Modern Hardness Assurance: A Brand New Game Except When it Isn't

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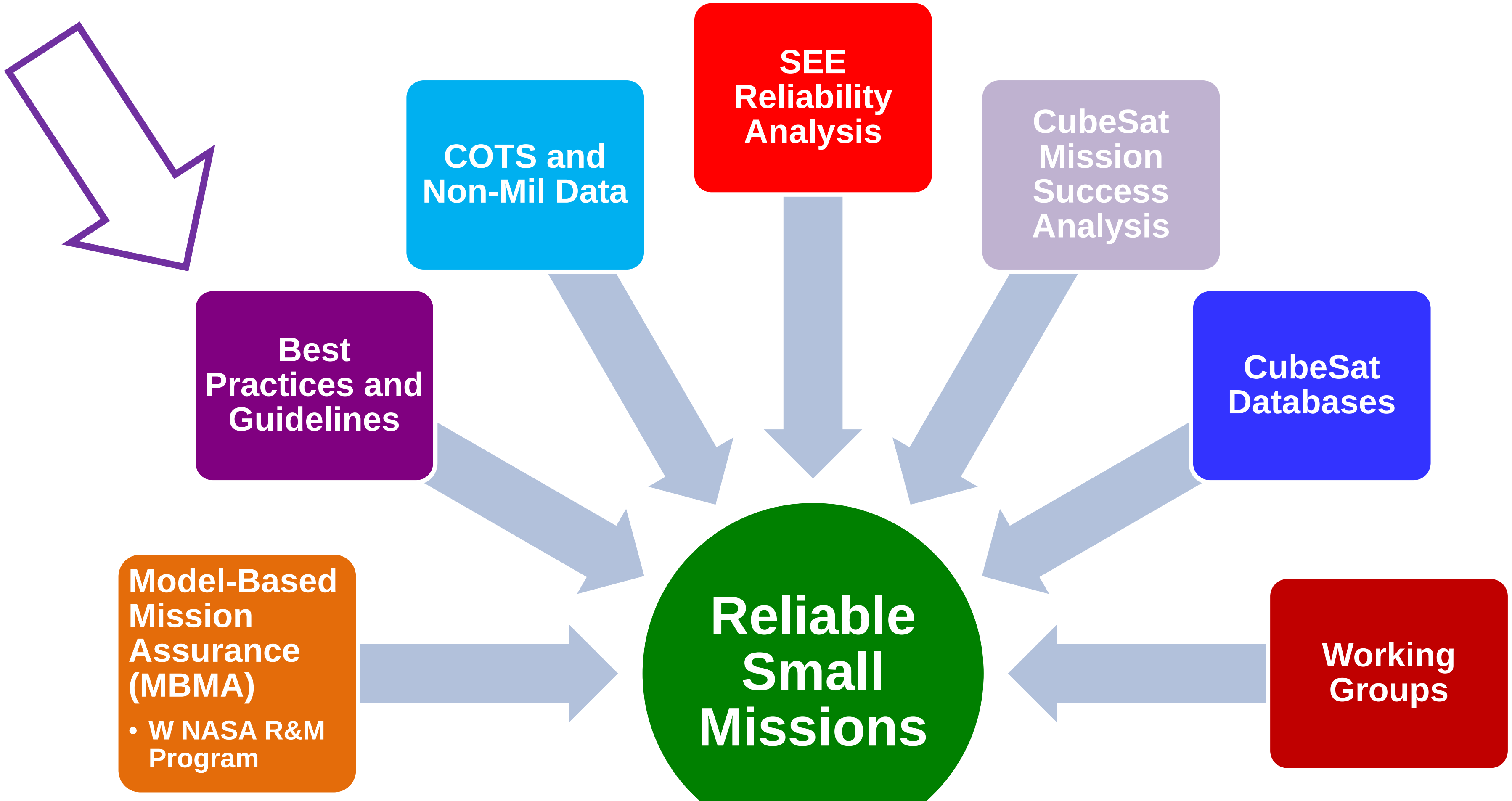
To be presented by Michael J. Campola at the 2019 SEE-MAPLD Single Event Effects (SEE) Symposium and Military and Aerospace Programmable Logic Devices (MAPLD) Workshop, La Jolla, CA, May 20-23, 2019.

Acronyms

COTS	Commercial Off The Shelf
DD	Displacement Damage
GEO	Geostationary Earth Orbit
GSFC	Goddard Space Flight Center
LEO	Low Earth Orbit
LET	Linear Energy Transfer
MBU	Multi-Bit Upset
MCU	Multi-Cell Upset
NEPP	NASA Electronic Parts and Packaging

RDM	Radiation Design Margin
RHA	Radiation Hardness Assurance
SEB	Single Event Burnout
SEDR	Single Event Dielectric Rupture
SEE	Single Event Effects
SEFI	Single Event Functional Interrupt
SEGR	Single Event Gate Rupture
SEL	Single Event Latchup
SOA	Safe Operating Area
TID	Total Ionizing Dose

NEPP - Small Mission Efforts



* NASA Reliability & Maintainability

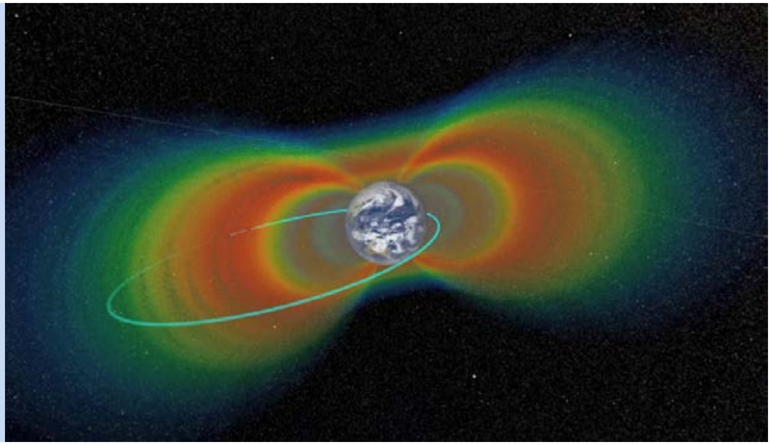
Outline

- **New Space and SmallSat Considerations**
- **The Natural Space Radiation Environment Hazard**
- **Radiation Effects on Micro-Electronics**
- **Hardness Assurance, as a Discipline, with its Challenges**
  - **New Technologies**
  - **New Architectures**
  - **Unbound Risks**
- **Building Smart Requirements**
- **Risk Acceptance and Guidance**

New Space & SmallSats – Same Old Radiation

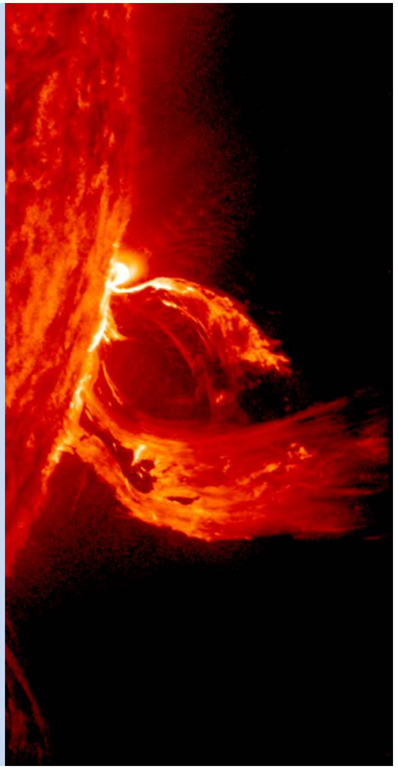
- **The need for Radiation Hardness Assurance (RHA)**
  - Radiation effects are a mix of disciplines, evolve with technologies and techniques
  - Misinterpretation of failure modes / misuse of available data can lead to over/under design
- **New mission concepts and SmallSat paradigm**
  - Challenges identified in the past are here to stay; adoption of new technologies are often the risk driver
  - Commercial Space, Small missions, Constellations will benefit from detailed hazard definition and mission specific requirements
  - RHA flow doesn't change, risk acceptance needs to be tailored
- **Some Top Level Resources**
  - NPR 7120.5 – NASA Agency Program Management
  - GPR 8705.4 – Goddard Risk Assessments

Trapped Radiation



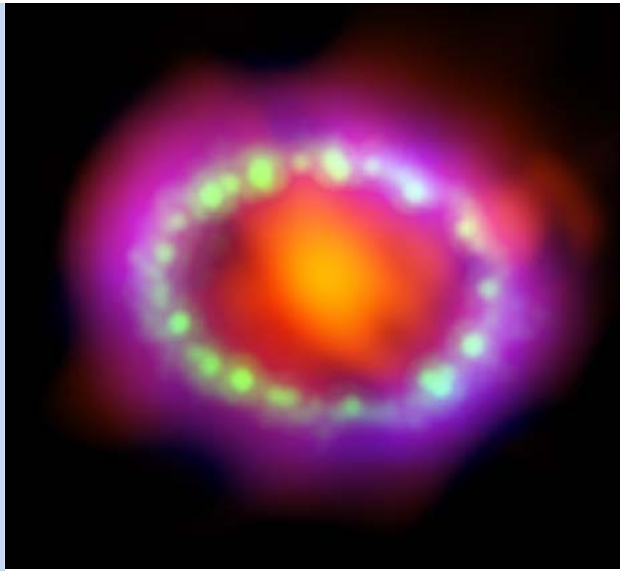
https://www.nasa.gov/van-allen-probes

Solar Events & Activity



https://sdo.gsfc.nasa.gov

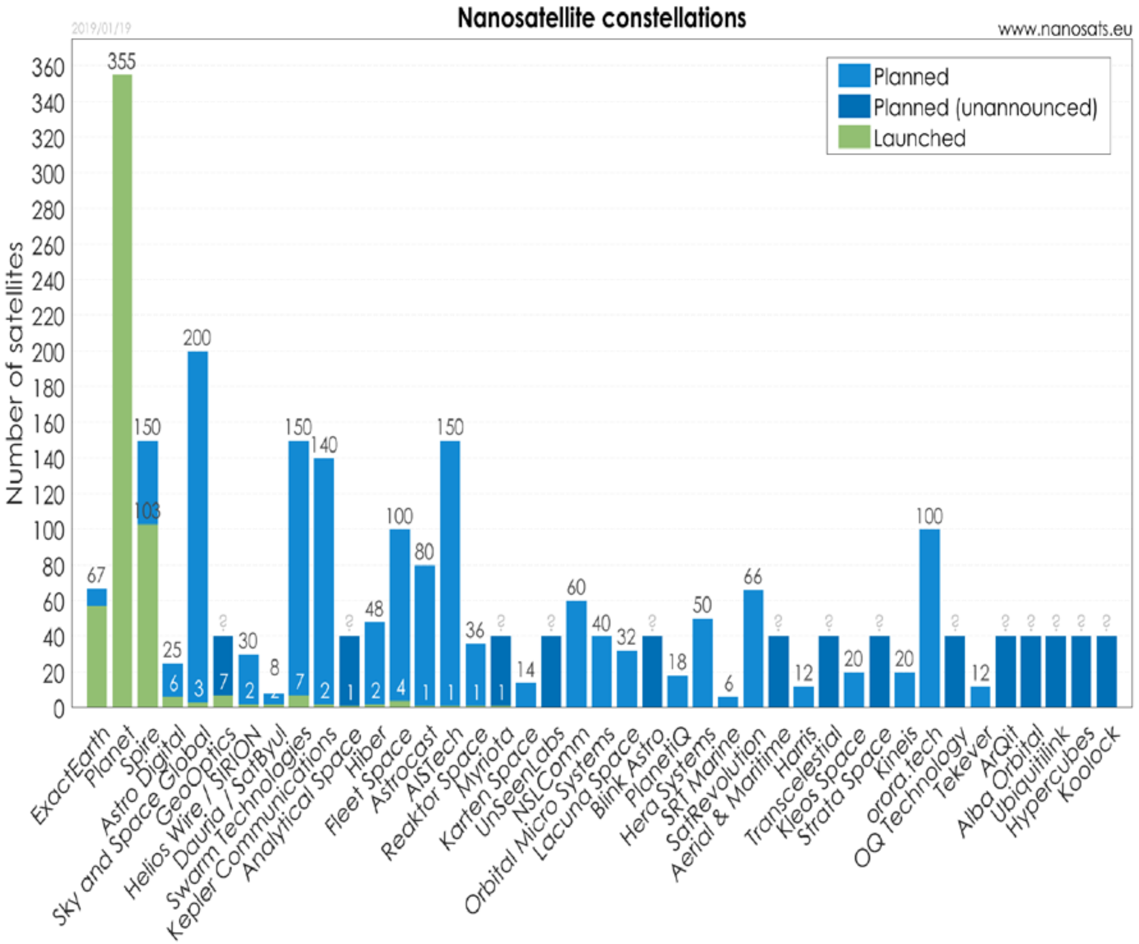
Supernovae



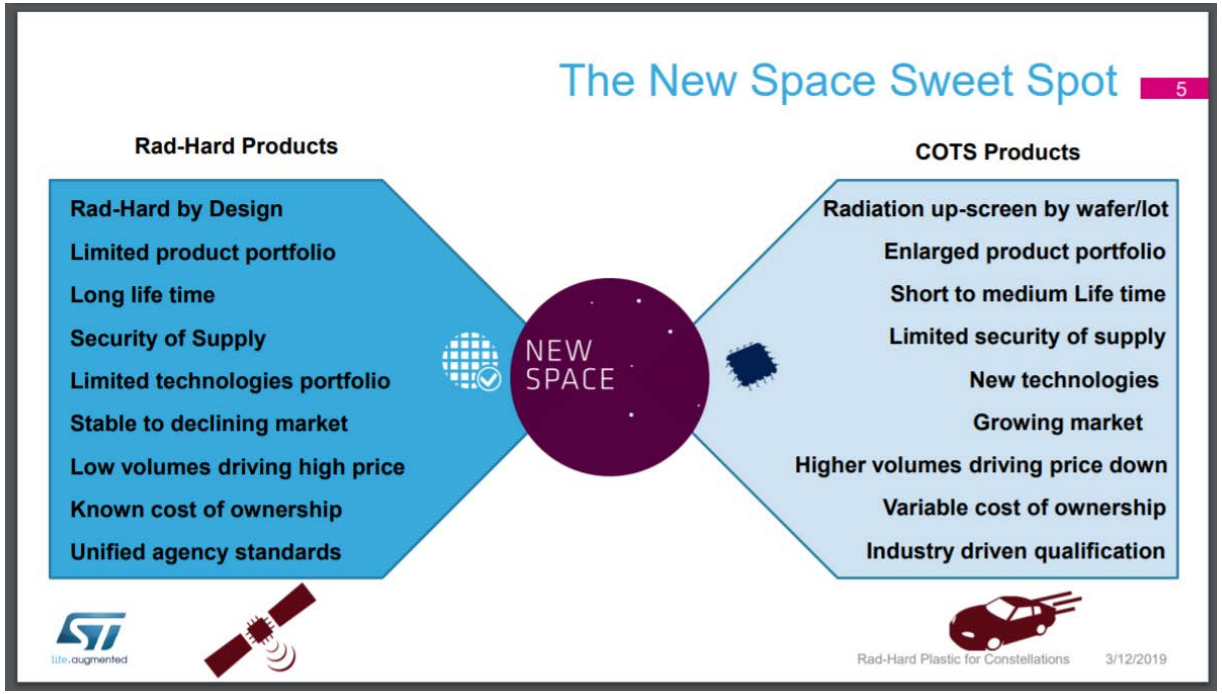
NASA, ESA, and L. Hustak (STScI)

New Space – New Point of View

SmallSats / Constellations / Swarms



Component Grades are Merging



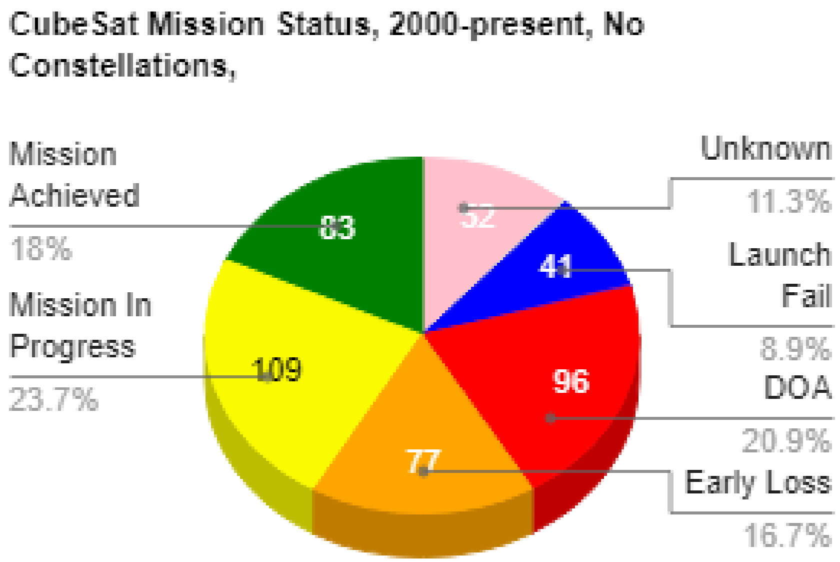
ESSCON : Eccofet

Risk acceptance is being used as a means to enable innovation

Who Needs This Guidance?

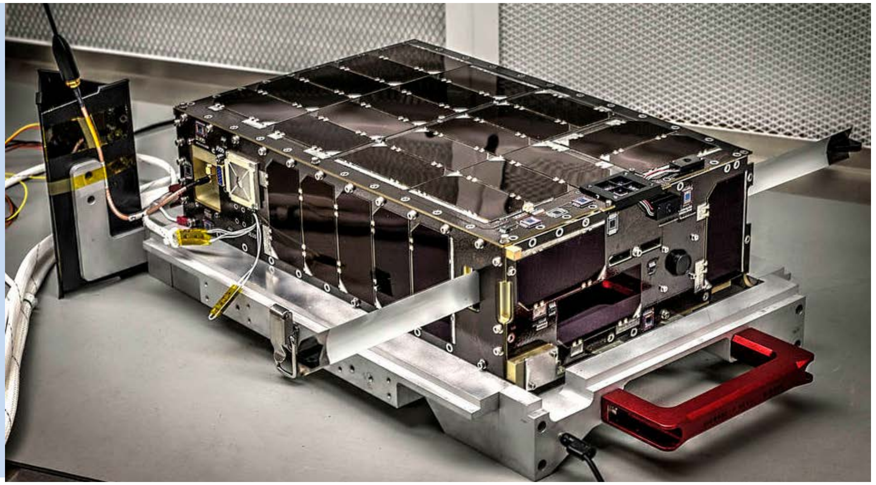
- **Universities / CubeSats**
  - May be first-time designers, or previous missions did not have requirements
  - Schedule driven, limited time for development
  - Rideshares – could end up in multiple environments
- **Space Agencies / Government**
  - More designs in new destinations
  - Cost savings of SmallSat platform, with more reliable outcome
  - More risk acceptance
- **Device / Subsystem Manufacturers**
  - Product / Device offerings (middle of the road seems to be the target)
  - Fault tolerance in designs

CubeSat Metrics



Michael Swartwout, SLU CubeSat Database

Dellingr



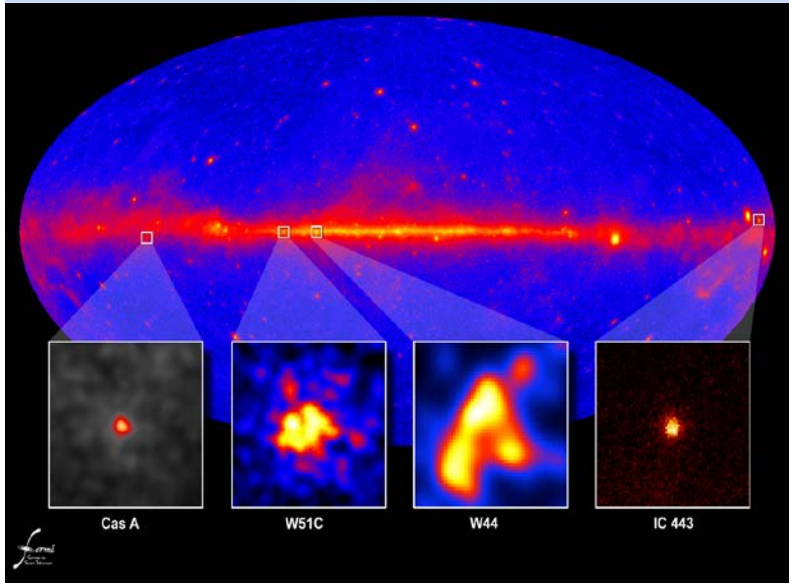
NASA's Goddard Space Flight Center/Bill Hrybyk

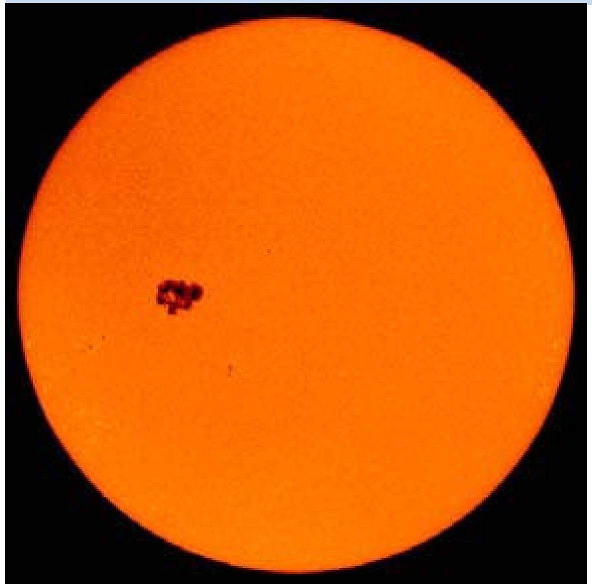
Notional Questions to Keep in Mind

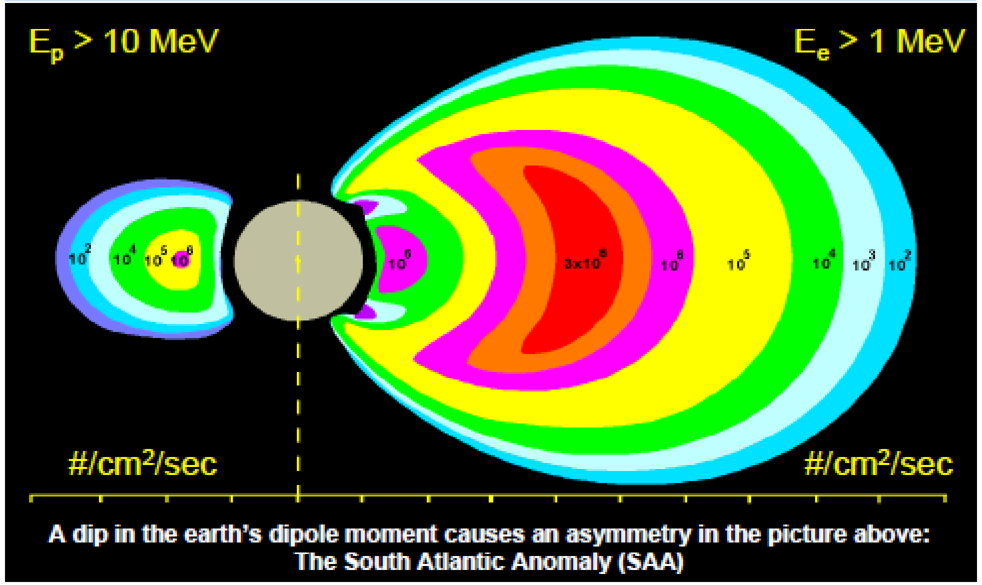
- What are the radiation risks:
  - What is the hazard?
  - What are the challenges?
- What can you do to reduce the risk for a given hazard?
- How do *similar* systems/devices react in the space environment?
- What does changing that radiation environment mean for success?
- Need availability throughout the mission or at specific times?

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

Solar Wind, Solar Cycle
CMEs (proton rich)
Flares (heavy ion rich)

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

Natural Space Radiation Environment

- Plasma
- **Particle Radiation**
- Neutral Gas Particles
- UV and X-Ray
- Orbital Debris

wear-out

Degradation of micro-electronics
Degradation of optical components
Degradation of solar cells

instantaneous

Data corruption
Noise on images
System shutdowns or resets
Circuit Damage
Part tolerances exceeded

Spacecraft Charging, Ionizing Dose, Non-Ionizing Dose, Single Event Effects, Drag, Surface Erosion, Debris/Micro-Meteoroid Impacts, Thermal Cycles

Natural Space Radiation Environment

- **Particle Radiation**

wear-out

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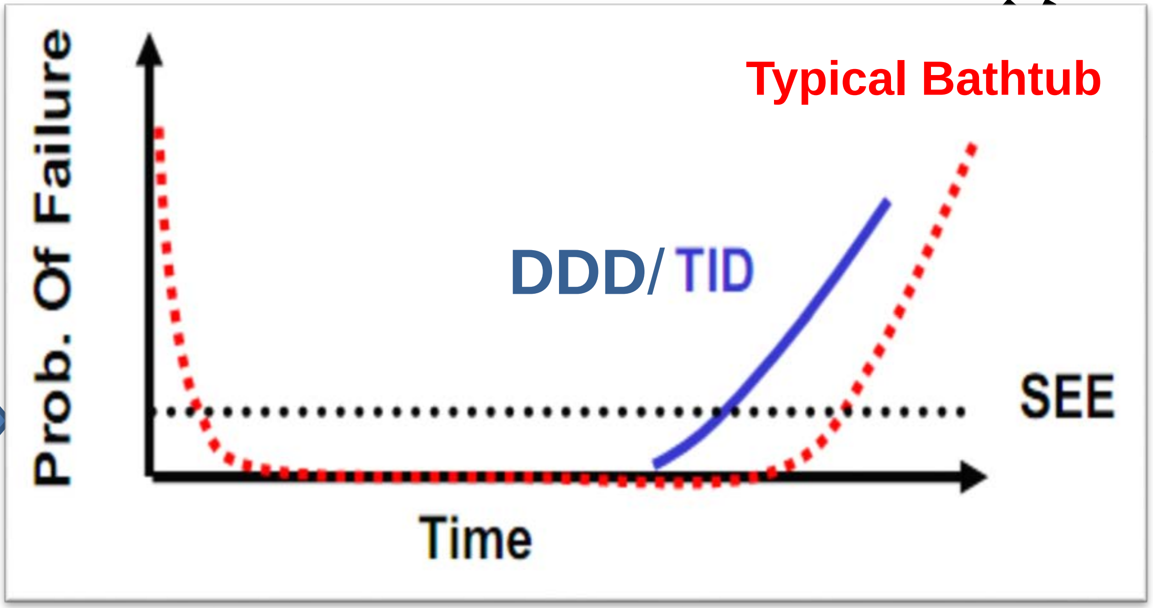


Units explanation

Degradation

- **Total Ionizing Dose (TID)**
  - Absorbed Dose (rad(Si))

    1 rad = 100 erg/g = 0.01 J/kg; 100 rad = 1 Gy
  - Always specified for a particular material

    1 rad(SiO2), 10 krad(Si), 100 Gy(H2O)
  - This is not exposure (R), or dose equivalent (Sv)
- **Non Ionizing Energy Loss (NIEL)**
  - Fluence (p/cm2)

    Number of particles per unit area

Single Events

- **Linear Energy Transfer (LET)**
  - Stopping Power Normalized to target material

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

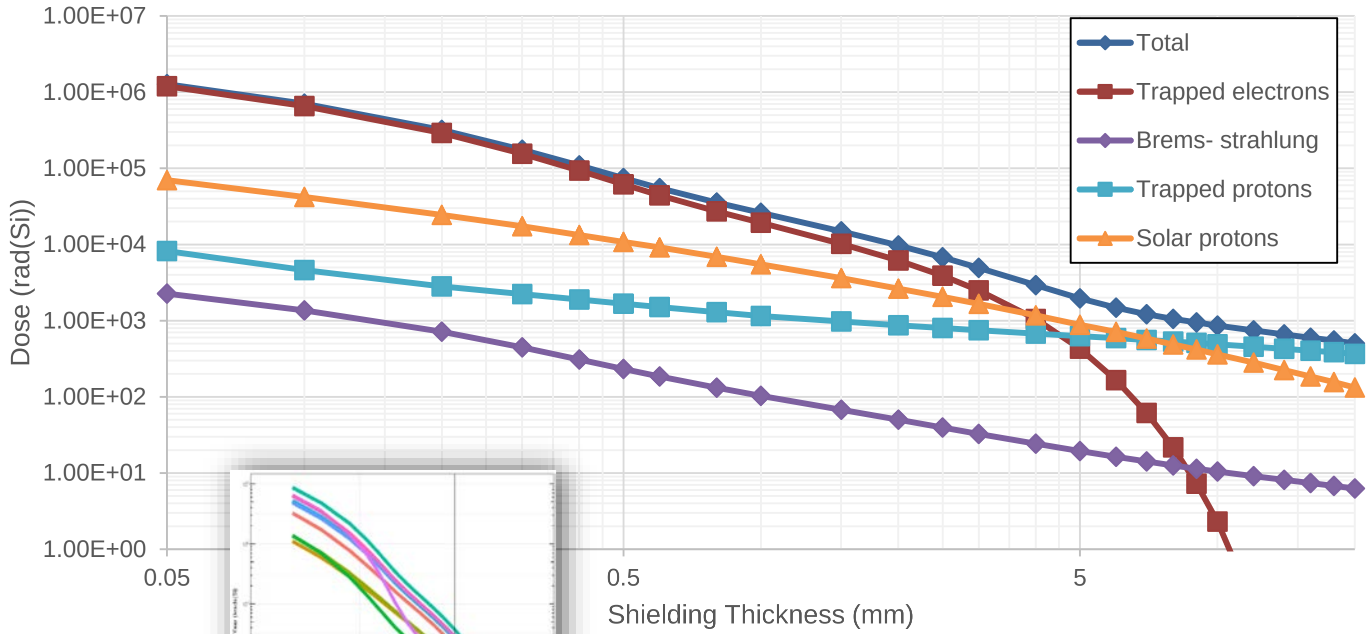
  - Units are MeV·cm^2/mg
  - Rate (/device or /bit per time interval)

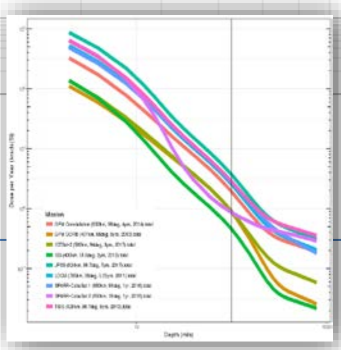
Degradation Contributors vs. Single Event

- **Cumulative effects**
  - Depend highly on which contributors and duration in their presence
  - Mimic wear-out/aging
  - NIEL and TID must be accounted for
- **Typical destinations (LEO, GEO)**
  - LEO at low altitude/inclination is more protected by the Geomagnetic field
  - Proximity to the poles & SAA show a large variability in dose despite short mission durations
  - Electrons and their braking radiation are the big offender in Geostationary orbits (don't forget about spacecraft charging…)
- **Note that**
  - A little bit of shielding goes a long way
  - Altitude plays a huge role when in/near the radiation belts (even transiting)
  - Beyond Geomagnetic field, highly variable solar environment contributions (Solar cycle)

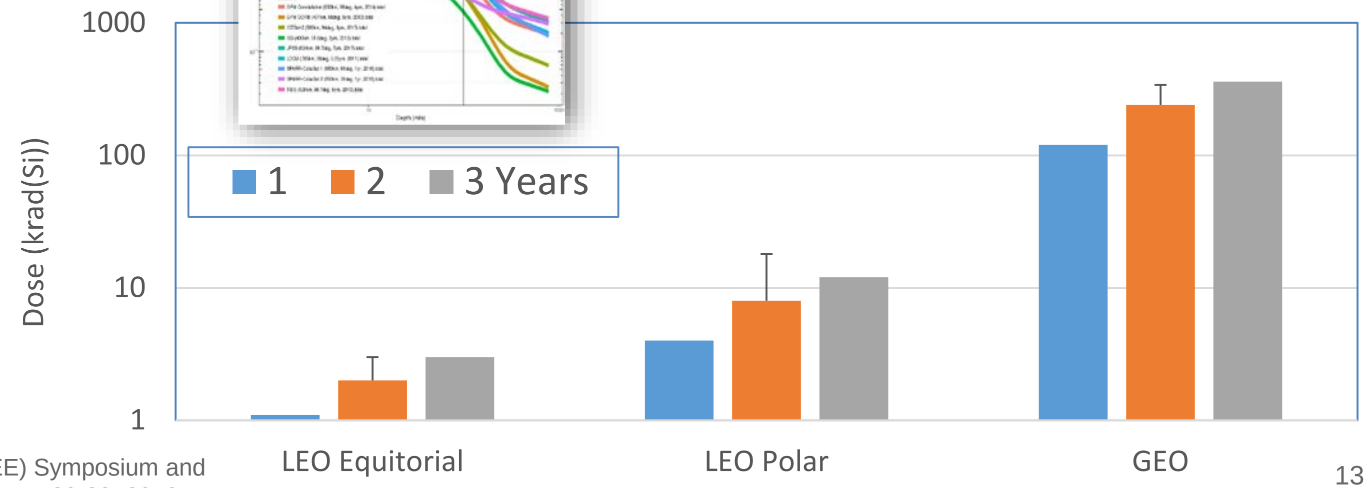
Degradation has a strong dependence on where you go, not just how long you are on orbit

Total Ionizing Dose vs. Shielding





Approximate Dose Behind 100mil Al



Degradation vs. **Single Event Contributors**

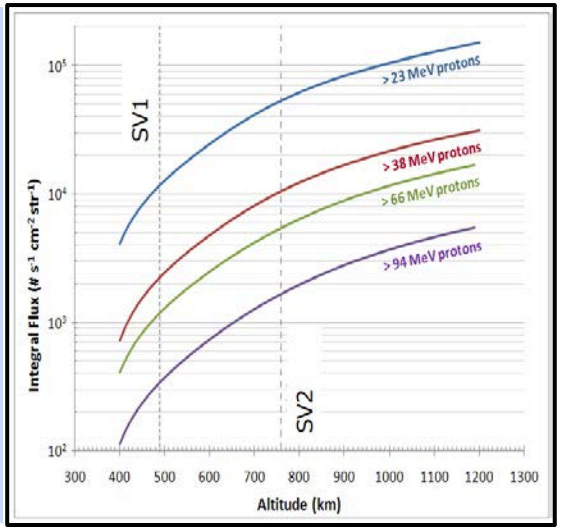
- **One particle causes the effect**
  - Random in nature, particle must traverse sensitive structure within device and have sufficient charge creation along its path
  - Shielding doesn’t do so much for highly energetic particles
  - Device technology can be dependent on particle species

- **Typical Destinations (LEO, GEO)**
  - Again altitude plays a role; for some devices that is a direct threat
  - You are exposed to more GCR + Solar contribution as geomagnetic protection is reduced
  - Natural phenomena (SAA, magnetic poles) are temporal drivers

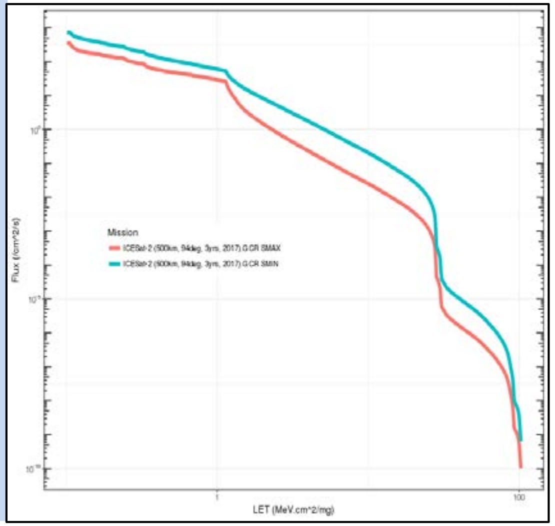
- **Note that**
  - There will be a background rate, solar cycle dependence, solar event rate, increased rate for poles or SAA – not just one rate to consider
  - Always dependent on mission

Single event contributors benefit very little from shielding, have dependence on materials near the sensitive volume

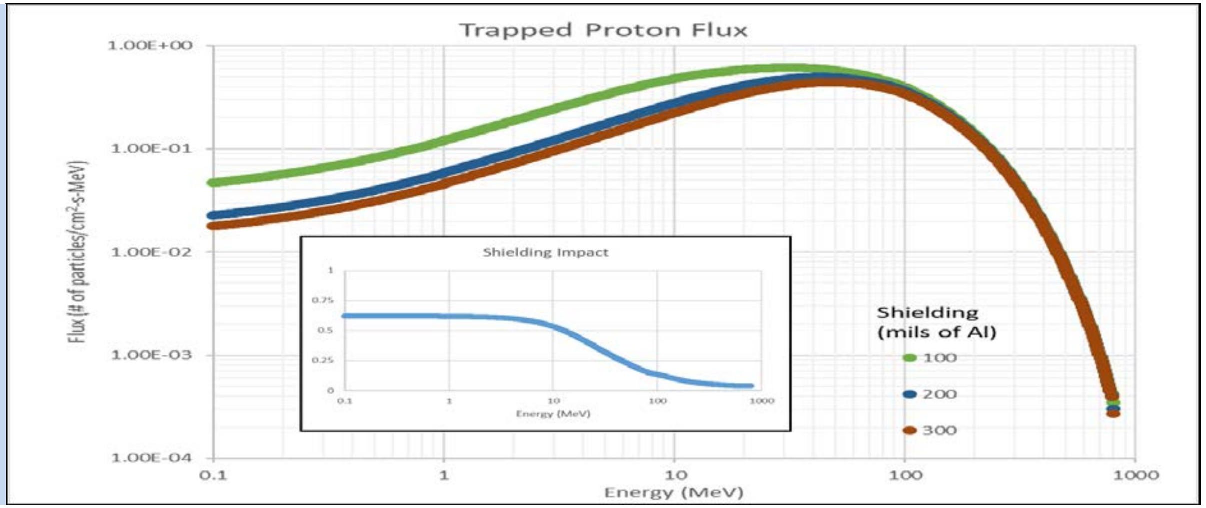
Altitude and Orbit



GCR – Solar Cycle



Shielding Effectiveness



Summary of Environmental Hazards

	Plasma (charging)	Trapped Protons	Trapped Electrons	Solar Particles	Cosmic Rays	Human Presence	Long Lifetime (>10 years)	Nuclear Exposure	Repeated Launch	Extreme Temperature	Planetary Contaminates (Dust, etc)
GEO	Yes	No	Severe	Yes	Yes	No	Yes	No	No	No	No
LEO (low-incl)	No	Yes	Moderate	No	No	No	Not usual	No	No	No	No
LEO Polar	No	Yes	Moderate	Yes	Yes	No	Not usual	No	No	No	No
International Space Station	No	Yes	Moderate	Yes - partial	Minimal	Yes	Yes	No	Yes	No	No
Interplanetary	During phasing orbits; Possible Other Planet	During phasing orbits; Possible Other Planet	During phasing orbits; Possible Other Planet	Yes	Yes	No	Yes	Maybe	No	Yes	Maybe
Exploration – Lunar, Mars, Jupiter	Phasing orbits	During phasing orbits	During phasing orbits	Yes	Yes	Possibly	Yes	Maybe	No	Yes	Yes

https://radhome.gsfc.nasa.gov/radhome/papers/SSPVSE05_LaBel.pdf

Radiation Hazard Contributors for Dose and SEE

Environment

Mission Lifetime	LEO Equatorial	LEO Polar (Sun Sync)	GEO / Interplanetary
> 3 Years	Moderate Dose / Attenuated GCR, Trapped Proton, SAA, Some Solar Proton dependence for variation	High Dose / Higher GCR, High Energy Trapped Protons in SAA and Poles, Some Solar Proton dependence for variation	High Dose / High GCR, High Solar Proton Variability
1- 3 Years	Manageable Dose / Attenuated GCR, Trapped Proton, SAA, Some Solar Proton dependence for variation	Moderate Dose / Higher GCR, High Energy Trapped Protons in SAA and Poles, Some Solar Proton dependence for variation	High Dose / High GCR, High Solar Proton Variability
< 1 Year	Manageable Dose / Attenuated GCR, Trapped Proton, SAA, Some Solar Proton dependence for variation	Moderate Dose / Higher GCR, High Energy Trapped Protons in SAA and Poles, Some Solar Proton dependence for variation	Moderate Dose / High GCR, High Solar Proton Variability

Radiation Effects on Active Microelectronic Devices

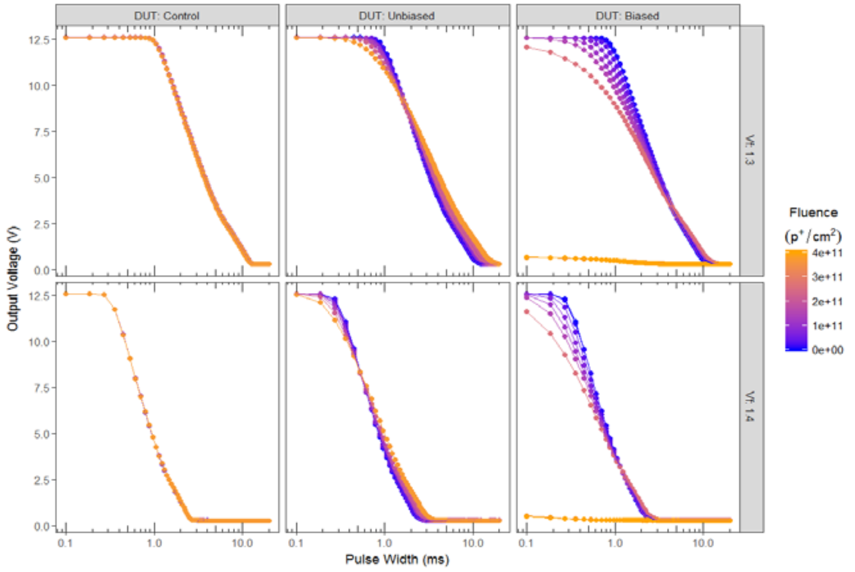
- **Cumulative effects and single event effects can both be permanently damaging**
  - TID/DDD lead to wear-out of device operation and degrade devices beyond acceptable operations internally and externally
  - Single Event Effects can be catastrophic instantaneously by turning on parasitic devices within the semiconductor or inducing electric field across dielectrics that eventually break down
  - Synergistic effects can make ground based testing very difficult

- **Destructive Single Event Effects (SEEs)**
  - Irreversible processes
  - Terms: Latchup, Burnout, Gate Rupture

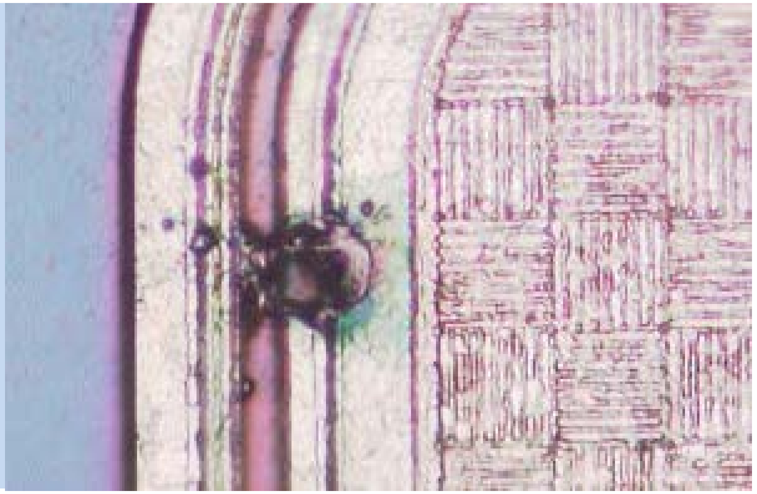
- **Non-Destructive SEEs**
  - Lead to interruptions in operation and/or errors leading to unknown state spaces or loss of science / mission if not accounted for
  - Terms: Functional Interrupt, Transients, Upsets

- **Short Courses / Presentations / Papers / IEEE**
  - NSREC, RADECS, SEE/MAPLD, NEPP ETW, HEART, GOMAC, SPWG, MRQW, SERESSA

Degradation

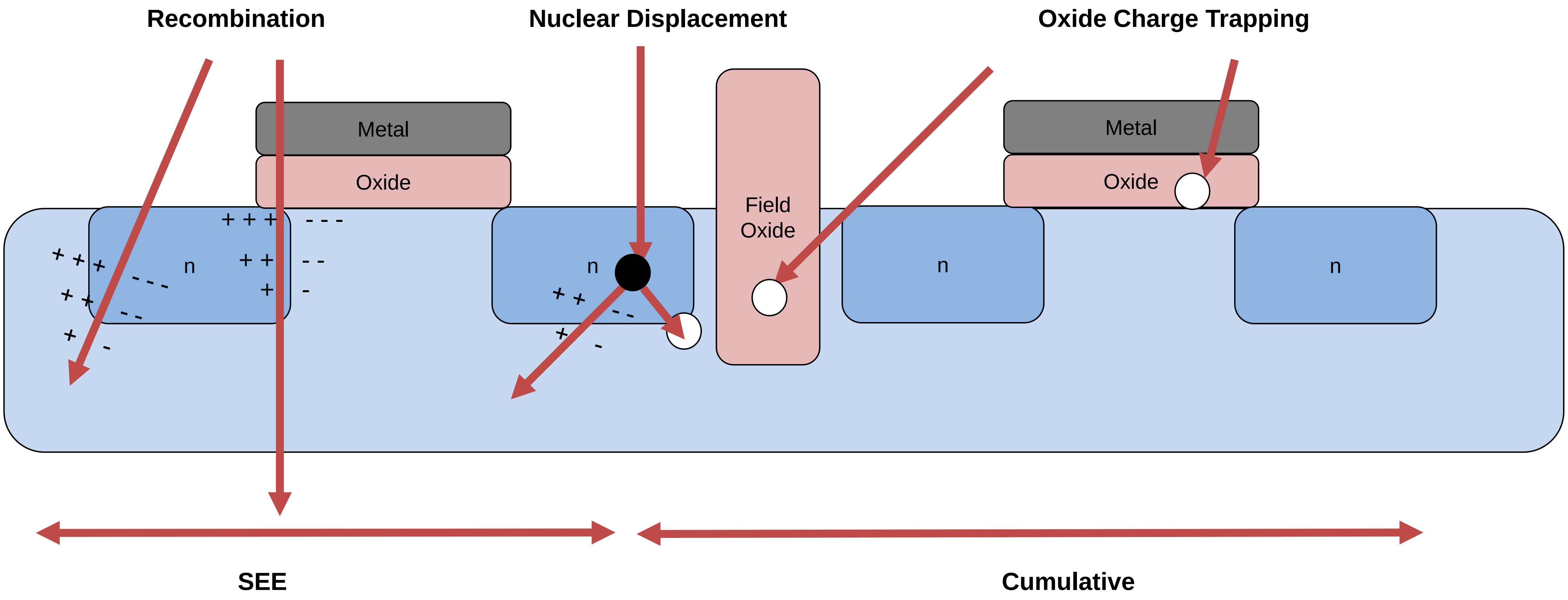


Single Event



Megan Casey - https://nepp.nasa.gov/files/26196/2014-561-Casey-Final-Web-Pres-ETW-Diodes-TN16278_v2.pdf

Device and Particle Interraction



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

Table of SEE susceptibility

SEL	SEGR	SEB	SEDR	Stuck Bit	SEU/MCU	SET	SEFI
CMOS	MOSFET	POWER MOSFET	One-time Prog. FPGA	SRAM	Digital/bistable technologies	bipolar technology	Complex Microcircuits
Bipolar?	FLASH	Power JFET	Bipolar Microcircuits	DRAM	Deep submicron CMOS more MCU susceptible	Analog microcircuit	ADCs
	Schottky Diode	Power BJT		FLASH		Digital microcircuit	PWMs

Part-Level Consequences

- Catastrophic failure possible
- Destructive but limited
- Nondestructive

How Common is Issue?

- Common in technology
- Catastrophic failure possible
- Not seen but possible in principle

Ray Ladbury, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170006865.pdf

List is not exhaustive, but new failure modes are found in new devices, so it would not be possible to capture all

Outline

- New Space and SmallSat Considerations
- The Natural Space Radiation Environment Hazard
- Radiation Effects on Micro-Electronics
- **Hardness Assurance, as a Discipline, with its Challenges**
  - **New Technologies**
  - **New Architectures**
  - **Unbound Risks**
- **Building Smart Requirements**
- **Risk Acceptance and Guidance**

The Job: Watch out for the 'ilities

Survivability

- Must survive until needed
- Entire mission?
- Screening for early failures in components

Availability

- Must perform when necessary
- Subset of time on orbit
- Operational modes
- Environmental response

Criticality

- Impact to the system
- Part or subsystem function
- Mission objectives

Reliability

- Resultant of all
- Many aspects and disciplines
- Known unknowns

The People: Radiation Effects Engineers

Materials

- Material Property degradations with radiation
- Energy loss in materials

Device Physics

- Charge transport
- Device Process Dependencies
- Charge dependency of device operation

Electrical Engineering

- Part to part interconnections
- Understanding circuit response
- Device functions and taxonomy

Systems Engineering

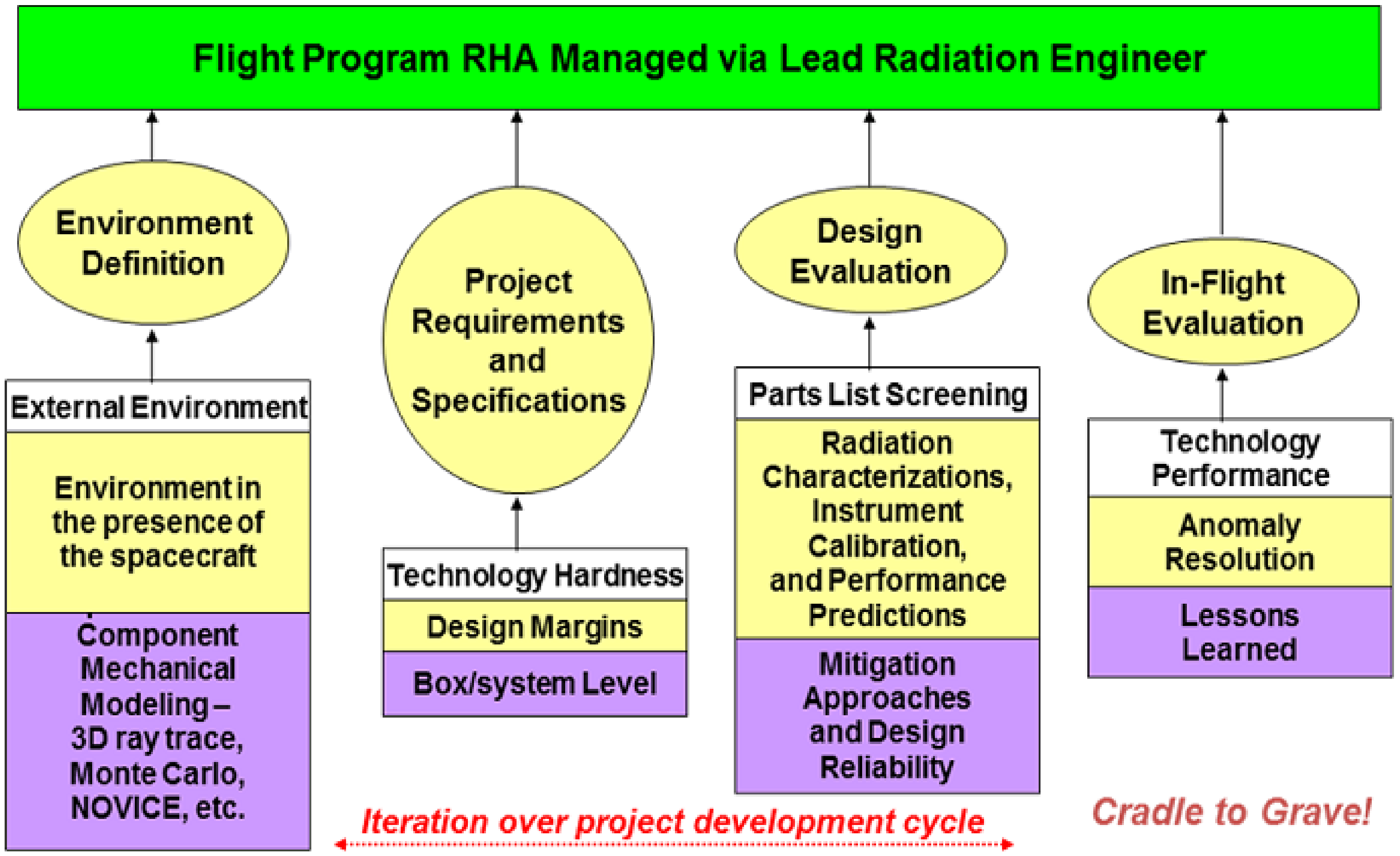
- Requirements
- System Level Impacts
- Understanding interconnections
- Understanding functionality

Space Physics

- Space weather
- Environment models/modeling
- Radiation Sources and variability

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



(Poivey)

(LaBel)

Radiation Hardness Assurance Flow

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

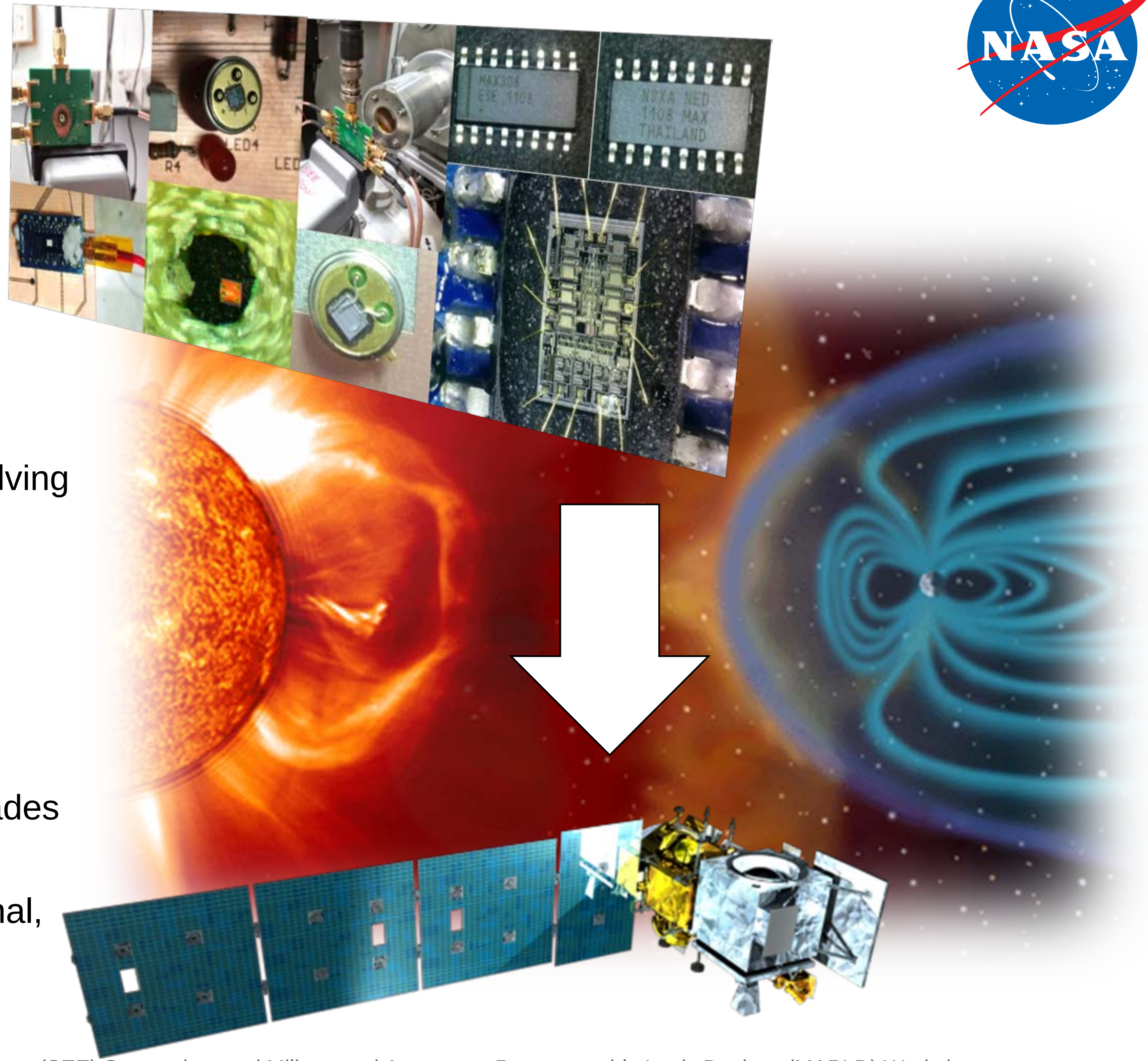
- **Define the Environment**
  - External to the spacecraft
- **Evaluate the Environment**
  - Internal to the spacecraft
- **Define the Requirements**
  - Define criticality factors
- **Evaluate Design/Components**
  - Existing data/Testing
  - Performance characteristics
- **"Engineer" with Designers**
  - Parts replacement/Mitigation schemes
- **Iterate Process**
  - Review parts list based on updated knowledge

K.A. LaBel, A.H. Johnston, J.L. Barth, R.A. Reed, C.E. Barnes, "Emerging Radiation Hardness Assurance (RHA) issues: A NASA approach for space flight programs," IEEE Trans. Nucl. Sci., pp. 2727-2736, Dec. 1998.

RHA Challenges… Not So Small

- **Always in a *<u>dynamic</u>* environment**
- **New Technologies**
  - Device Topology / Speed / Power
  - Increased COTS parts / subsystem usage
- **New Mission Architectures**
  - Profiles of mission life, objective, and cost are evolving
  - Oversight gives way to insight in some mission classifications
  - Ground systems, do no harm, hosted payloads
  - Similarity and heritage data requirement widening
- **Quantifying Risk**
  - Translation of system requirements to radiation trades can be problematic
  - Determining appropriate mitigation level (operational, system, circuit/software, device, material, etc.)

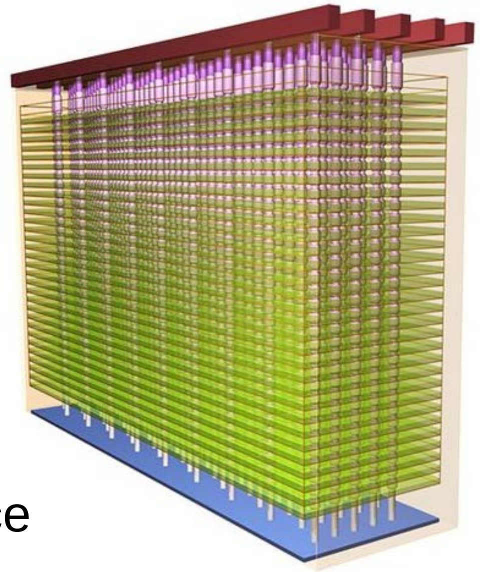
Unbound radiation risks are likely



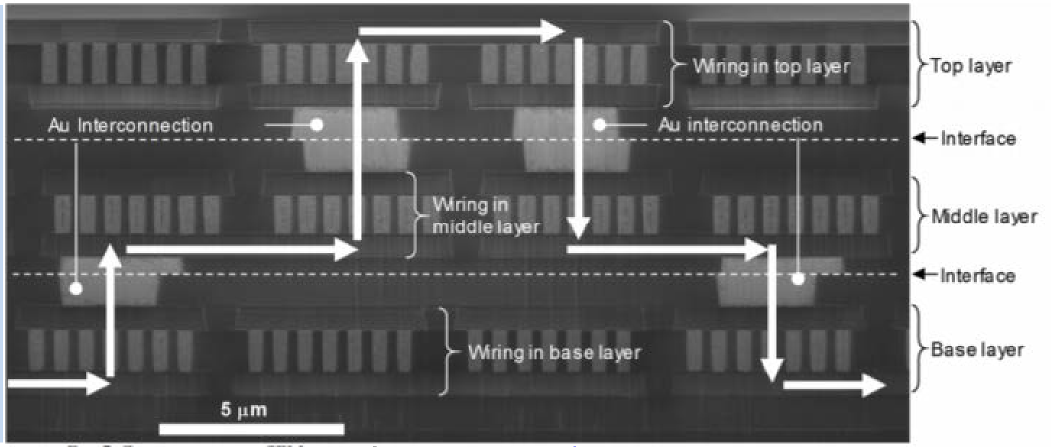
New Technologies - New Susceptibilities

- **Feature Size / Critical Charge –**
  - Will we now have sensitivity to muons? Low energy protons?
- **3D Stacking/Structures**
  - Deep sensitive volumes
  - New materials
- **Testing Challenges**
  - Complexity (e.g. SoCs)
    - Speed of interfaces
    - Obfuscation of state space
  - Flux / Range of beam @ facilities

3D Memory Structures

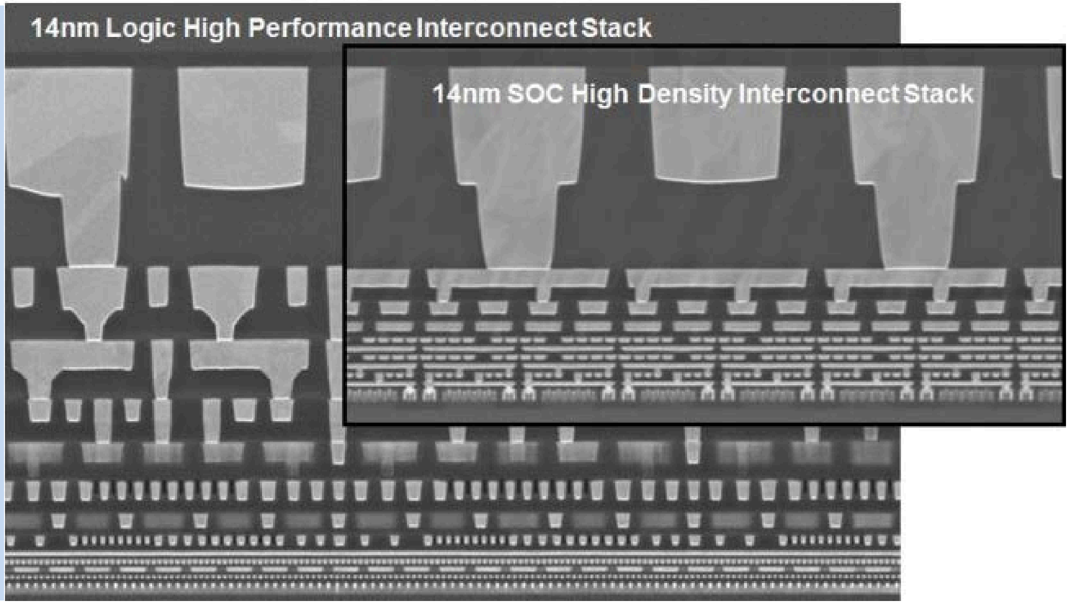


Gold Interconnects



IEEE/DOI: 10.1109/TCPMT.2019.2910863

High Density Stacks

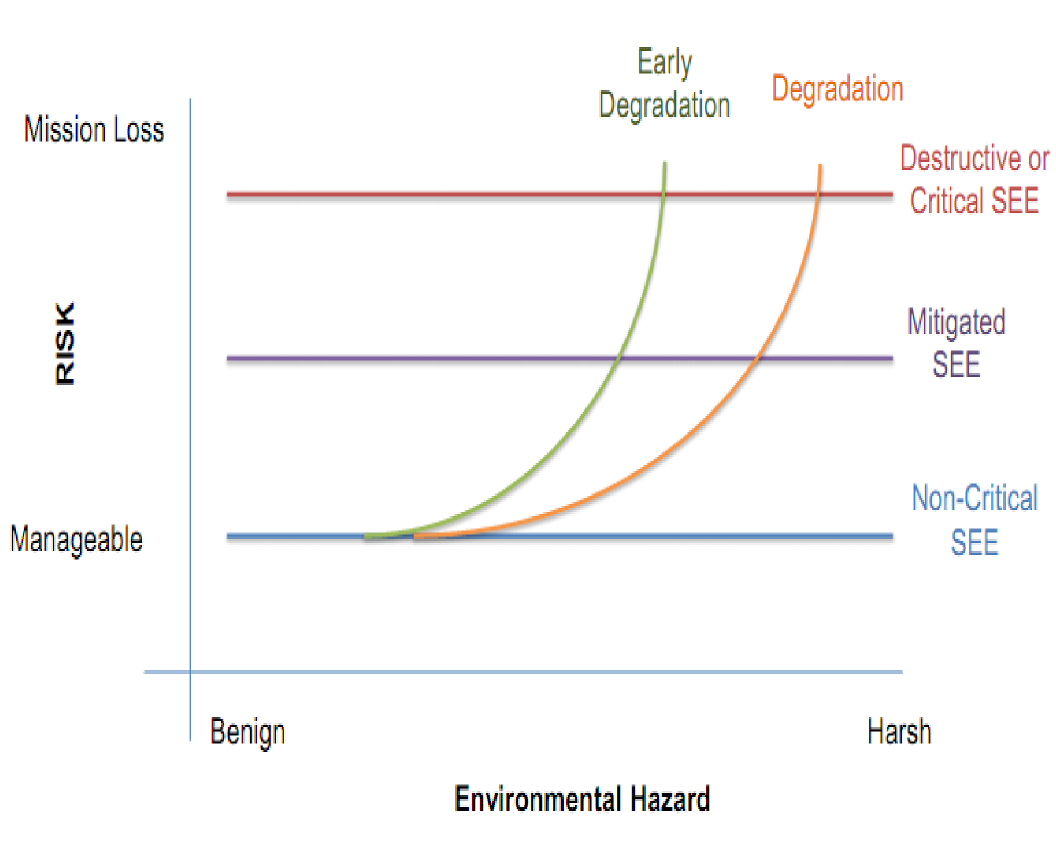


IEEE/DOI:10.1109/IITC-AMC.2016.7507637

Without a lot of part information you may not have a representative characterization of the radiation threats to the device or technology.

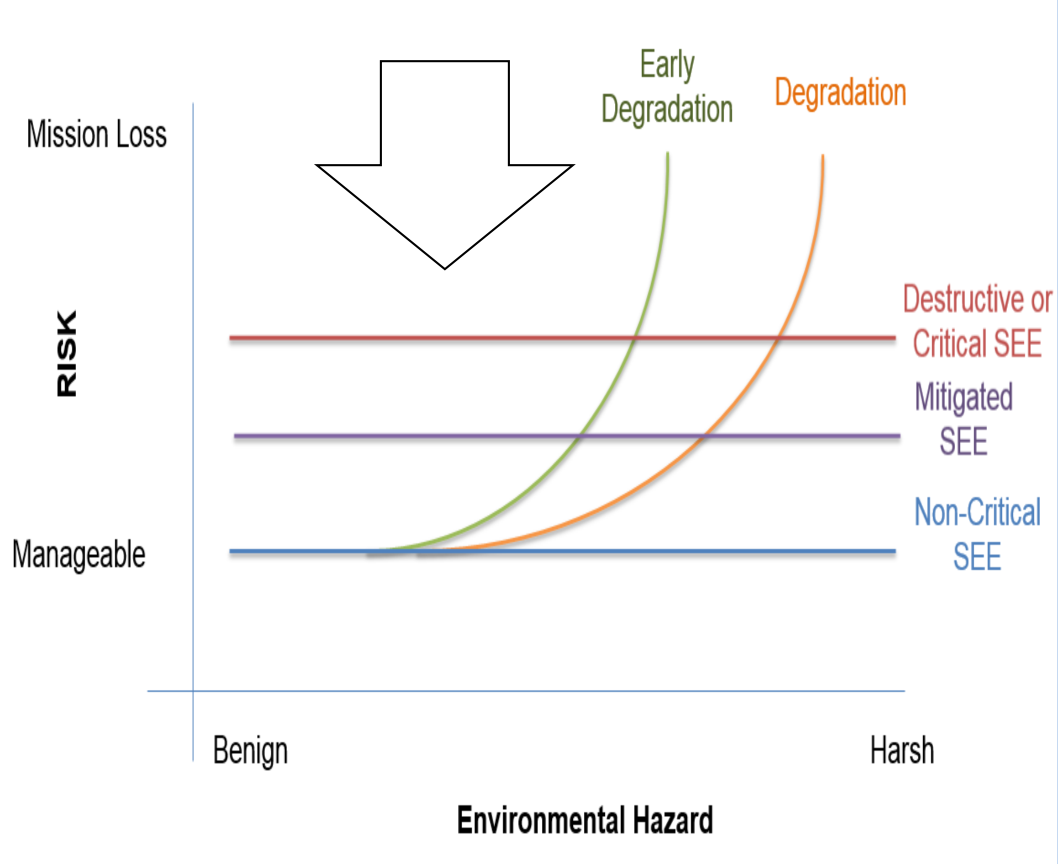
New Mission Architectures - How Many to Succeed?

Single Strain



vs

Allowable Losses

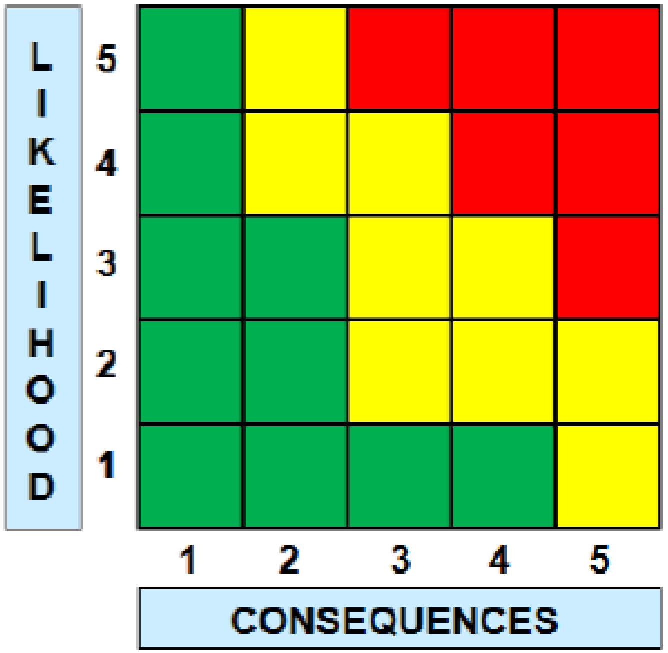


Redundancy alone does not remove the threat, adds complexity

Quantifying Risk – Likelihood vs. Consequence

From Risk Assessment GPR 7120.5

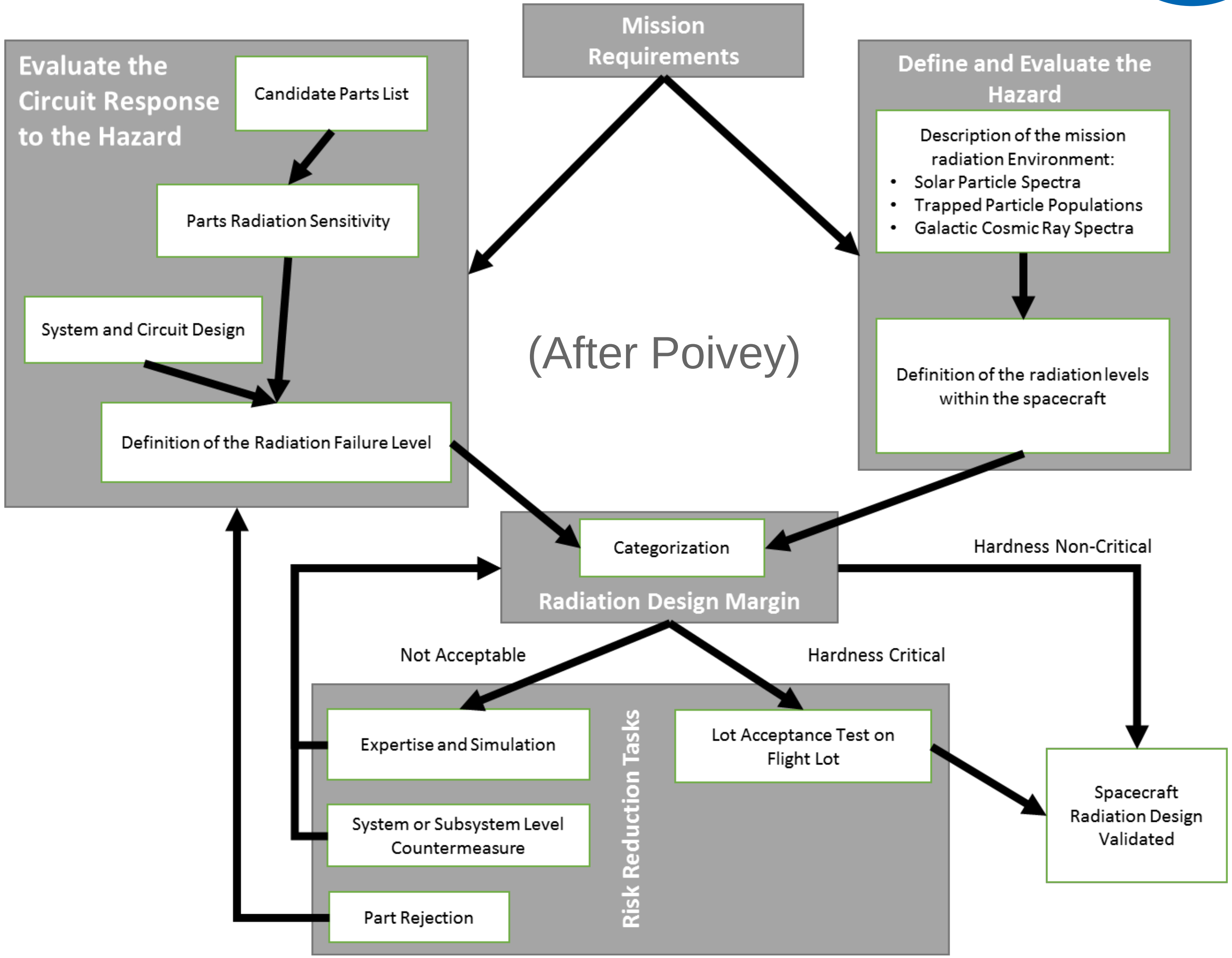
Likelihood	Safety Estimated likelihood of Safety event occurrence	Technical Estimated likelihood of not meeting performance requirements	Cost Schedule Estimated likelihood of not meeting cost or schedule commitment
5 Very High	$(P_{SE} > 10^{-1})$	$(P_T > 50\%)$	$(P_{CS} > 75\%)$
4 High	$(10^{-2} < P_{SE} \leq 10^{-1})$	$(25\% < P_T \leq 50\%)$	$(50\% < P_{CS} \leq 75\%)$
3 Moderate	$(10^{-3} < P_{SE} \leq 10^{-2})$	$(15\% < P_T \leq 25\%)$	$(25\% < P_{CS} \leq 50\%)$
2 Low	$(10^{-5} < P_{SE} \leq 10^{-3})$	$(2\% < P_T \leq 15\%)$	$(10\% < P_{CS} \leq 25\%)$
1 Very Low	$(10^{-6} < P_{SE} \leq 10^{-5})$	$(0.1\% < P_T \leq 2\%)$	$(2\% < P_{CS} \leq 10\%)$



Can only get there with enough information about the system or the chosen device, need to have a known hazard and a known response

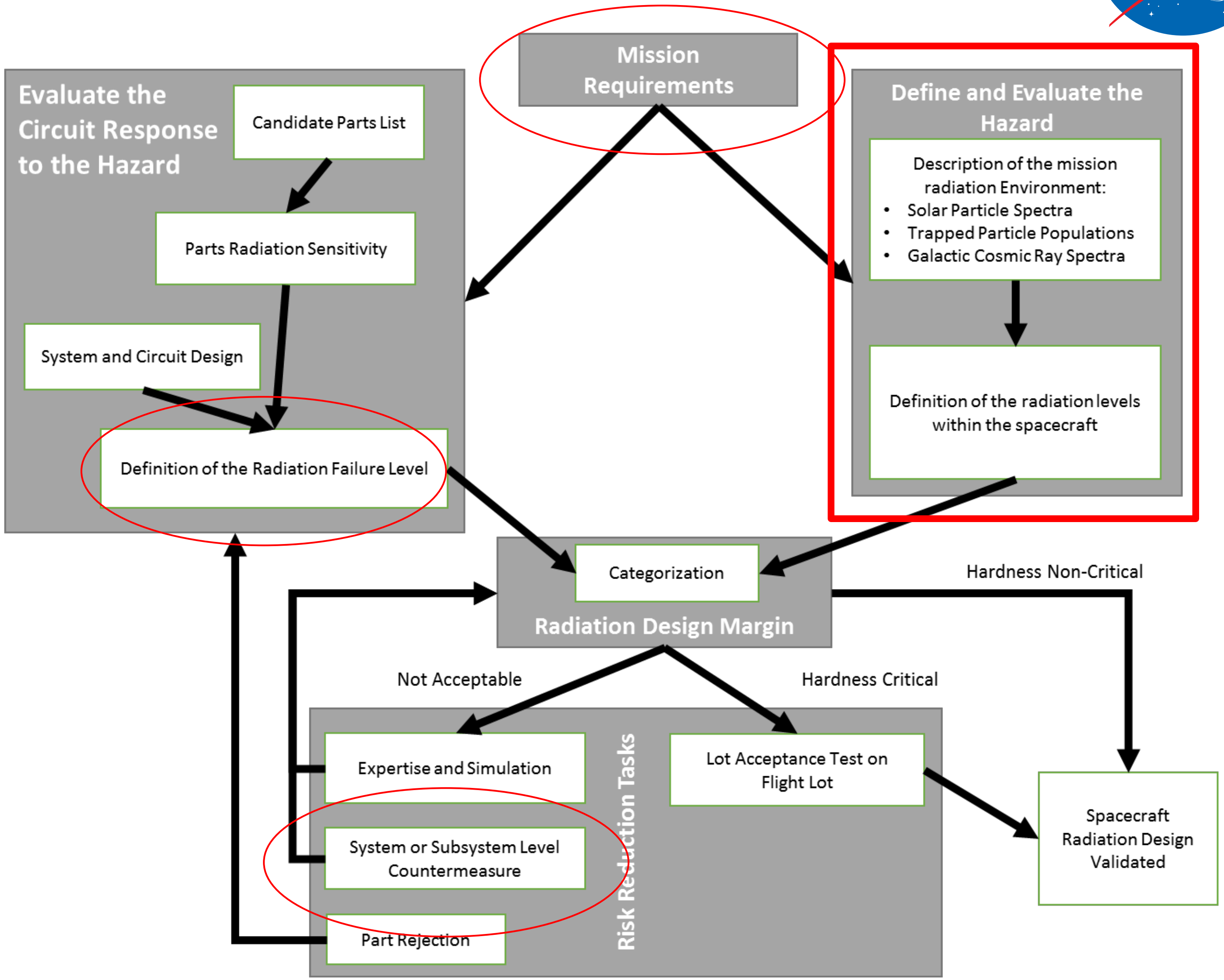
RHA Flow Doesn't Change With Accepted Risk

- **Hardness Assurance is the practice of designing for radiation effects**
- **What it takes to overcome the radiation challenges**
- **Competing failure modes**



RHA Flow Doesn't Change With Accepted Risk

- **Hardness Assurance is the practice of designing for radiation effects**
- **What it takes to overcome the radiation challenges**
- **Competing failure modes**
- **Focus for impact on risk acceptance:**
  - Failure Awareness
  - Countermeasures/Mitigation
  - Mission Requirements



Focus For Risk Acceptance

- **Failure Awareness**
  - Know your hazard from the natural environment
  - Know your devices potential failure mechanisms or response (data)
- **Countermeasures and Mitigation**
  - Where are they necessary?
  - Where are they effective?
  - At what level (part, card, box, mission)
- **Smart Requirements – and Eventually Smart Trades**

Failure Awareness

Define and Evaluate the Hazard

Free-Field Environment Definition → Shielding → Internal Environment Definition → Known Hazard

System → Sub-system → Parts

Reliability Requirements → Performance Requirements → Parametric Requirements → Known Risk

Derive Smart Requirements

Define and Evaluate the Hazard

- **Define the Environment**
  - External to the spacecraft
- **Evaluate the Environment**
  - Internal to the spacecraft
- **Define the Requirements**
  - Define criticality factors
- **Evaluate Design/Components**
  - Existing data/Testing
  - Performance characteristics
- **"Engineer" with Designers**
  - Parts replacement/Mitigation schemes
- **Iterate Process**
  - Review parts list based on updated knowledge

Environment Severity/Mission Lifetime

Criticality/Availability	Low	Medium	High
High	Manageable Dose / SEE impact to survivability or availability	Moderate Dose / SEE impact to survivability or availability	High Dose / SEE impact to survivability or availability
Medium	Manageable Dose / SEE needs mitigation	Moderate Dose / SEE needs mitigation	High Dose / SEE needs mitigation
Low	Manageable Dose / SEE do no harm	Moderate Dose / SEE do no harm	High Dose / SEE do no harm

Derive Smart Requirements

- **Define the Environment**
  - External to the spacecraft
- **Evaluate the Environment**
  - Internal to the spacecraft
- **Define the Requirements**
  - Define criticality factors
- **Evaluate Design/Components**
  - Existing data/Testing
  - Performance characteristics
- **"Engineer" with Designers**
  - Parts replacement/Mitigation schemes
- **Iterate Process**
  - Review parts list based on updated knowledge

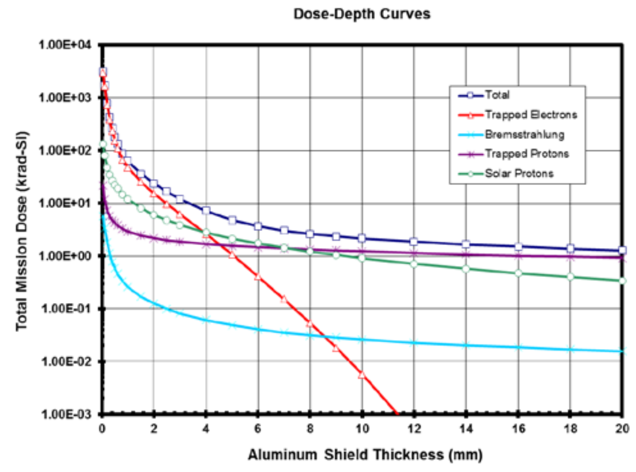
Environment Severity/Mission Lifetime

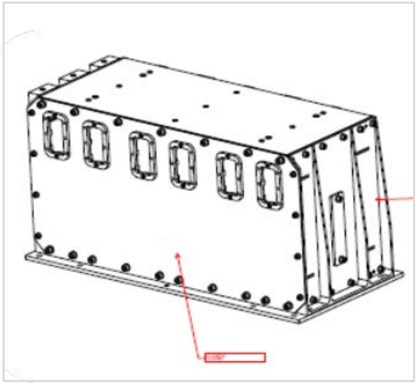
Criticality/Availability	Low	Medium	High
High	**Dose-Depth / Ray-trace GCR and Proton Spectra for typical conditions**	**Dose-Depth / Ray-trace GCR and proton Spectra for all conditions**	**Ray-Trace for subsystem / GCR and proton Spectra for all conditions**
Medium	**Dose-Depth / GCR and proton spectra for background**	**Dose-Depth / GCR and Proton Spectra For background**	**Dose-Depth evaluation at shielding / All spectra conditions**
Low	**Similar mission dose, same solar cycle / GCR spectra**	**Dose-Depth / GCR spectra**	**Dose-Depth / GCR and Proton Spectra For background**

Mitigation and Countermeasure Optimization

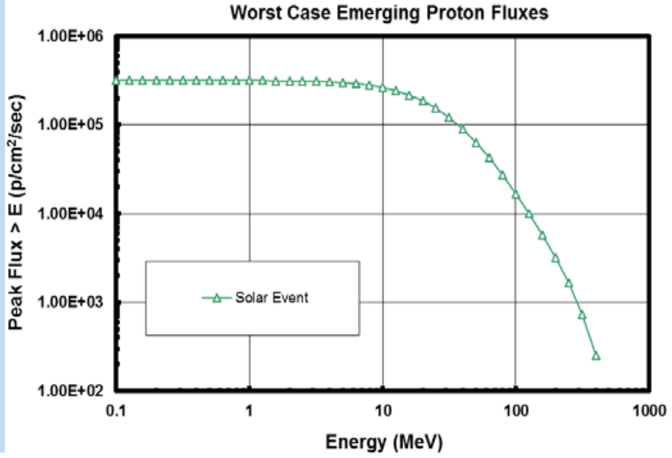
- **Define the Environment**
  - External to the spacecraft
- **Evaluate the Environment**
  - Internal to the spacecraft
- **Define the Requirements**
  - Define criticality factors
- **Evaluate Design/Components**
  - Existing data/Testing
  - Performance characteristics
- **"Engineer" with Designers**
  - Parts replacement/Mitigation schemes
- **Iterate Process**
  - Review parts list based on updated knowledge

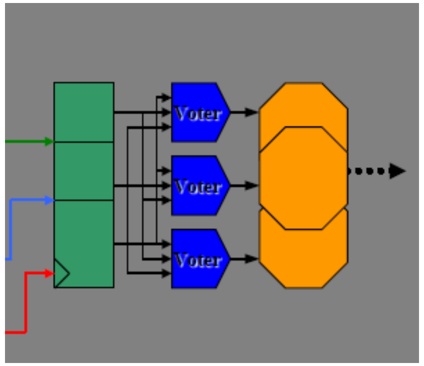
Degradation





Single Event



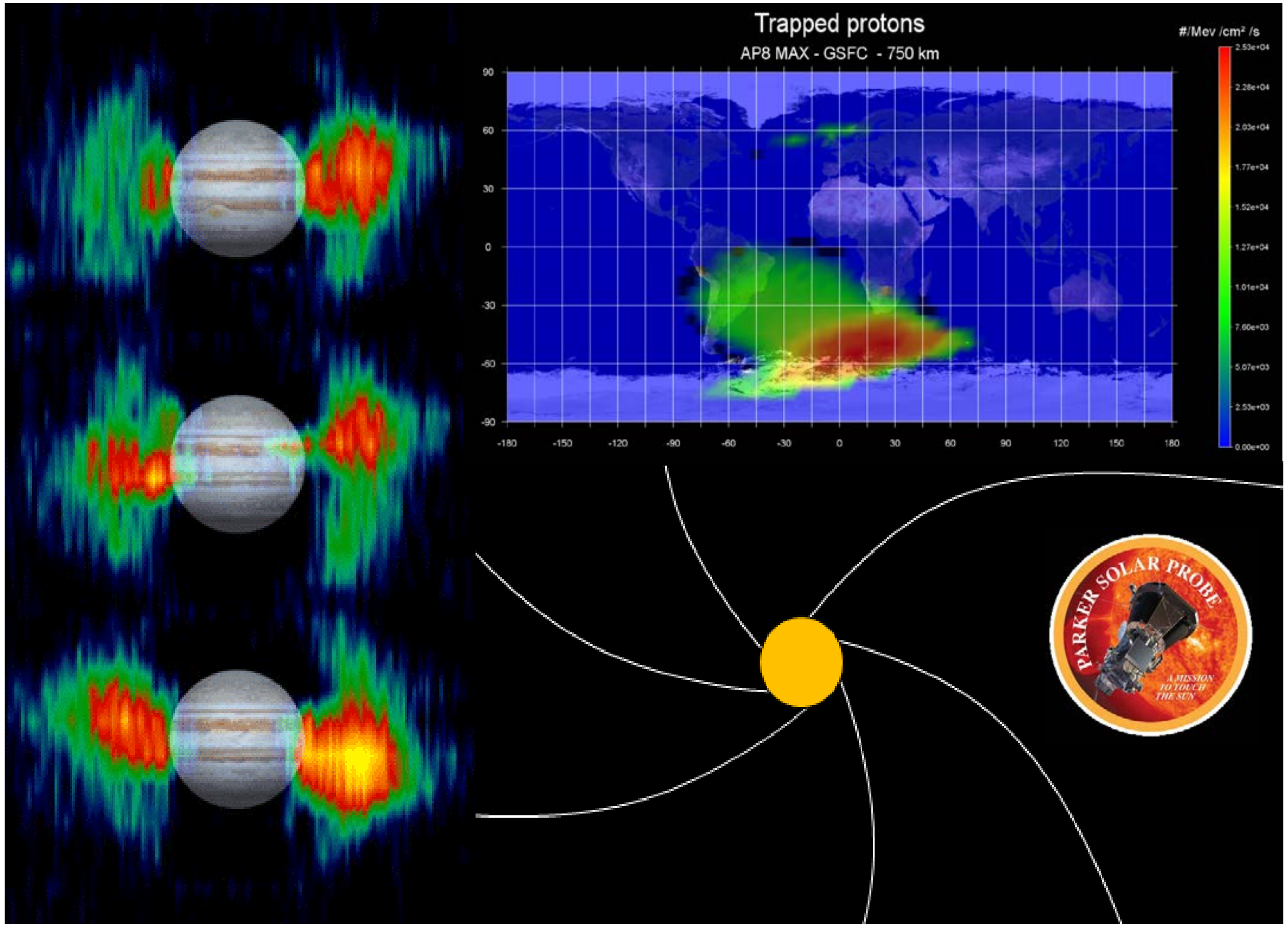


Building Requirements

- **Requirements by Environment**
- **Requirements by Technology**
- **Cases that may need additional considerations**

Requirements by Environment

- **Van Allen Belts**
  - Can lead to high doses in a short mission: Jovian
  - Can lead to spatially dependent SEE responses: South Atlantic Anomaly
- **Solar Orbits**
  - Solar Events, highly dynamic, energetic, directional
  - Solar Wind, will depend on the solar cycle



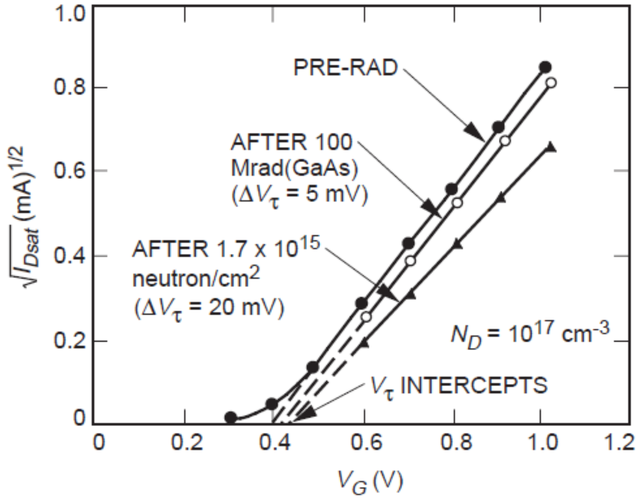
In essence the requirements are always driven by the environment, some more than others create a unique challenge

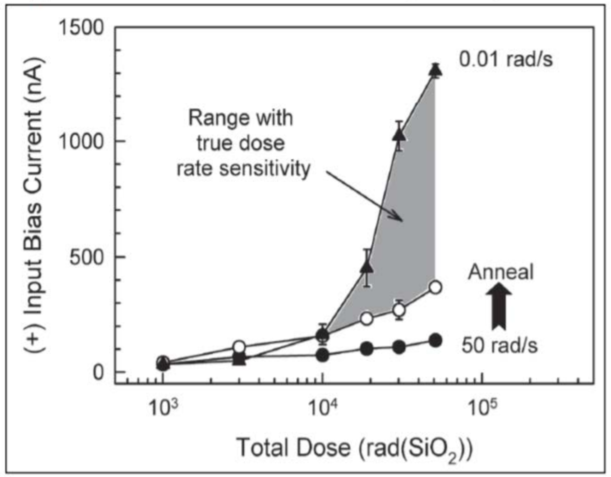
Requirements by Technology

- **Technologies exhibit specific physics of failure**
  - *Not easy to group them all*
  - Opto-electronics - Displacement in the material
  - Bipolar - Enhanced Low Dose Rate Sensitivity
  - Digital CMOS - Latchup and SEFI
  - Power devices - SEGR/SEB

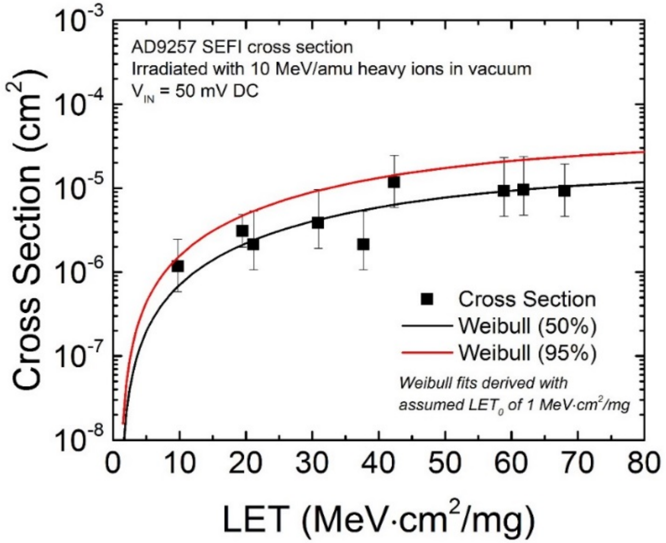
- **Test Data requirements**
  - Failure distributions, often not enough parts
  - Destructive effects are one data point, variability from part to part
  - Statistics of the fit for rate calculations

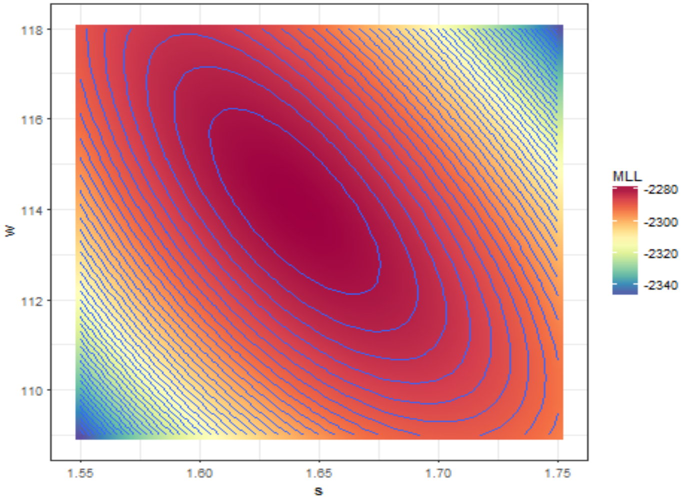
Requirements should only be made applicable to the technologies that need to meet mission objectives and can benefit





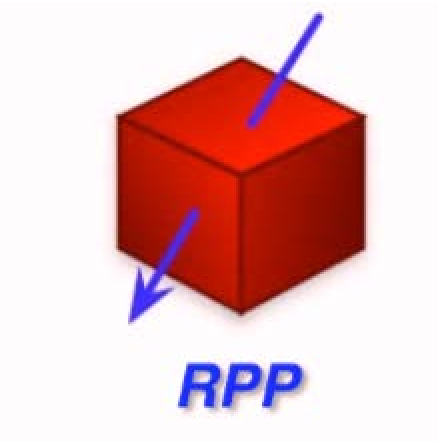
M. R. Shaneyfelt, et al., *IEEE TNS*, 2000.

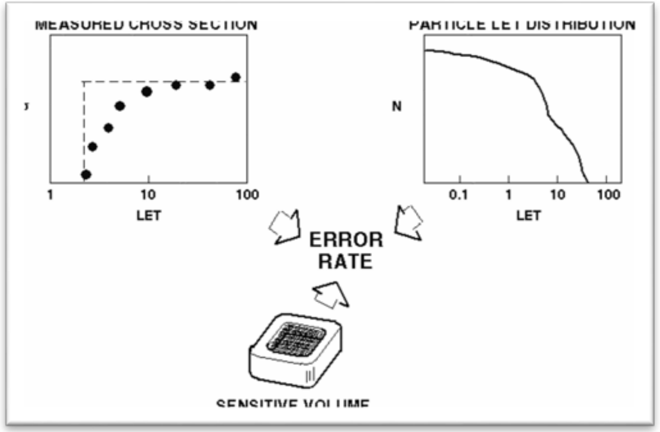


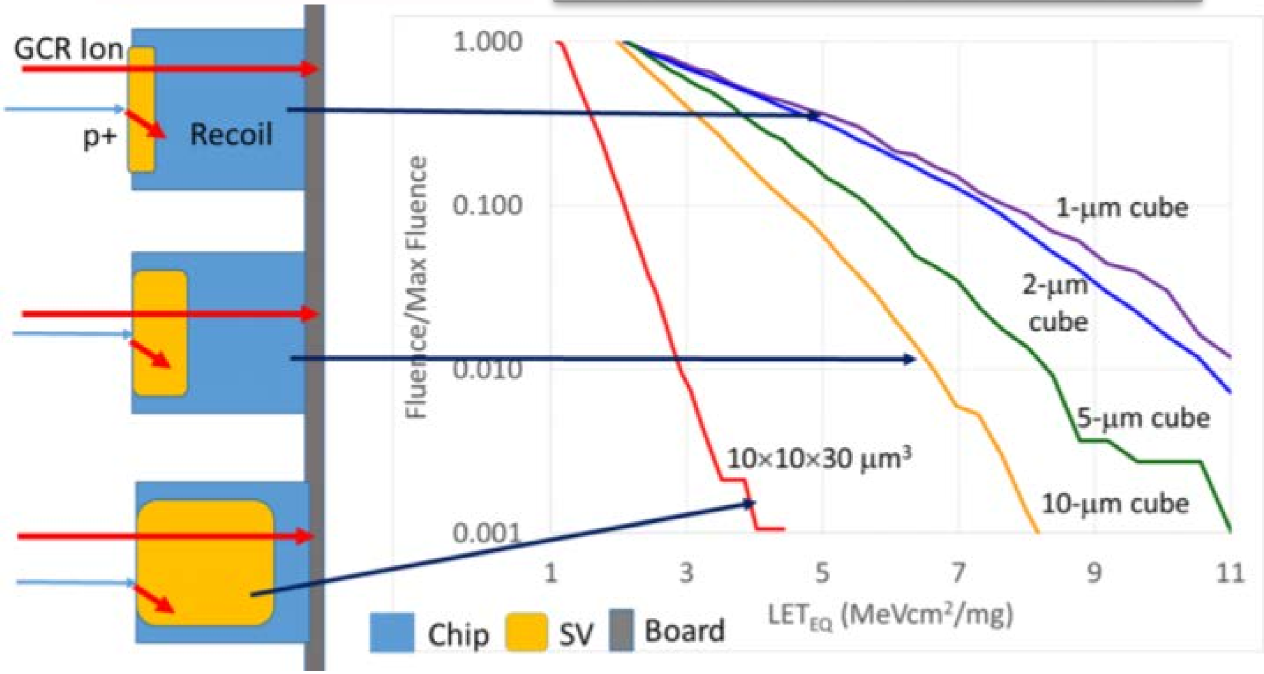


Why you can't relax an LET requirement

- **Not like wear-out, flat-line risk**
- **Rate calculations are not the same for DSEE vs. Non-destructive**
  - Data are a limiting factor
  - One part = one data point
- **When you require by LET:**
  - Spectrum from environment is then imparted on sensitive volumes
  - LET increases at angle – critical charge is what we are trying to determine
  - Deep SV doesn't get same LET each time
  - CRÈME Calculation integrates





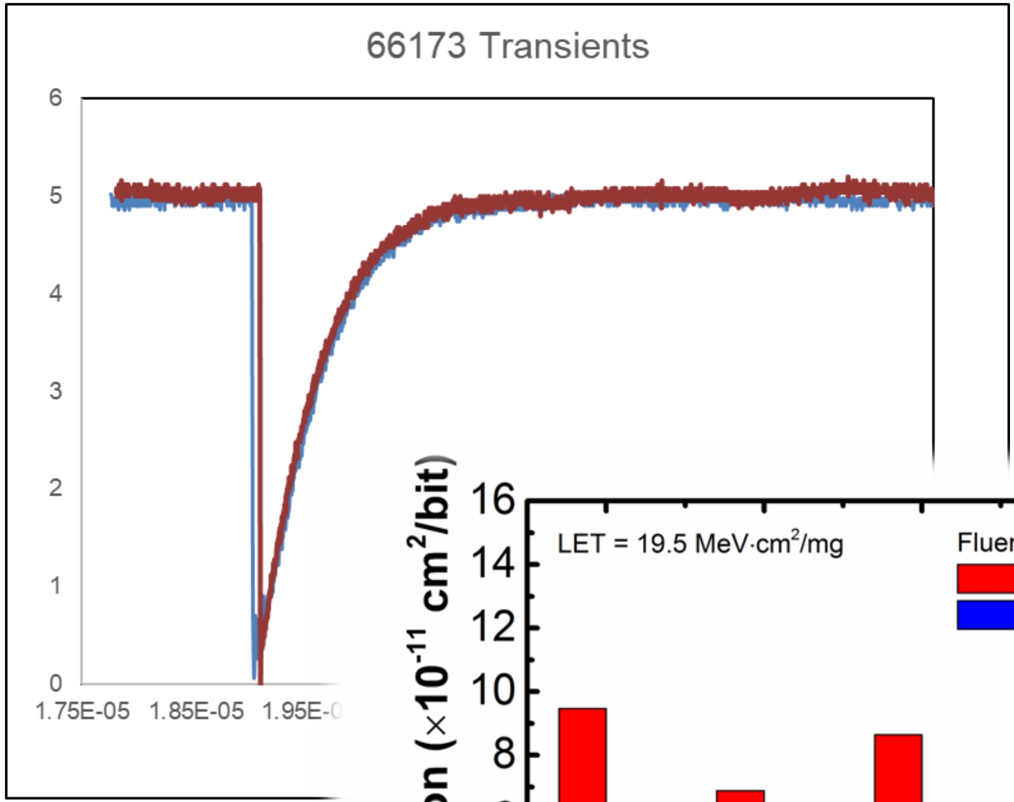


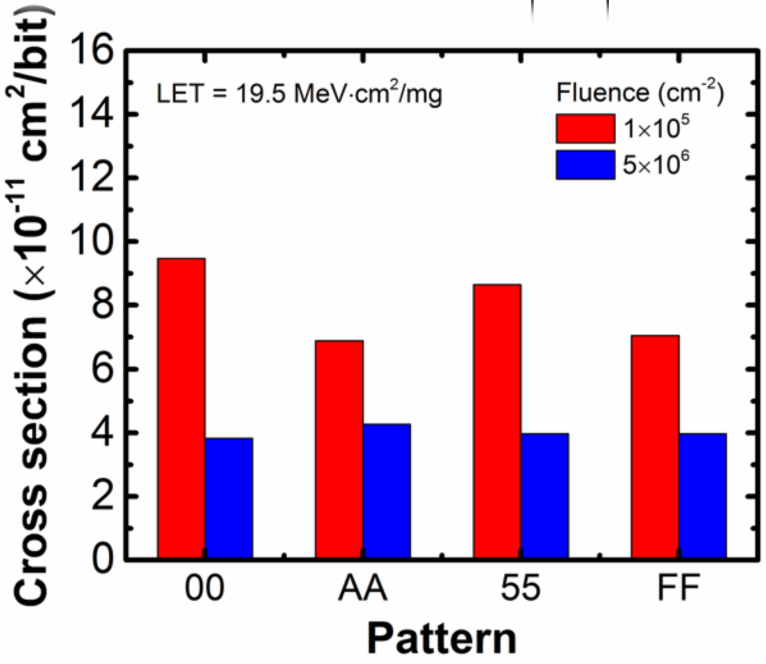
Ray Ladbury, NSREC2017 SC, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170006865.pdf

Considerations for SEE Requirements

- **SEE, SET**
  - Don't harm downstream parts, or accumulate
  - Tailored Filtering, EDAC, or Scrubbing
- **SEL**
  - Environment and technology driven, risk avoidance
  - Protection circuitry / diode deratings
- **SEGR, SEB**
  - Effect driven, normally incident is worst case
  - Testing to establish Safe Operating Area (SOA)
- **MBU, MCU, SEFI, Locked States**
  - Application Voltage or Pattern dependence
  - Watchdogs / reset capability
- **Proton SEE susceptible parts need evaluated in detail:**

https://nepp.nasa.gov/files/25401/Proton_RHAGuide_NASAAug09.pdf





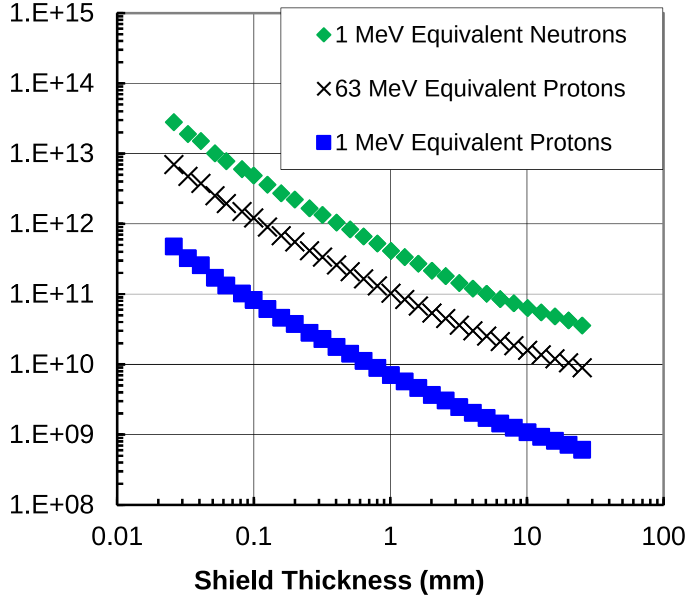
So you don't care about dose?

- Maybe degradation of a part beyond usage is okay?
- Did you forget about DDD?

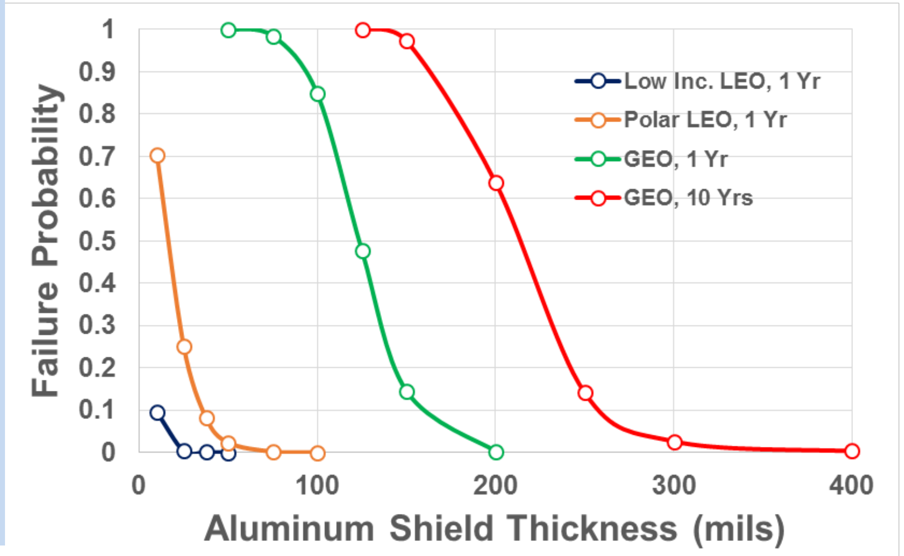
Maybe you do!

- Short Mission, common failure mode
- Low mass budget, can optimize shielding if you have failure distribution of parts.

Non-Ionizing Energy Loss – Displacement Damage Dose



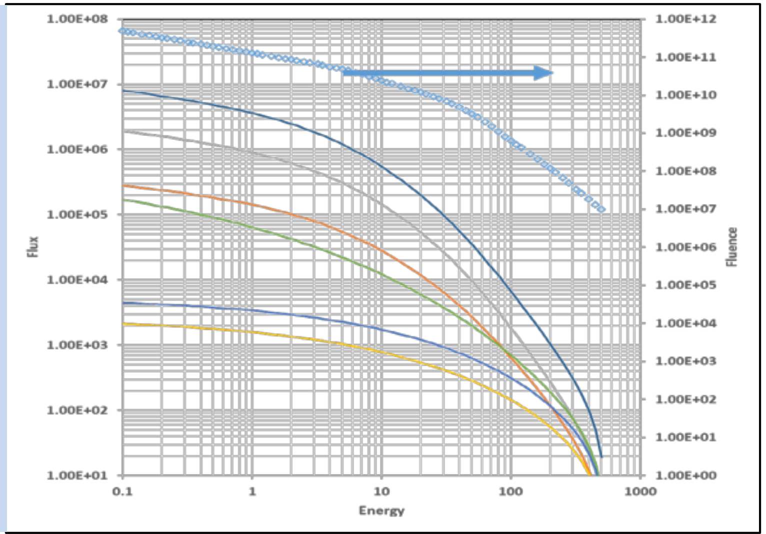
Shielding Optimization



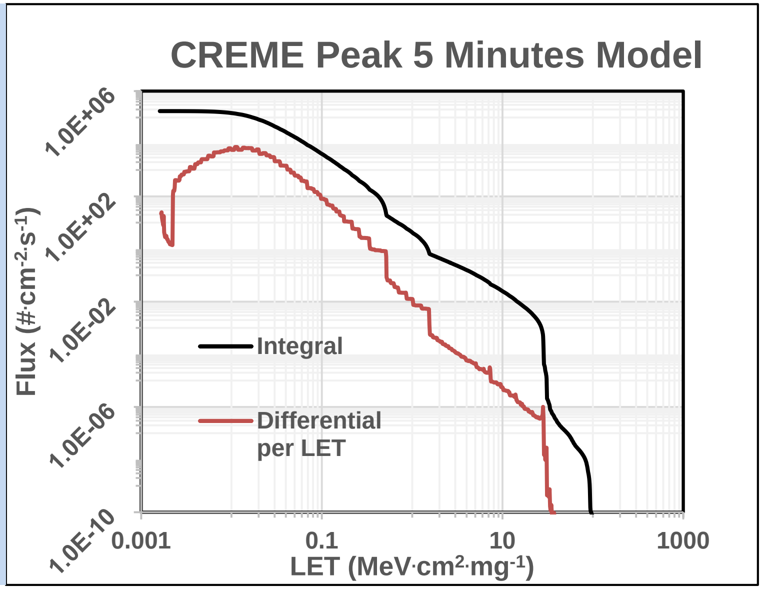
Say you want to survive a flare? Think Availability

- **Don't dose out during storm (nor the full mission)**
  - Calculate the dose (TID/DDD) of the mission in full - 95% confidence level recommended
  - Calculate the dose contribution from N number of events (protons & x-rays)
  - If dose from N is > 5% of the total dose, increase confidence level of full mission model
- **Don't destructively fail from a single particle during the storm (nor the full mission)**
  - Standard risk-avoidant SEE approach: no destructive effects allowed
  - LET threshold for single event latchup (SEL) > 75 MeV.cm2/mg
  - LET threshold for single event burnout, gate rupture, dielectric rupture (SEB, SEGR, SEDR) > 37 MeV.cm2/mg (particles must come from normal incidence to cause effect)
- **If you have non-destructive single event upsets, they can't overwhelm critical instruments/systems during the storm**
  - Rate calculation requires part data representative of the application, looking for cross-section over LET.
  - If a parts' LET threshold is anywhere from 20 to 75 MeV.cm2/mg, need heavy ion rate
  - If a parts' LET threshold is below 20, need direct ionization from protons (can be built-in to heavy ion calculation) and indirect ionization from recoil ions contribution to rate (need proton data) – make sure packaging materials don't add to this
  - Do you need to mitigate or not – confirm that event rates are not higher than mitigation (Markov process… i.e. EDAC beats the number accrued, scrub rate is faster than critical number of upset accumulation)

Many Solar Models



Spectrum Translates to LET

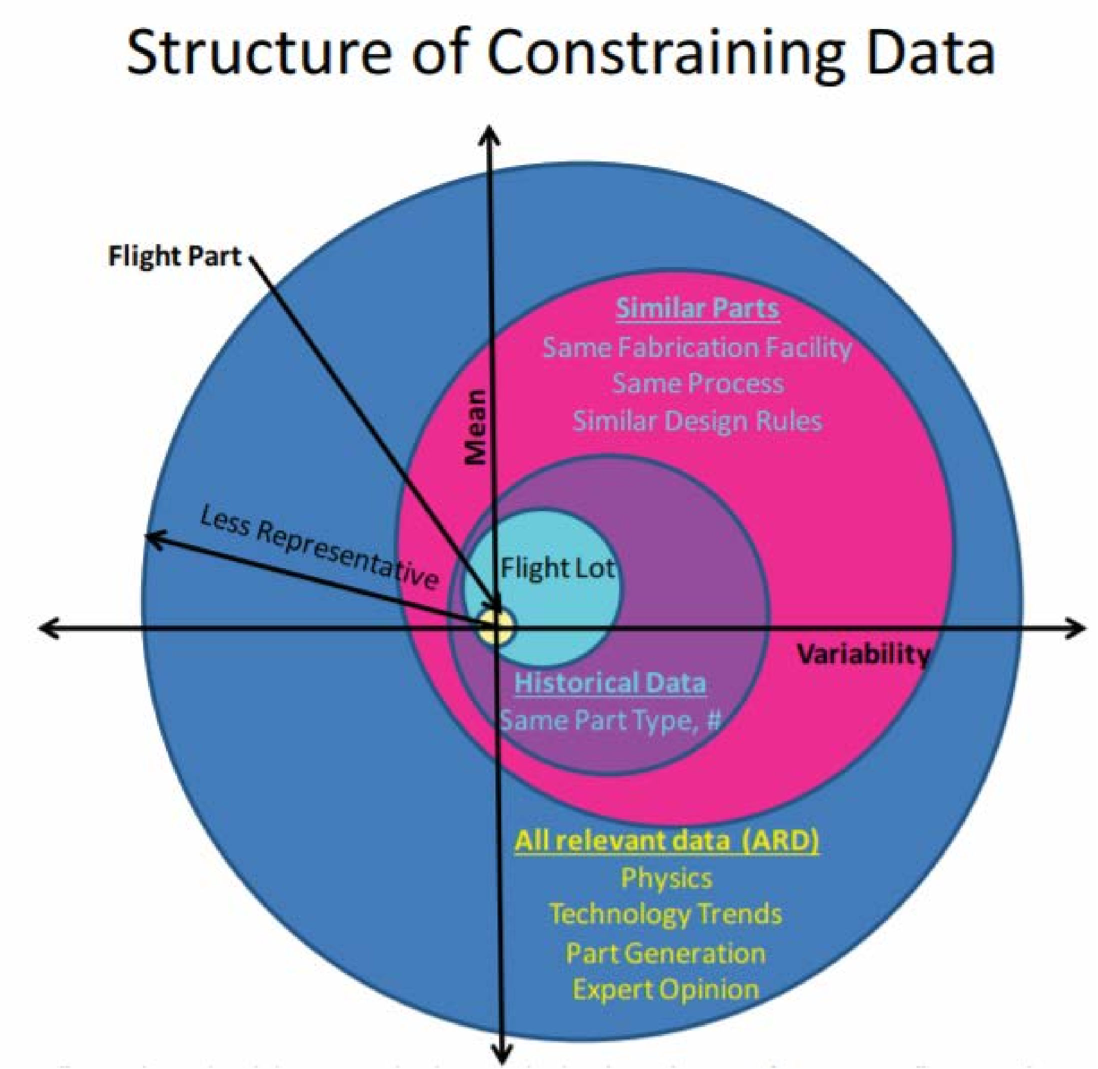


Risk Acceptance – Data Available?

- **Part Classifications Growing**
  - Mil/Aero vs. Industrial vs. Medical
  - Automotive vs. Commercial vs. Modified HiRel

- **Substitute in COTS**
  - Now you have another degree of separation
  - Failure modes not fully understood
  - Unlikely to have historical data
  - Similarity data no applicable due to fab, process, or design rules
  - Cost of testing usually too high

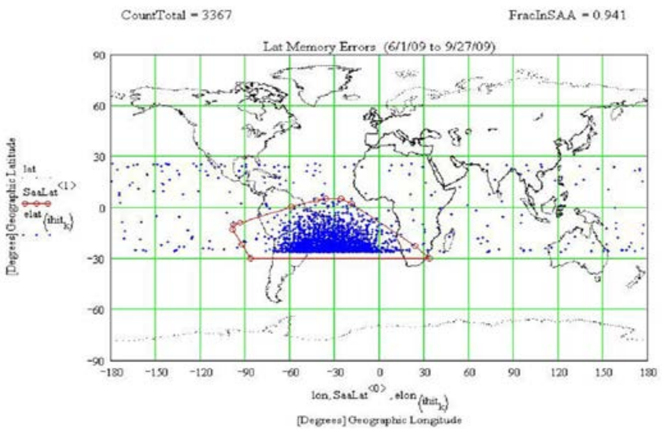
Without traceability you may be depending on non-representative data.

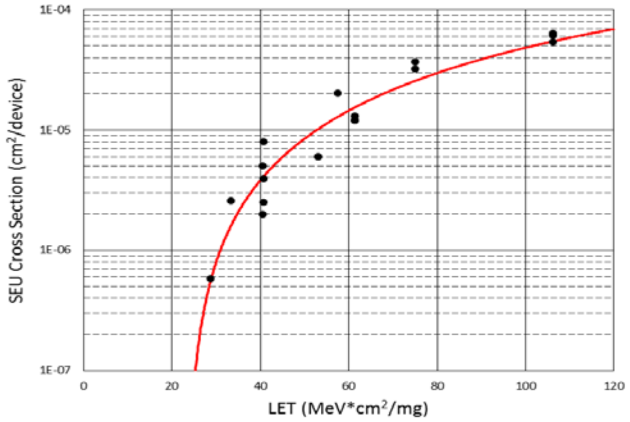


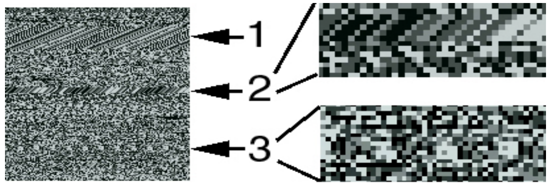
Ray Ladbury, NSREC2017 SC, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170006865.pdf

Risks abound, would you know the root cause?

- **Parts**
  - Parametric degradation and leakage currents allowable in application?
  - Downstream/peripheral circuits considered?
  - Reset/refresh capability?
  - Mitigation within too complex?
  - Predicted radiation response unknown– loss of part functionality critical?
- **Subsystem**
  - Criticality to mission that the subsystem work?
  - Interfaces allow you to get to a known state if all goes wrong?
- **System**
  - Increased power dissipation a mission ender?
  - Availability outweighed by error circumvention?
  - Data retention through reboots? What if there is science data loss?
  - Communications interruptions overwhelm?
  - Navigation or Attitude determination unable to deal with faults?

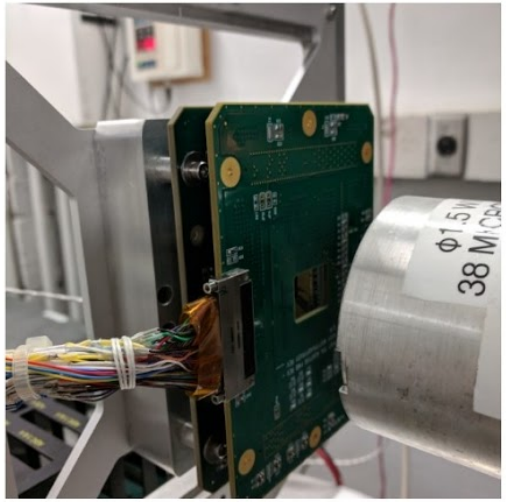
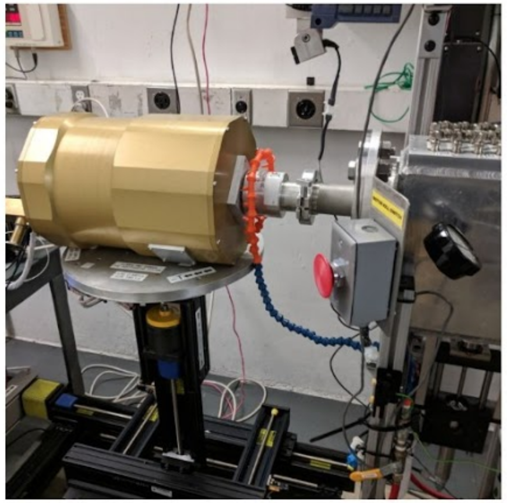


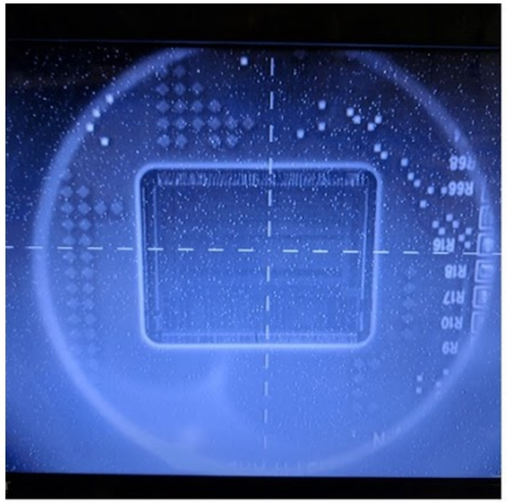




When do you test?

- **Divine your risk threshold**
  - There's a doc coming for that… radhome.gsfc.nasa.gov/nepp.nasa.gov
- **Unknown failure modes that would not be acceptable to the mission**
  - Known unknowns can be carried as a risk if you already know that the outcome is mitigated at the board or box level
  - New technologies should be identified early on
- **Fault propagation may be the problem you wish to mitigate**
  - This can include cumulative effects!
  - Fault injection may not be able to cover the state space
- **Destructive single event effects are an obvious target**
- **Can you tolerate a part replacement in your design cycle?**

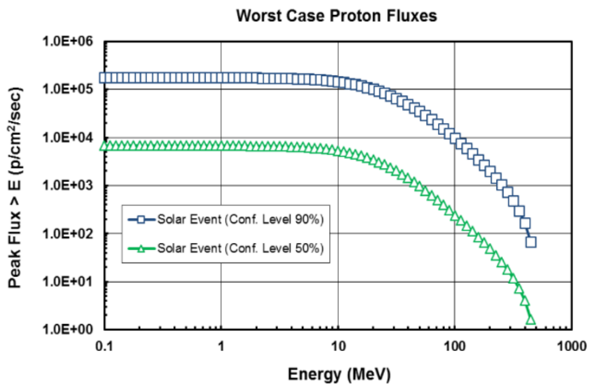


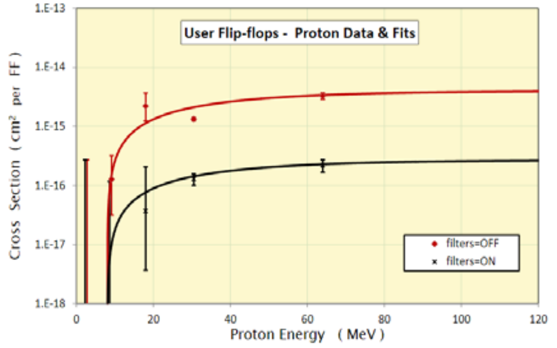
Notional SmallSat Radiation Guidelines

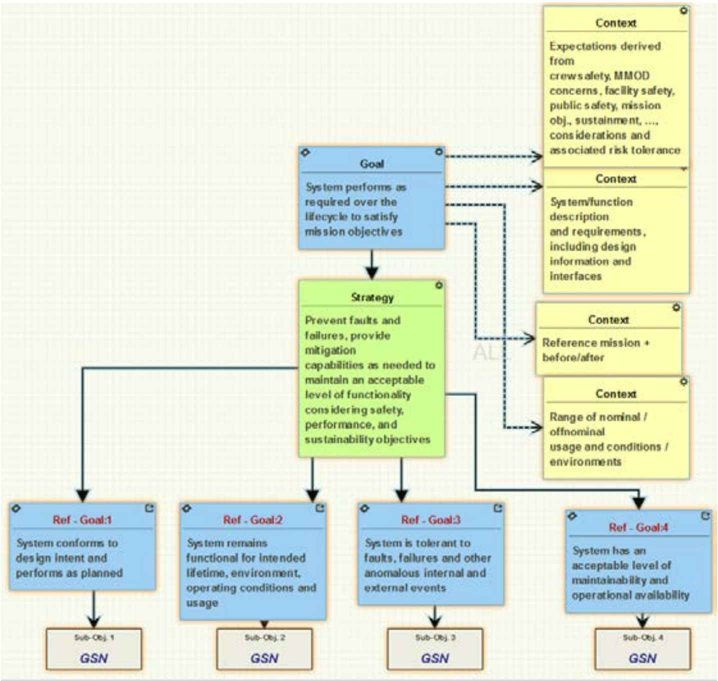
Environment

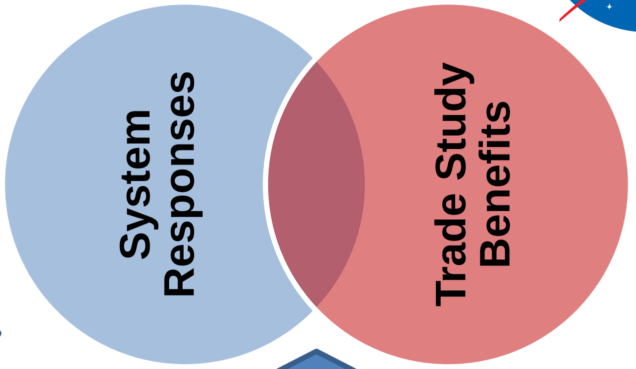
Mission Lifetime (With Assumed Risk Acceptance)	LEO Equatorial	LEO Polar (Sun Sync)	GEO / Interplanetary
> 3 Years	Data on all SEE for critical parts, and have data on dose failure distribution on similar parts	Consider mission consequences of all SEE (Data for critical parts), have Dose failure distribution on lot	Have Data on all SEE, Have Data Dose failure distribution on lot
1- 3 Years	Have Data on DSEE for critical parts	Consider mission consequences of all SEE (Data for critical parts), have data Dose failure distribution on similar parts	Have Data on all SEE for critical parts, Have Data on Dose failure distribution on similar parts
< 1 Year	Look for data on DSEE for critical parts	Consider mission consequences of all SEE, and look for data on dose failure distribution on similar parts	Consider mission consequences of all SEE, and have data on dose failure distribution on similar parts

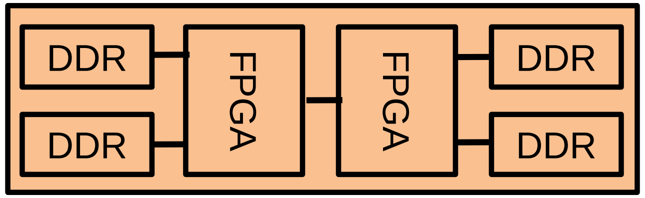
Model Based Systems Engineering as a Tool











Environment, Device, & Design

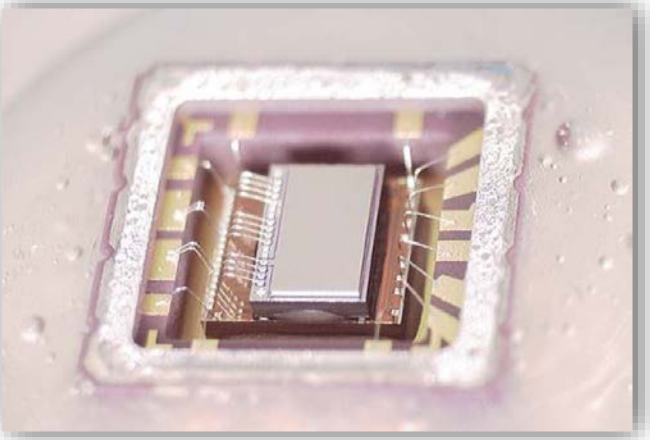
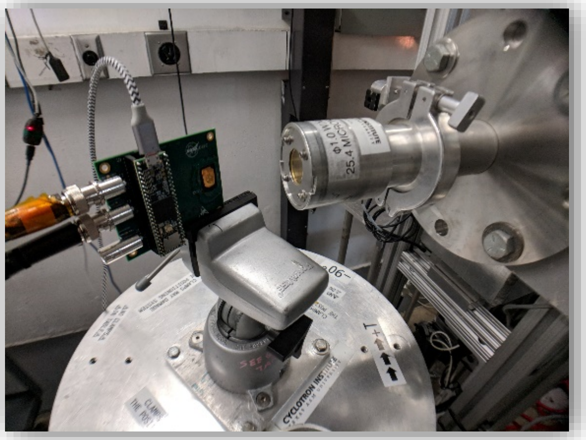
- ***Models and Test Data*** are brought together to get rates of upset / failure distributions
- ***Resources and Utilization*** are the scaling factors with criticality

Goal Structured Notation (GSN)

- Concept of operations
- ***Requirements and Availability*** are fed down correctly to subsystem
- Evidence is presented
- Assumptions are tracked

Systems Modeling Language

- Description of System Connections and Dependencies
- Receives GSN readily
- ***Fault propagation*** can be identified

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THANK YOU