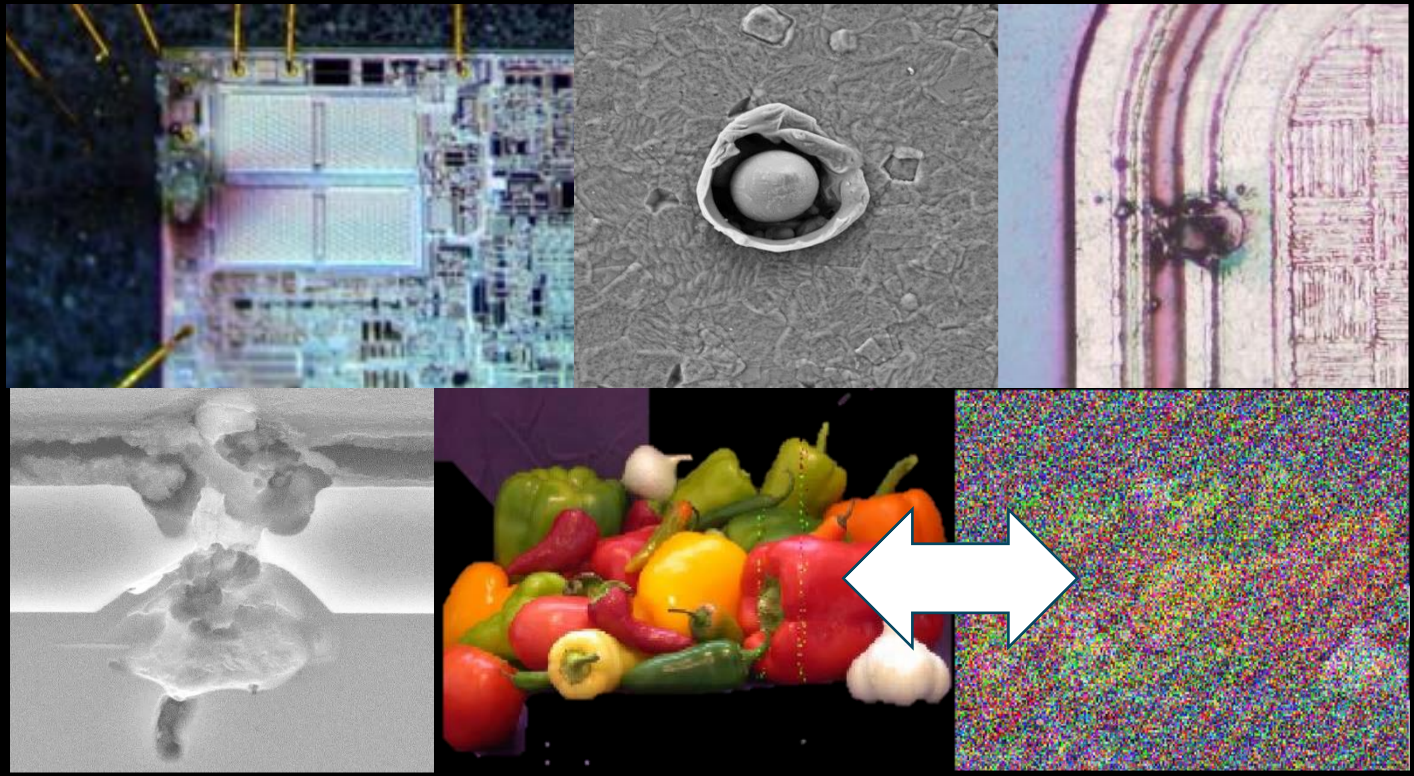
Charging leads to arcing



Dose leads to degradation/functional failure



SEE leads to failures/functional disruptions



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)

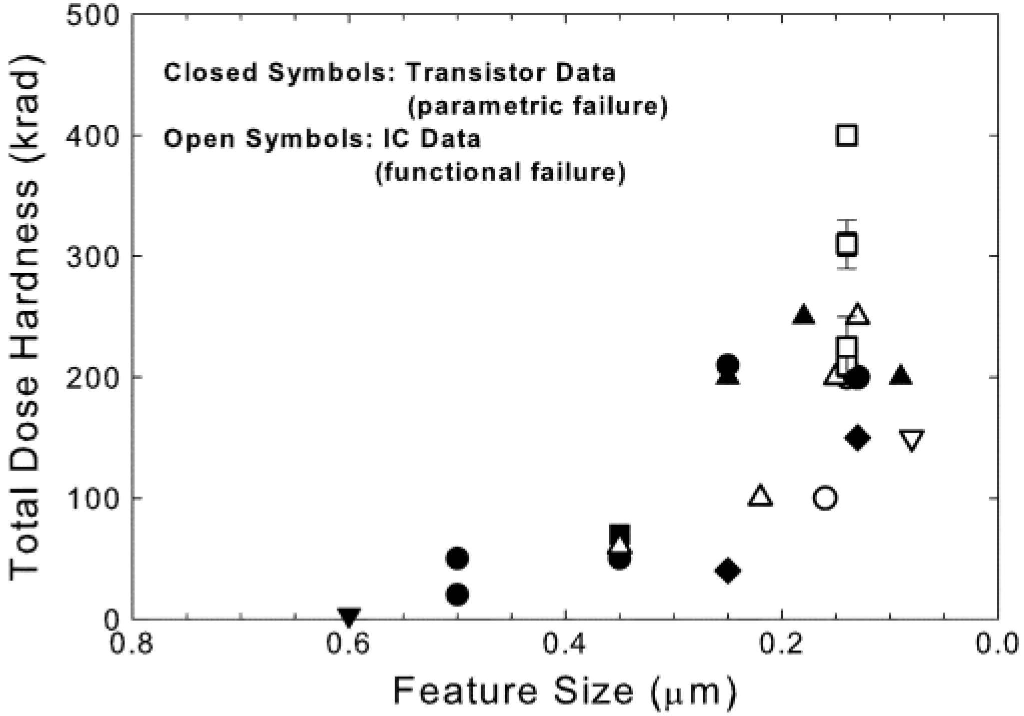
Charging:

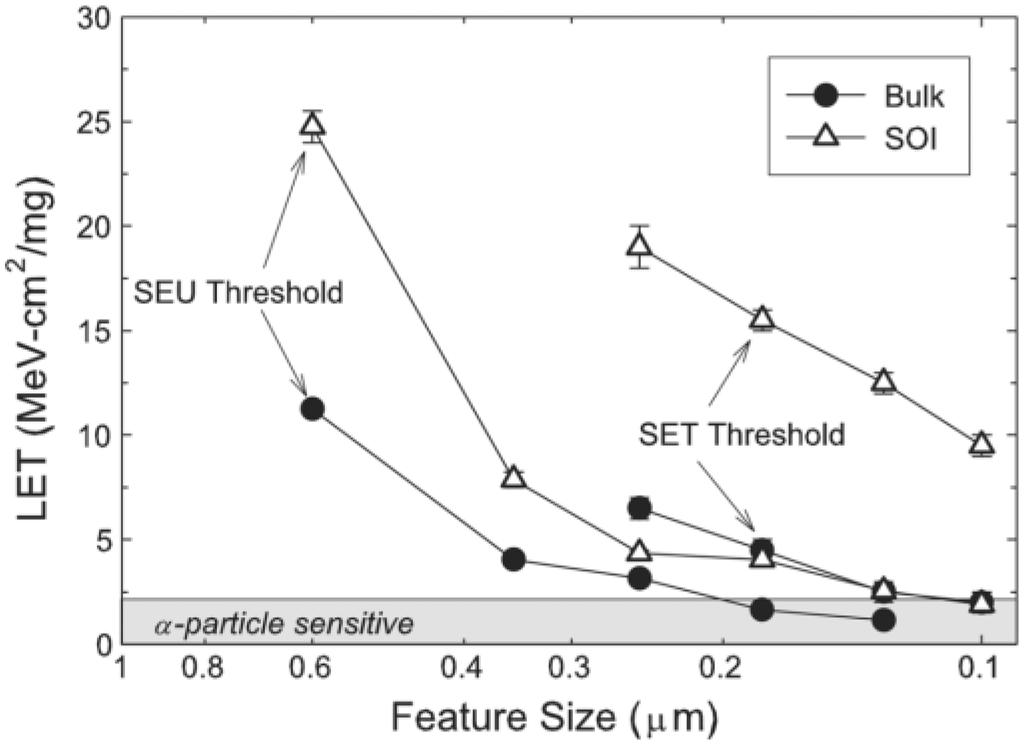
- Electrostatic discharge
- Arcing
- Enhanced surface contamination
- Local dielectric breakdown

(After K. Ryder)

CMOS Technology Trends

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

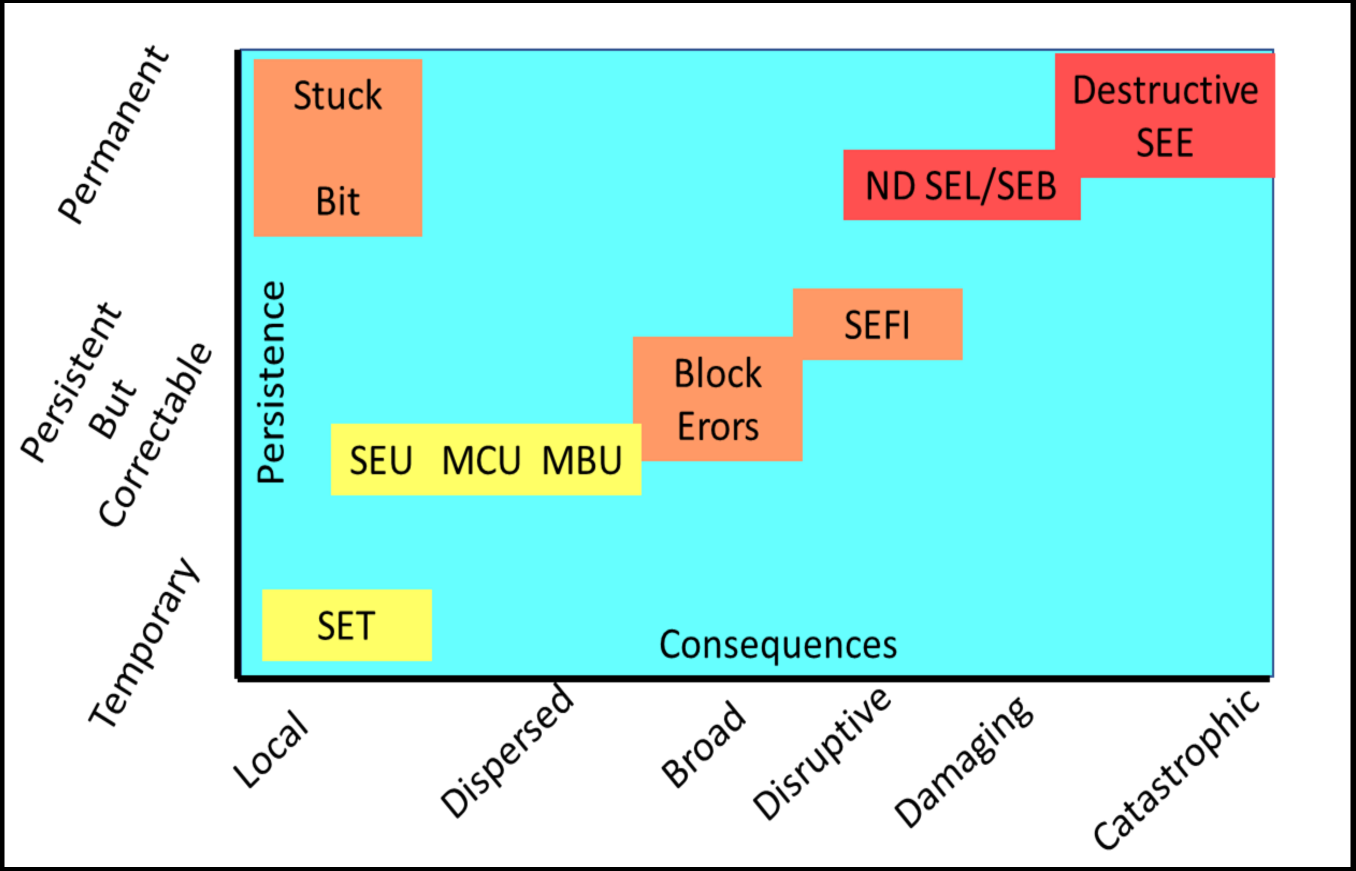




P. E. Dodd, M. R. Shaneyfelt, J. R. Schwank and J. A. Felix, "Current and Future Challenges in Radiation Effects on CMOS Electronics," in IEEE Transactions on Nuclear Science, vol. 57, no. 4, pp. 1747-1763, Aug. 2010, doi: 10.1109/TNS.2010.2042613.

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 could be in my part?

- 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	✓	✓	✓	✓	✓	✓	

Part selection flow

Requirements
- Mission life
- Environment
- Concept of operations

System Function
- Criticality
- Application constraints

Data
- Part categorization
- Ratings
- Testing

Selection
- Additional mitigation
- Risk acceptance
- Rejection

Parts categories (rad engineer perspective)

- Guaranteed hardness
  - Radiation-hardened by process (RHBP)
  - Radiation-hardened by design (RHBD)
  - "Other" manufacturer offerings

Come with radiation "ratings" from governments/manufacturers

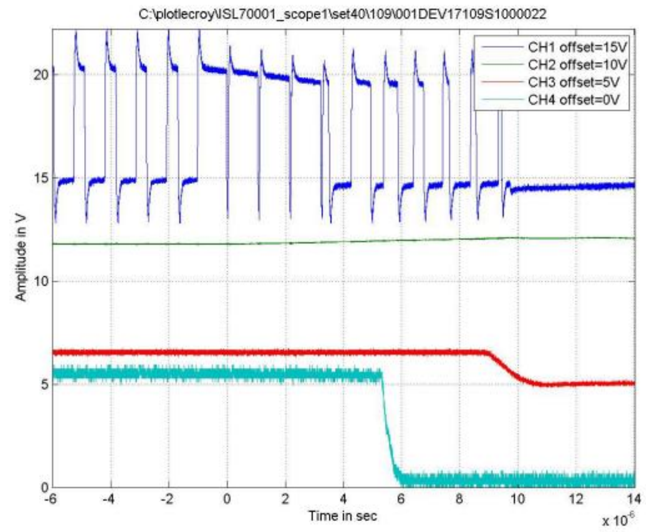
- Historical ground-based radiation test data
- Historical flight usage
- Unknown assurance – new device/technology or one with no data or guarantee

Guaranteed hardness

- A limited number of semiconductor manufacturers, either with fabs or fabless, will guarantee radiation performance of devices - Examples: Frontgrade, Honeywell, BAE Systems, etc.
- Radiation qualification usually is performed on either one or multiple of
  - Qualification test vehicle,
  - Device type or family member, or
  - Lot specific qualification
- The devices themselves can be hardened via
  - Process or material (RHBP or RHBM),
  - Design (RHBD), or
  - Serendipity (RHBS)
    - Nothing specifically has been done to harden / Test results show sufficient tolerance
- Some vendors sell “guaranteed” radiation tolerant devices by “cherry-picking” commercial devices coupled with mitigation approaches external to the die such as SEL mitigation or shielding, the number of these are increasing steadily
- Need to consider TID, TNID, and SEE – not all are always guaranteed either by MIL-STD slash sheets or the manufacturer’s testing budget – you will most frequently see TID ratings and nothing else

Example: Hardened but does have response

- Datasheet lists
  - TID, dose rate of testing
  - SEE threshold of destructive effects with access to a report



Note: Blue trace shows four full-width LX pulses followed by current limited LX pulses and overcurrent protection shutdown. Red trace shows soft-start discharge. Aqua trace shows a PGOOD fault.

Figure 11. Non-Benign SET at LET = 43.2MeV/mg/cm²

intersil™ Datasheet

ISL71001SLHM

Radiation Hardened 6A Synchronous Buck Regulator with Integrated MOSFETs

The ISL71001SLHM is a radiation hardened and high-efficiency monolithic synchronous buck regulator with integrated MOSFETs. This single-chip power solution operates across an input voltage range of 3V to 5.5V and provides a tightly regulated output voltage that is externally adjustable from 0.8V to ~85% of the input voltage with an output load current capacity of 6A. The ISL71001SLHM is available in a plastic 64 Ld Thin Quad Flatpack (EP-TQFP) package.

The ISL71001SLHM uses peak current-mode control for excellent output load transient response and features integrated compensation and switches at a fixed frequency of 1MHz to reduce component size and count. In applications where two regulators are needed, two ISL71001SLHM devices can be synchronized 180° out-of-phase to reduce the overall input RMS ripple current. The internal synchronous power switches are optimized for high efficiency and good thermal performance.

The ISL71001SLHM incorporates fault protection for the regulator. The protection circuits include input

Features

- Production testing and qualification follow the AS6294/1 standard (see Radiation Hardened Plastic Production and QCI Flow)
- Passes NASA low outgassing specifications
- Operates from 3V to 5.5V supply
- Current mode controlled feedback
- Fixed 1MHz switching frequency
- ±1.2% reference voltage
- Highly efficient: 95% peak efficiency
- SYNC pin allows synchronization of two devices
- Adjustable output voltage
- Output undervoltage and output overcurrent protection with power-good output voltage monitor
- Radiation acceptance testing - ISL71001SLHM
  - 75krad(Si) at a low dose rate (< 10mrad(Si)/s)
- SEE hardness (see SEE report for details)
  - Single-event effects at LET = 86MeV•cm²/mg

Example: DLA might only cover TID

- 5962-8992901VXA

1.2.1 RHA designator. Device classes Q and V RHA marked devices meet the MIL-PRF-38535 specified RHA levels and are marked with the appropriate RHA designator. A dash (-) indicates a non-RHA device.

- RHA Designator: **Section 1.2.1** of the Standard Microcircuit drawing.
  - Non-RHA device in this case. Probably going to need some level of testing of other data can't be found.
- **Section 1.5** (usually) has information on the dose rate and total dose when available. These may differ for different device types, the "yy" in the part number.
- **Section 4.4.4** will have even more detail.

PMIC N/A	PREPARED BY RICK OFFICER	DLA LAND AND MARITIME COLUMBUS, OHIO 43218-3990 http://www.dla.mil/landandmaritime
STANDARD MICROCIRCUIT DRAWING THIS DRAWING IS AVAILABLE FOR USE BY ALL DEPARTMENTS AND AGENCIES OF THE DEPARTMENT OF DEFENSE	CHECKED BY RAJESH PITHADIA	
	APPROVED BY RAYMOND MONNIN	MICROCIRCUIT, LINEAR, PRECISION 1.2 V VOLTAGE REFERENCE, MONOLITHIC SILICON
	DRAWING APPROVAL DATE 00-05-22	
AMSC N/A	REVISION LEVEL C	SIZE A · CAGE CODE 67268 · 5962-89929 · SHEET 1 OF 8

RHA Prefix	*Total Ionizing Dose Level*
M	3K RADS
D	10K RADS
P	30K RADS
L	50K RADS
R	100K RADS
F	300K RADS
G	500K RADS
H	1000K RADS

Example: JANSR2N2222A (100K RADS)
JANSF2N7261 (300K RADS)

Historical ground-based radiation test data

- The number of parts investigated for their radiation response has dramatically increased due to capability enhancing functions and system performance
- You have to know what you are looking for and particularly what is the driver in your environment as well as what could be possible in the device

Example: known radiation response, no guarantees

- Datasheet has no radiation guarantees
  - TID was done on multiple lots
  - SEE testing was done for another program
    - Nothing destructive found
    - Single event transients captured to inform design
  - Publicly available

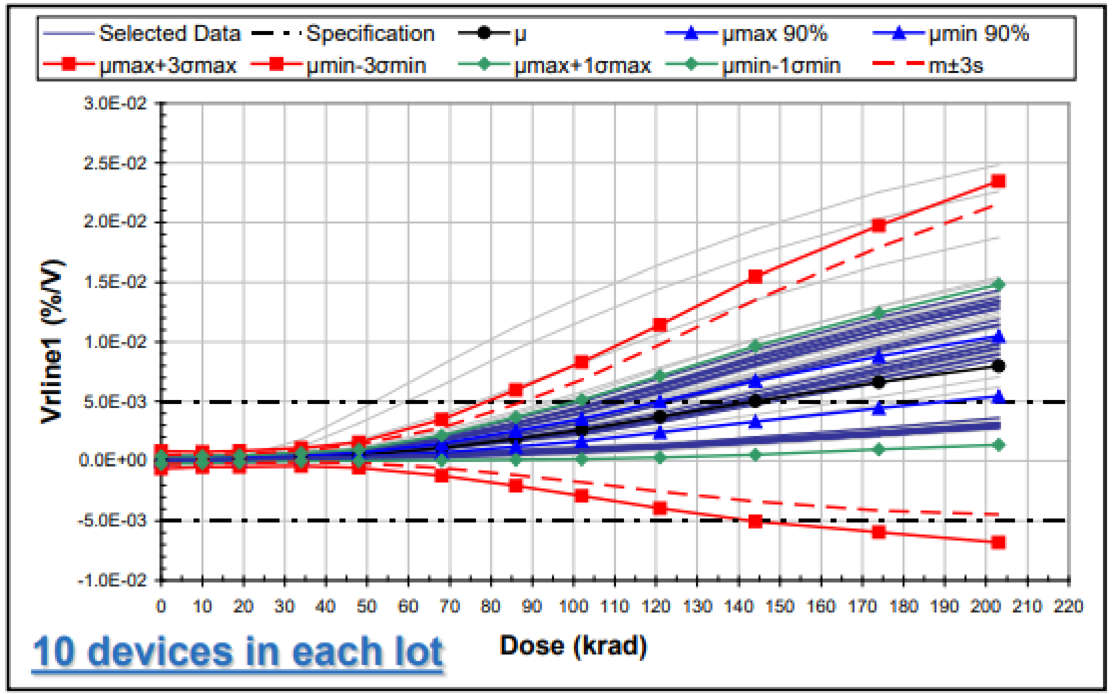
CONCLUSION

SEU test have been conducted on AD584 Voltage Reference from Analog Devices, using the heavy ions available at the University of Louvain facility.
SEU susceptibility was obtained through the cross section versus LET curve for two different transient amplitude ranges (small and medium, respectively 20 mV-312 mV and 312 mV-5,0 V).

On Figure 4, it can be seen that negative transients of up to approximately 1,8 V and positive pulses of less than 500 mV, have been observed. However, it might not be the worst case as the waveform envelop was recorded for few runs only.

These transients may affect circuits connected to the output of the DUT. Specific analysis is recommended for XMM particular applications.

Lastly, no SEL has been detected during the different runs performed on the two samples.



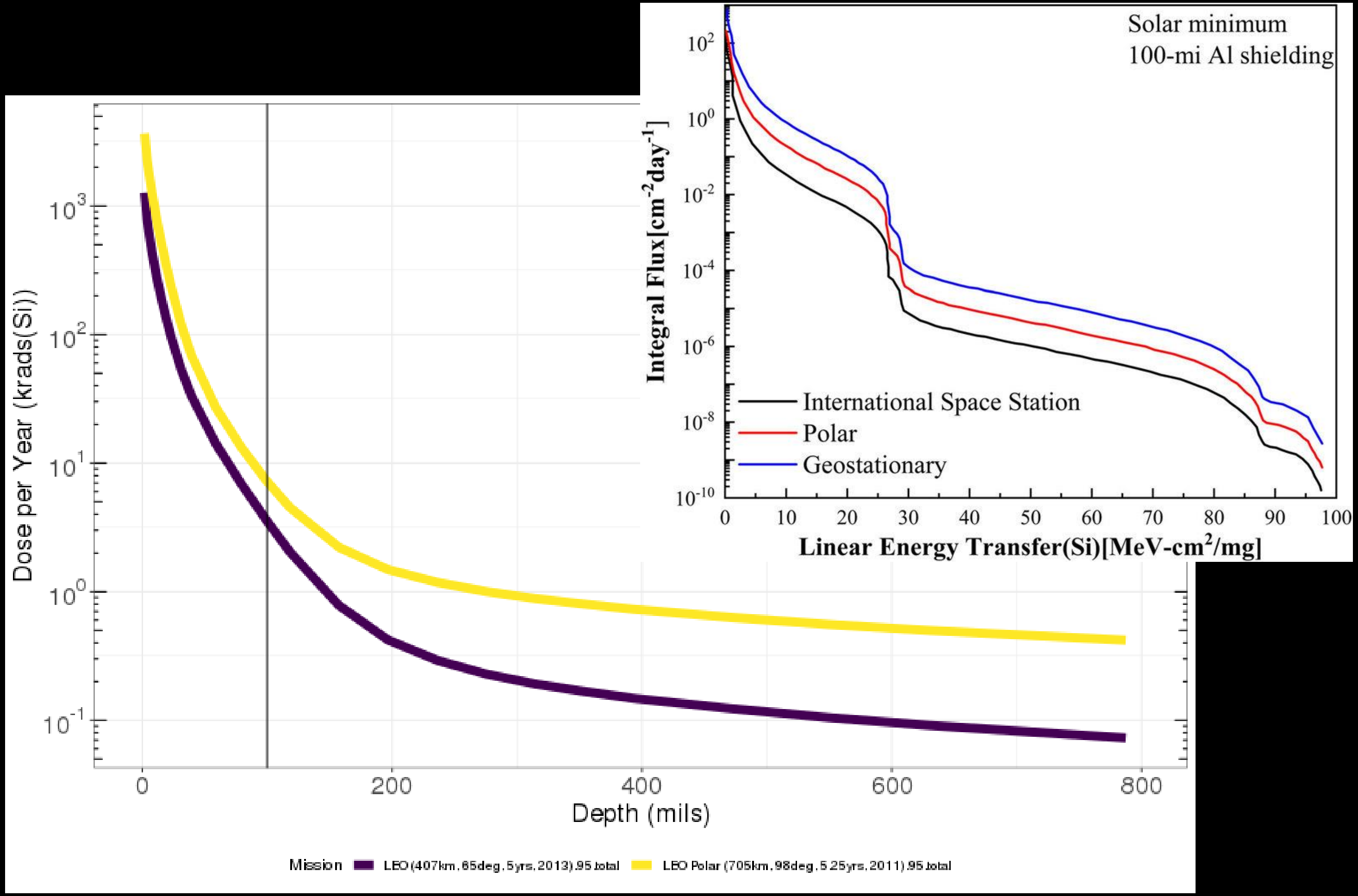
(3 lots plotted in grey, 30 selected devices in blue)

Historical flight usage

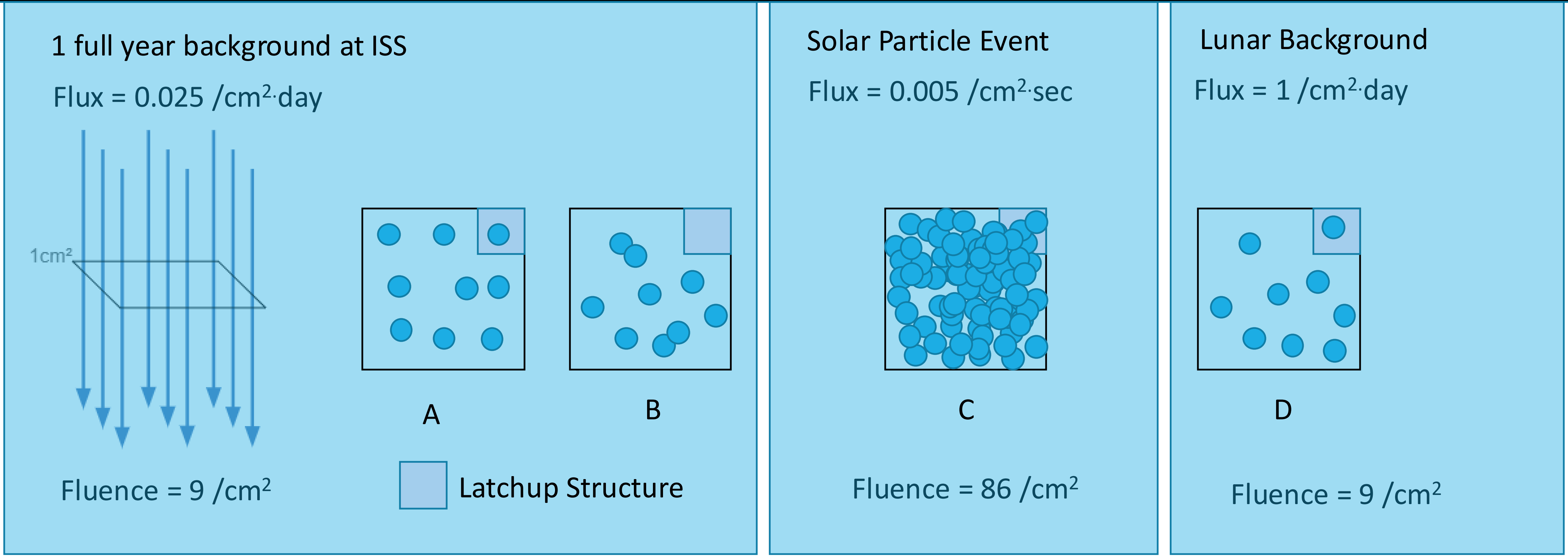
- Can we make use of parts with flight heritage and no ground data for new mission?
- Similar flow to searching for ground test data, but consider
  - Statistical significance of the flight data
    - Environment severity?
    - Number of samples?
    - Length of mission?
    - Application,
  - Process changes, LDCs, etc.
  - Has storage of devices affected radiation tolerance or reliability?
  - And so forth
- This approach is rarely recommended by the radiation expert

Example

- 1-Year success in LEO
  - Parts absorbed 2 krad(Si)
  - 500 SEE recorded in a memory during that year
- Will this work for a 1-year polar mission?
  - Parts will absorb 6 krad(Si)
  - Order of magnitude more SEE with SAA and particles at poles



Just LET > 10 $MeV{\cdot}cm^2/mg$



Mission A – Device latches up catastrophically
Mission B – Same duration as mission A, but no effect seen
Mission C – 1 day solar particle event
Mission D – Lunar orbit for 9 days

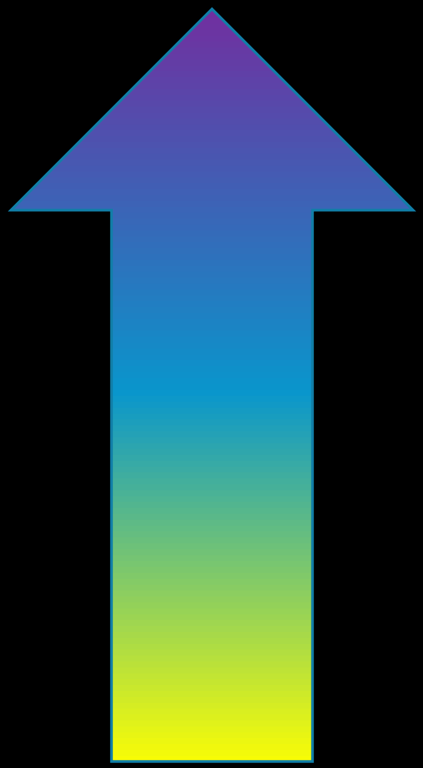
This ignores directional effects and is meant to be a simple example of why on-orbit heritage does not work for DSEE

Unknown assurance

- So what do we do with a part that has no data, family data, process history, etc..?
- Easy answer is to test, but
  - Again, look at it’s usage/criticality in the system and mission profile
  - Possible exceptions to testing include
    - Operational - Ex., The device is only powered on for a very short duration per orbit and the sensitive time window for a SEE is minimal
    - Acceptable data loss - Ex., System level error rate may be set such that data is gathered 95% of the time. Use physical device volume and assume every ion causes an upset, this worst-case rate may be tractable.
    - Negligible effect - Ex., A 2 week mission on a shuttle may have a very low TID requirement. TID testing could be waived.
- Some of these type of exceptions would even apply to known sensitive devices

Notional **dose** factors to keep in mind for parts

Inherently difficult to expect nominal operation of your parts

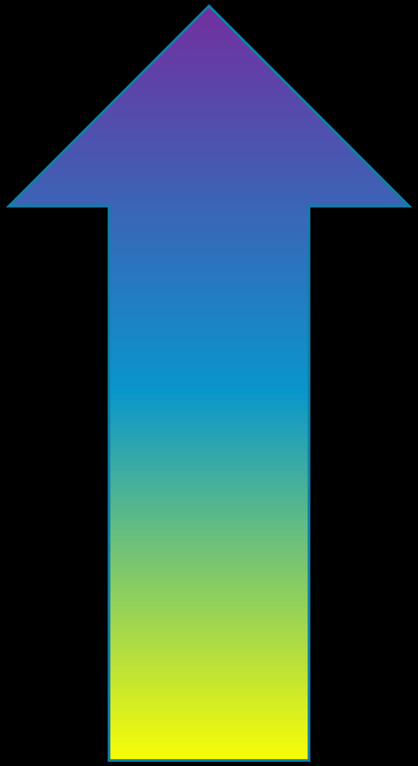


Dose signature predictable

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

Notional **SEE** risk factors to keep in mind

Inherently difficult to expect nominal operation of your parts



SEE signature predictable

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

Parts Selection Questions

- Is there evidence (test data, ratings, or physics of failure) to suggest that there aren't failure modes that will be realized in your system?
  - Could there be destructive SEE?
    - Does the system have a way to accommodate them and return to safe operation?
  - Could non-destructive SEE interrupt your operations?
    - Does the system have a way to accommodate them and return to safe operation?
  - Will the parts survive the full mission when considering dose?
    - Both Ionizing and Non-Ionizing?
- How critical is the part to the design?
  - What functions do you need it to provide?
- What technologies – semiconductor materials – make your part?

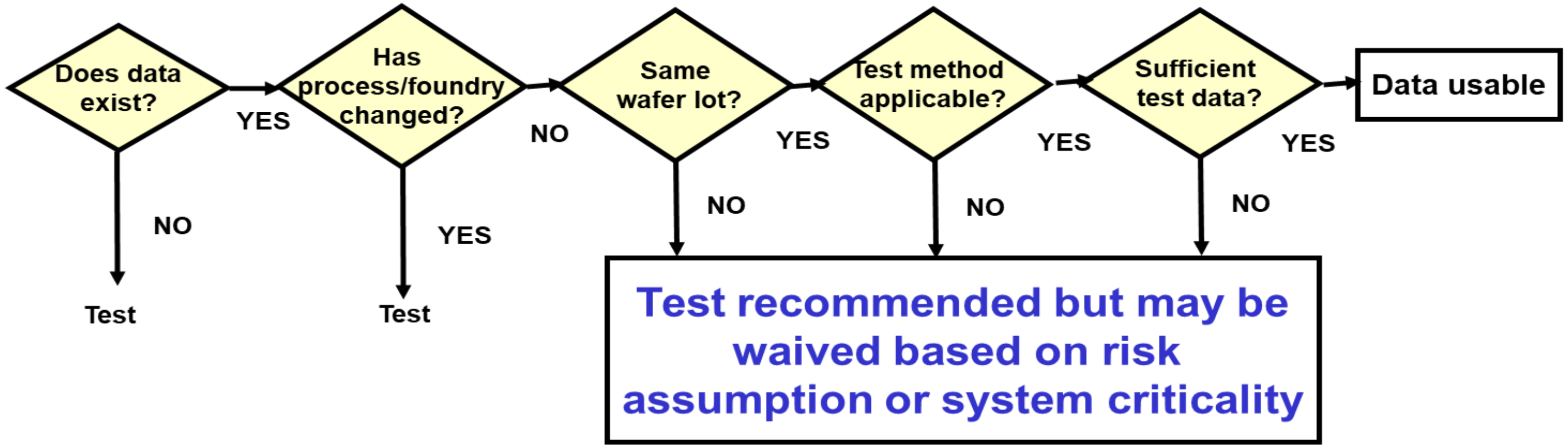
Radiation and process consistency

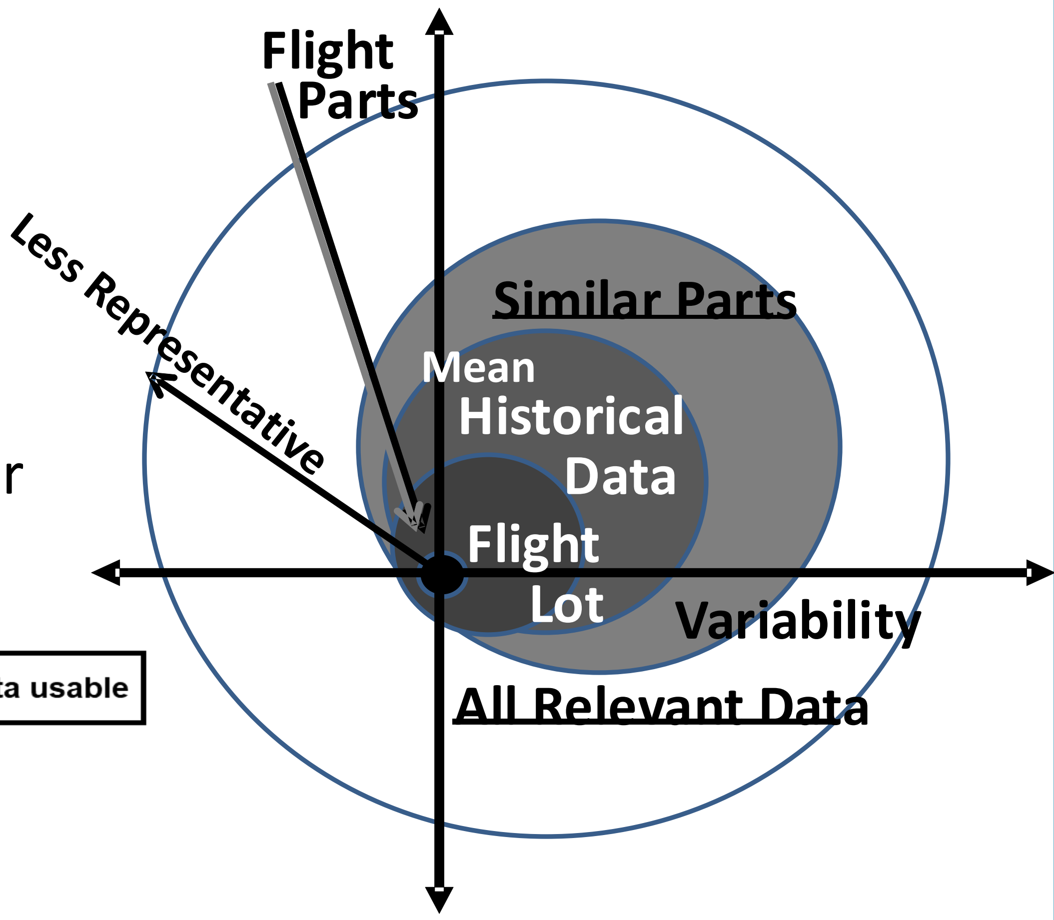
- The technology a device is built with (CMOS, Bipolar, etc…) as well as process particulars (material thicknesses, feature size,…) and electrical characteristics (Vdd, fmax, etc…) are all inter-related for radiation response
- In general, Mil/Aero manufacturers work to control process changes that might impact radiation characteristics while COTS vendors focus solely on improving yield (successful die per wafer)
  - There are examples from both sides where small process changes have impact to radiation tolerance
    - Ex., IR and TID hardness - Stored parts before packaging and no longer had a 100krad part!
    - Analog Devices XFCB process has shown consistent TID performance although many are not RH products
  - The process information is required to determine if the proper physics were used in the testing of the device
    - Example: low vs. high dose rate test or angular effects in memories
  - COTS parts may be a challenge for obtaining just one wafer lot
    - Multiple fabs sometimes produce the same product and not necessarily the same radiation result

Radiation engineer’s dream parts lists

Finding ground-based radiation test data

- Focus on application driven risks
- 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

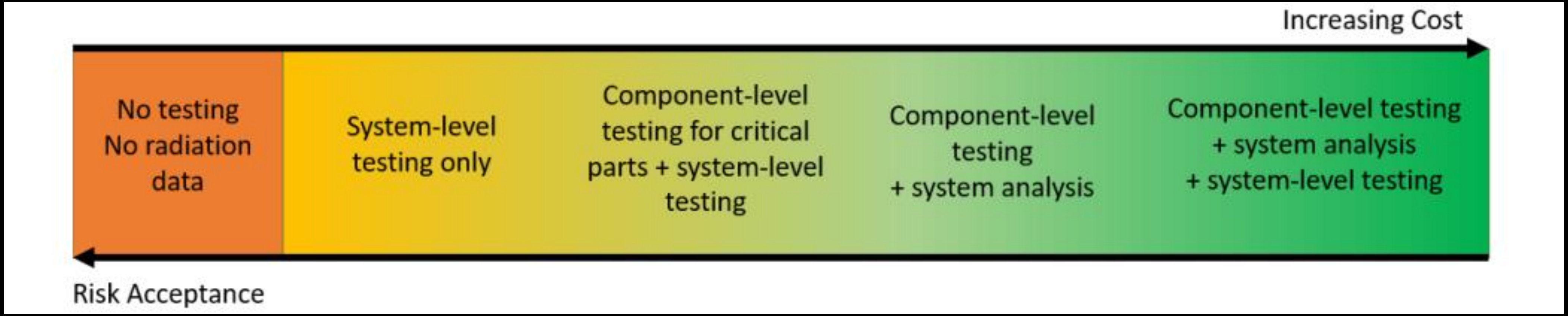
Databases and information

- Radhome – radiation test reports for flight projects and NEPP
  - radhome.gsfc.nasa.gov
- NEPP – publications/reports on technology trends
  - nepp.nasa.gov
- S3VI – data aggregator
  - s3vi.ndc.nasa.gov
- PMPedia – part data and reports
  - pmpedia.space
- NTRS – all REAG publications and presentations that are cleared for public consumption
  - ntrs.nasa.gov
- IEEE Xplore – one stop shop for radiation peer reviewed journal entries (TNS), data workshops, emerging methodologies, etc.
  - Data Workshop from NSREC:
    - https://ieeexplore.ieee.org/xpl/conhome/1000609/all-proceedings/
  - RADECS:
    - https://ieeexplore.ieee.org/xpl/conhome/1000608/all-proceedings/
- Internet search!
- Others out there ESA, JPL, SRHEC/DoD, some pay-for services exist

Interpreting findings

- TID
  - You are searching for lowest krads(Si) where the effect shows up (leakage or functional failure), and what the cumulative dose will be on your mission, you want to have margin
- TNID
  - You are searching for the lowest fluence (p/cm^2) where the effect shows up, and the cumulative fluence will be on your mission, you want to have margin
    - Focus on damage, single energy sources can be used to create damage, it will be important to map your environment into damage caused by a particular energy
- SEE
  - You are searching for LET thresholds where effects start to begin, this will determine how much of the environment spectra can contribute to the frequency of seeing those effects
  - Requirements are often listed as "if < a particular LET, take this action"
  - Rates may not apply to your orbit, you must check that
    - If you need a rate, you need a cross-section of the device

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-Ionzining 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

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
- Rad-hard parts might not be as expensive as you think with testing and analysis

- Mixed Signal and System on a Chip
  - Always going to be performance driven usage of new components
- FPGA types can drive response to focus on
  - Flash
  - SRAM
  - Antifuse
- Memories are
  - Flash, MRAM, FRAM, SDRAM

Complex devices and radiation assurance

Technology Feasibility (show-stoppers)

- **Partnerships**
  - Roadmaps & demand
  - Manufacturer testing
- **Preliminary testing**
  - Process performance
  - Independent verification

Radiation effects community driven:
NASA Electronic Parts and Packaging (NEPP)

Architectural Demonstration

- **Characterization**
  - Availability constraints
  - Corner cases
- **Reliability at extrema**
  - Worst case conditions
  - Physics of failure

Design community driven,
intentional test design

System Assurance

- **Concept of operations**
  - Likelihood in environment
  - Criticality and impacts
- **Requirements verification**
  - Risk quantification
  - Maintainability & validation

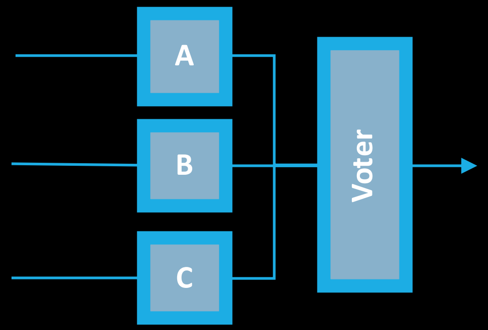
Environment and
end-user/project/program driven

Mitigation

Some typical mitigations

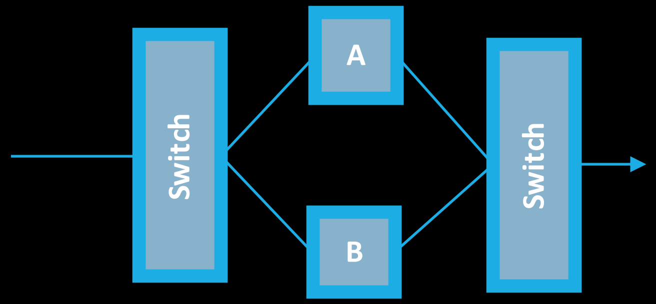
Triple Mode Redundancy

- Using redundancy and voting to mask SEE
- Frequently used in FPGA fabric of combinatorial logic
- Local, Block, Global all have trades associated with SEE response



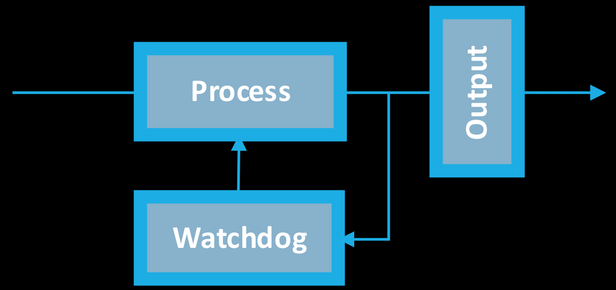
Cold Sparing

- Backup systems that are unpowered and can replace a faulty system (side A/B)
- Will still accrue dose and sometimes errors while in off state



Watchdog Timers

- Feedback loop with expectation of current or power draw
- If operation is not performing check



Example: Derating a 200V MOSFET

Table 7 Typical Single Event Effects Safe Operating Area

Ion	LET (MeV·cm²/mg)	Energy (MeV)	Range (µm)	V_{DS} (V)				
				V_{GS} = 0V	V_{GS} = -5V	V_{GS} = -10V	V_{GS} = -15V	V_{GS} = -20V
Cu	28	285	43	190	180	170	125	—
Br	36.8	305	39	100	100	100	50	—

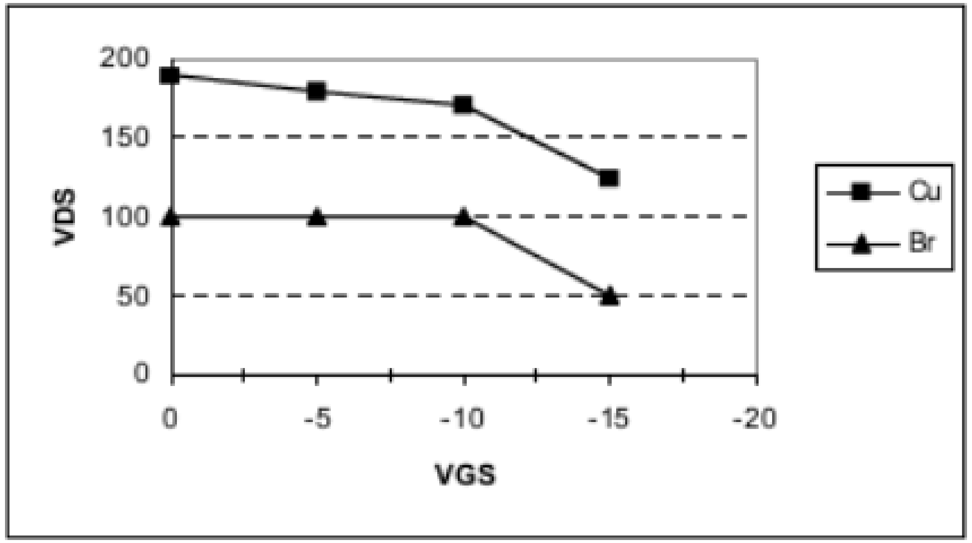
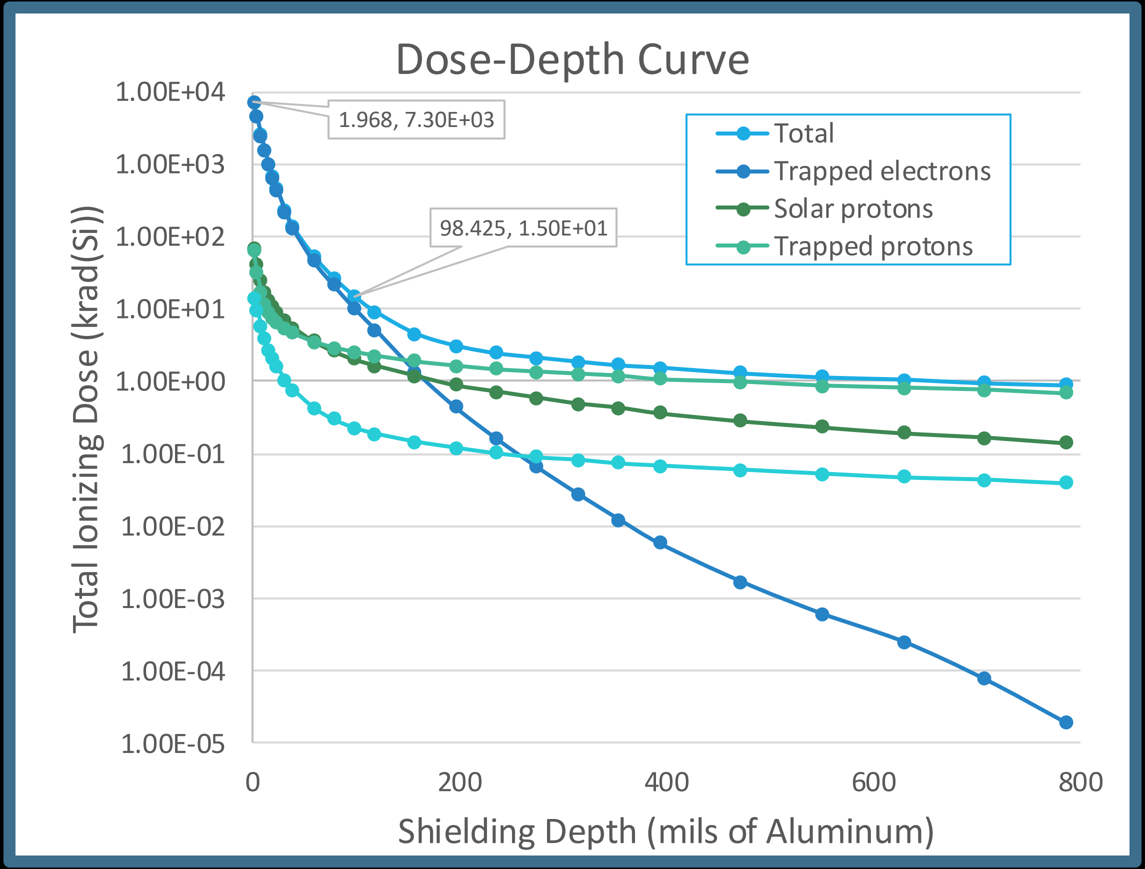


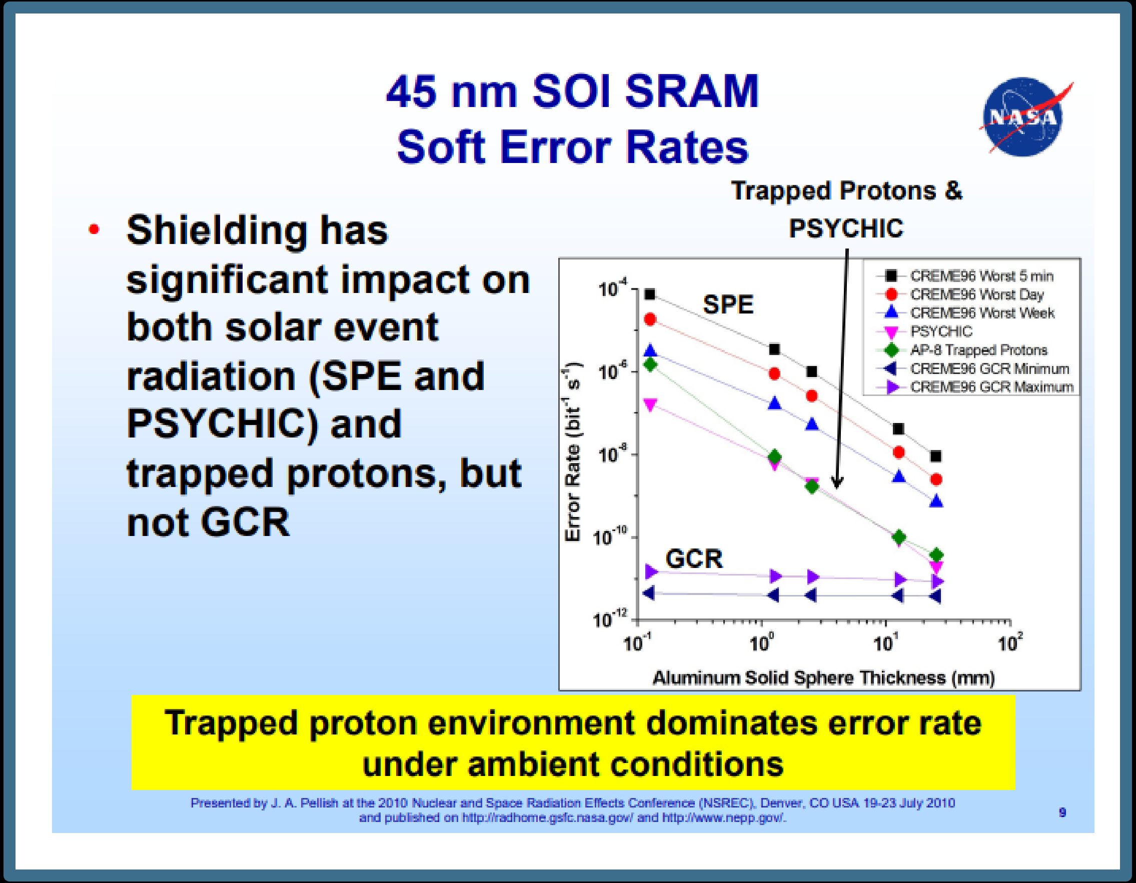
Figure 1 Typical Single Event Effect, Safe Operating Area

Shielding helps – to an extent

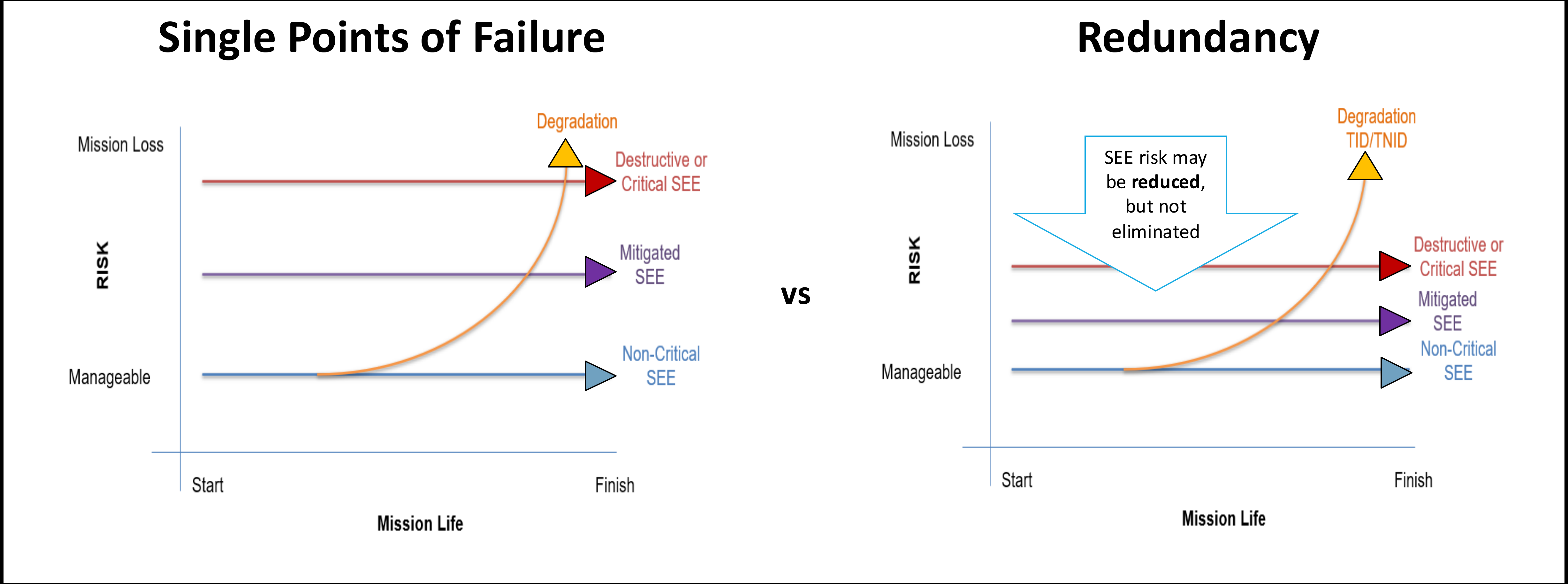
Cumulative Dose



Single Events



Redundancy works for some applications



Redundancy does **not** remove SEE risk; it reduces impact. Common failures like TID still exist.

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

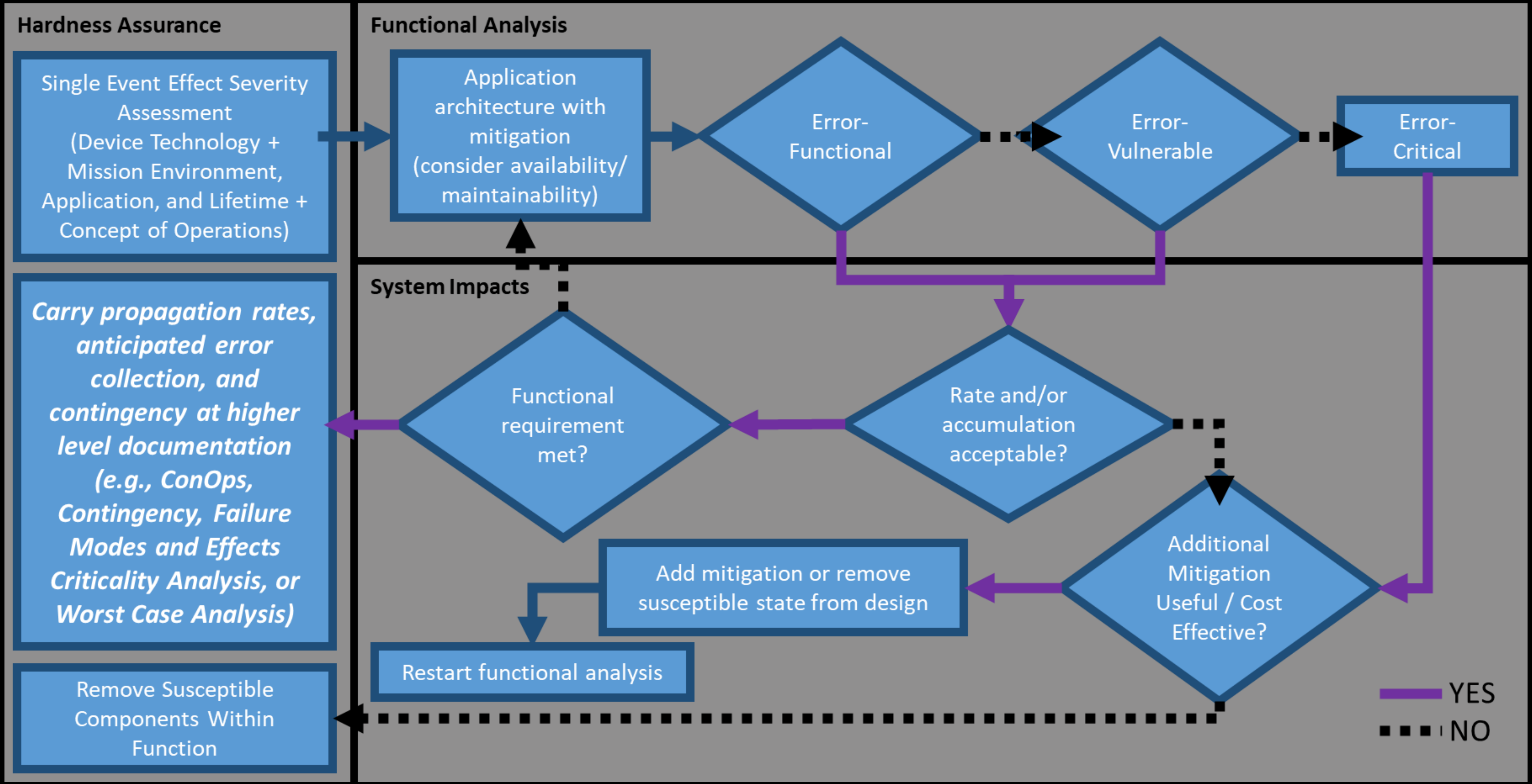
Error-Vulnerable

- 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

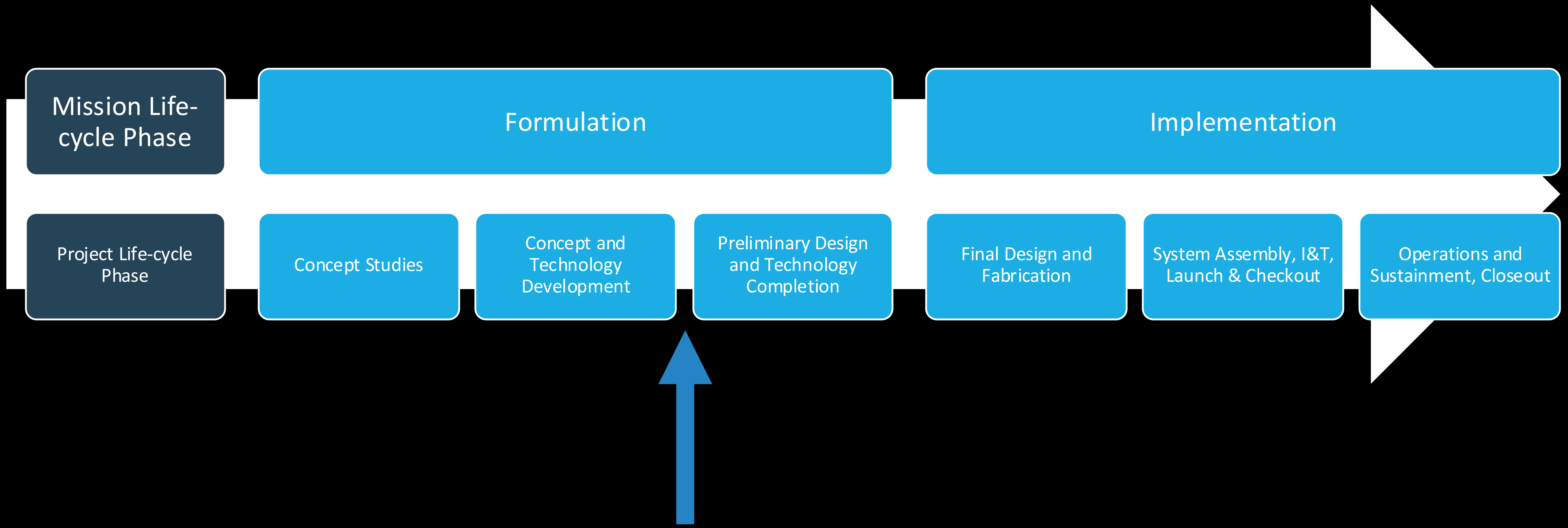
- SEE signature not allowable
- Disruption of function identified as single point of failure or design cannot continue to perform after SEE
- Mitigation needed in order to be reclassified as error-vulnerable (e.g. destructive SEL, many error accumulation, boot image corrupted due to error accumulation, 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)

Timing is everything

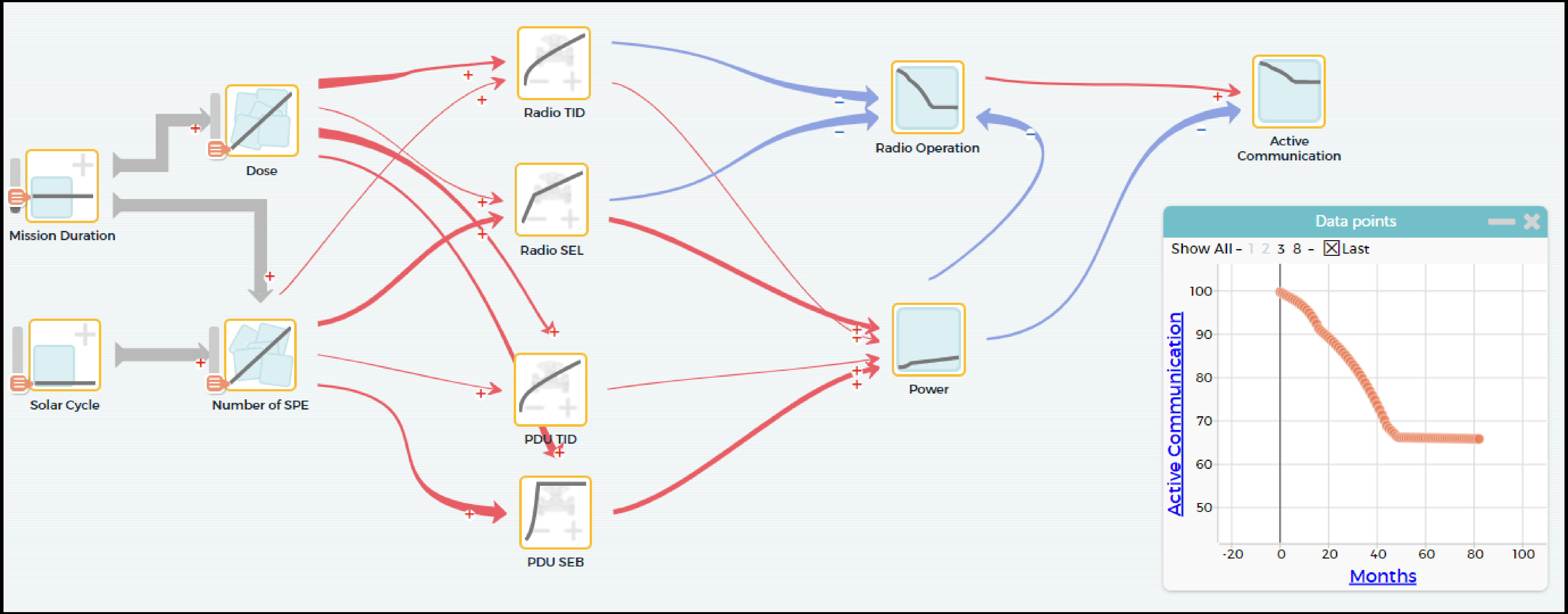


Last Call for Radiation Tests

Systems of systems

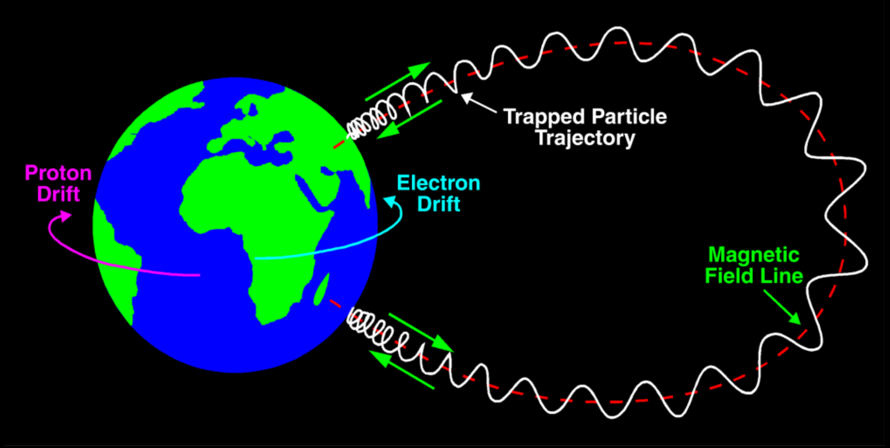
- How do we assess a sub-assembly (RWA, Radios, PDU, CDH, etc.)?
  1. Ask for BOM, work with radiation engineer
  2. Ask for their radiation assurance approach and how they've defined critical parts to the design (worth invoking through requirements)
  3. Beware of radiation ratings for a sub-assembly
     1. Top level numbers are murky if testing was done at assembly level
     2. Heritage claim or hours in flight need to be investigated for actual environment outcomes
  4. Many of the key points on redundancy, shielding, and mitigation apply at this level of abstraction as well, you may not be solving the highest risk or adding risk by trying to overcompensate
  5. Plan for impacts, focus on critical functions

System-level modeling



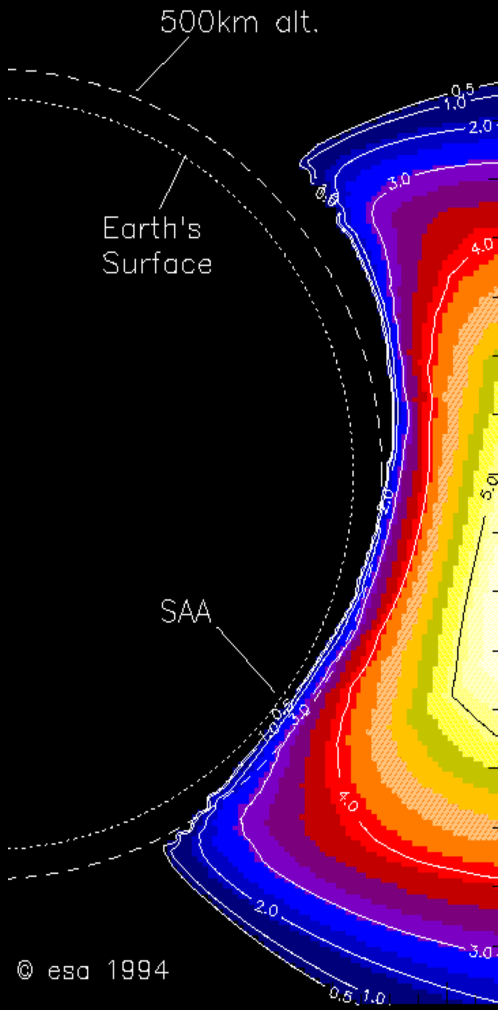
Common pitfalls

- 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



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 - NSE Tools (nasa.gov)
- Rate Calculations
  - CRÈME – https://creme.isde.vanderbilt.edu/



Agency level support

Office of the Chief Engineer

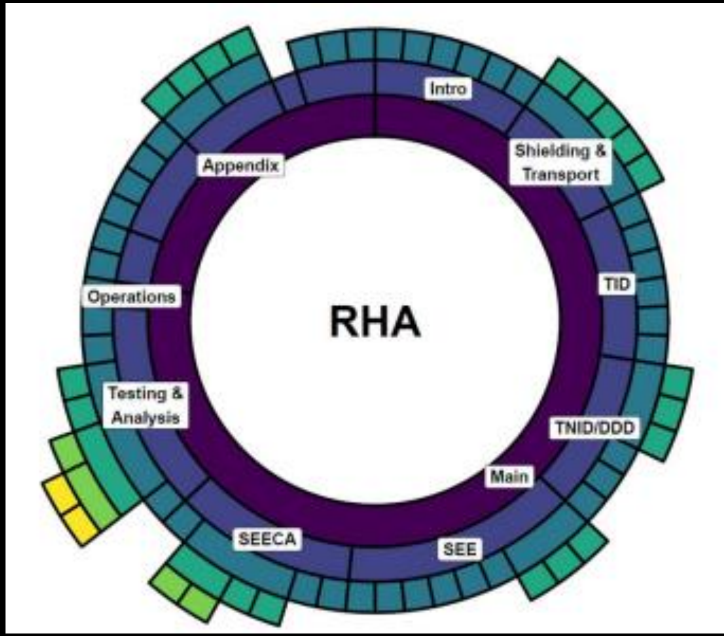
NASA Engineering and Safety Center

Contacts:
Pete Majewicz – PM
Susana Douglas - Deputy

Communities of Practice:
Bob Hodson – Avionics
Ray Ladbury – Radiation
Yuan Chen – EEE Parts
Joe Minow – Space Environments

NASA RHA Guidelines and Standardization

- Avionics Radiation Hardness Assurance (RHA) Guidelines (NESC-RP-19-01489)



- NASA technical standard for RHA to be released
  - Schedule of activities
  - Taxonomy

	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)

Big Takeaways

- Use the parts that get you the science you want
  - Gather relevant information on the process and pathfinding tests from research publications
  - Avoid pitfalls by not just using the newest thing because it’s new
  - 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
- Only add mitigation where you need it
  - Use shielding wisely -- A little bit of shielding goes a long way! Not joking, Reynolds wrap if you have to
  - Adding complexity can create more problems
- Radiation testing plays a crucial role
  - For pre-existing data, representation is caveat emptor
  - Application specific driven characterization will give you the best information for engineering trades
  - Test for what you perceive as risk, and think of future missions
- Model your environment
  - Low level efforts for impactful design trades and awareness
  - Radiation sources and intensity vary greatly
- Telemetry like dosimeters or memory upset counts can help with anomaly resolution

Thank you

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