

Strategies for SEE Hardness Assurance— From Buy-It-And-Fly-It to Bullet Proof

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SEE Hardness Assurance as Risk Management



- Identify the Threat
 - Space Radiation Environment
 - SEE Susceptibilities of technologies
- Evaluate the Threat
 - $\text{Risk} = \text{Probability(SEE)} \times \text{Consequences(SEE)}$
 - Bound SEE probability (rate) and consequences based on SEE mode characteristics, similarity data and SEE testing, etc.
- Mitigate the Threat
 - Can design for tolerance of “likely” SEE modes even before test data available
 - Mitigation may reduce either probability of SEE or its consequences
 - SEE probability → selecting benign environment, application modification, or part substitution
 - SEE consequences → usually involves redundancy, part substitution or limiting performance

Outline

- Introduction

- Preliminary Concepts
- Types of SEE

- Classical SEE Hardness Assurance

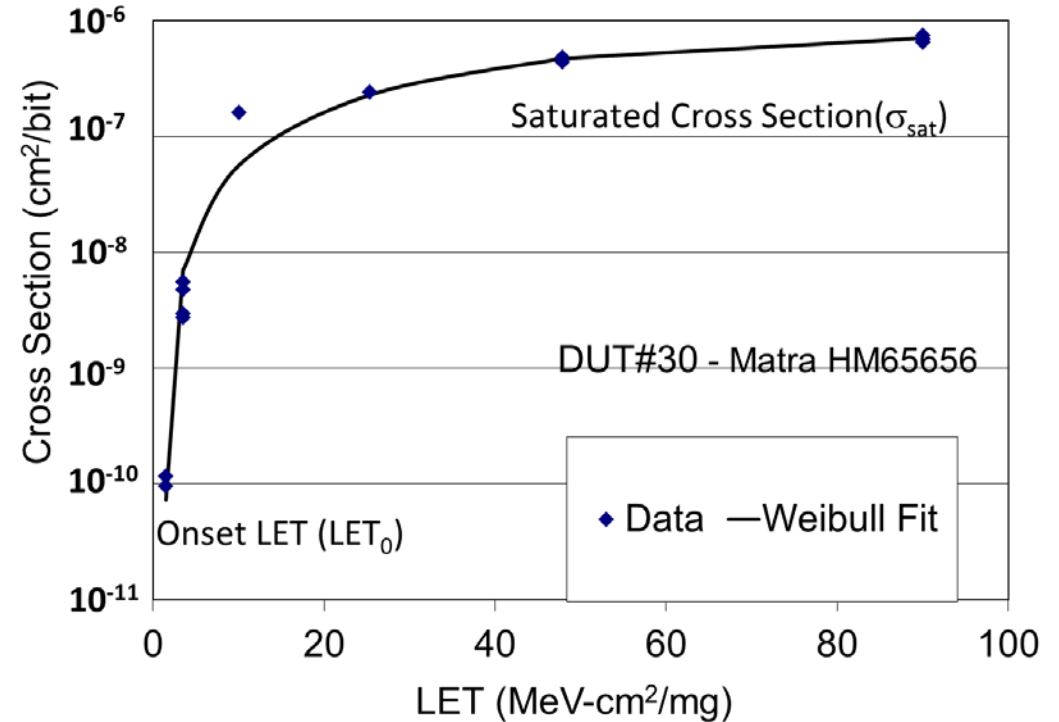
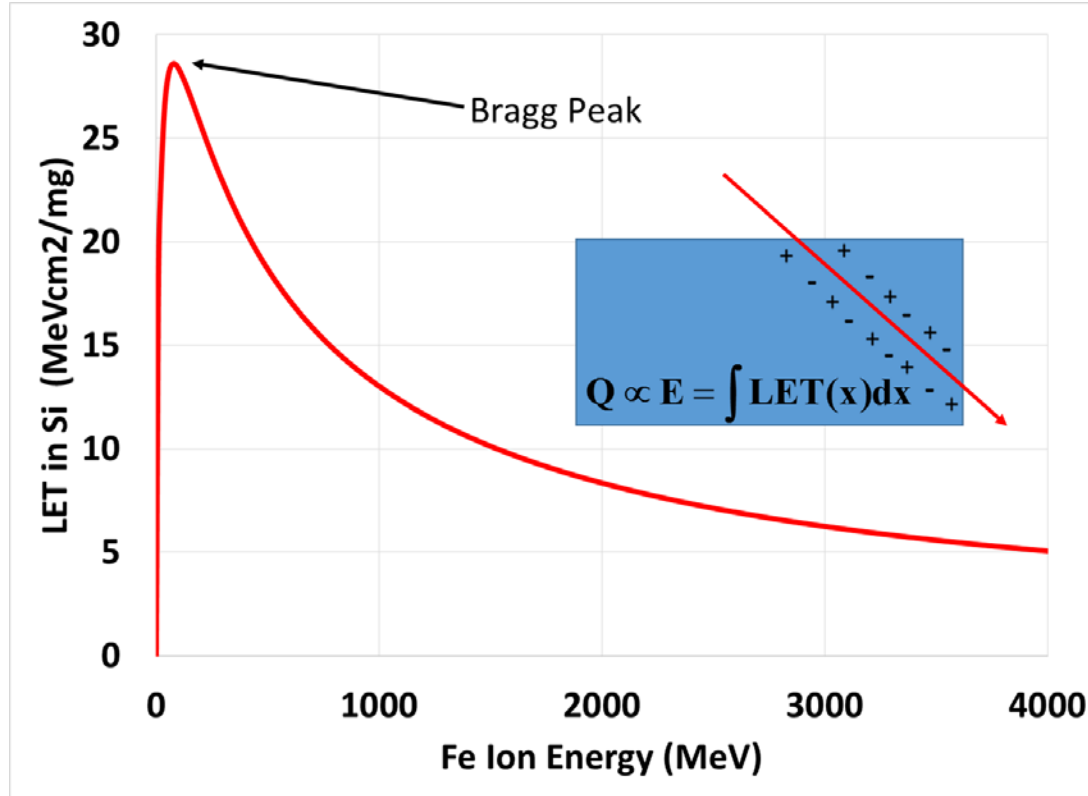
- Identify the Threat
 - Requirements, Environment, Technology Assessment and SEE Vulnerability
- Evaluate the Threat
 - Proxy data, SEE test data and analysis
- Mitigate the Threat
 - SEE Hardening Strategies

- New SEE Challenges and Opportunities

- Challenges of COTS—Profusion, Complexity and Testability
- Challenges of New Platforms—Budget, Error/Failure Tolerance and Performance
- Questioning Assumptions—even fundamental ones

- Conclusions

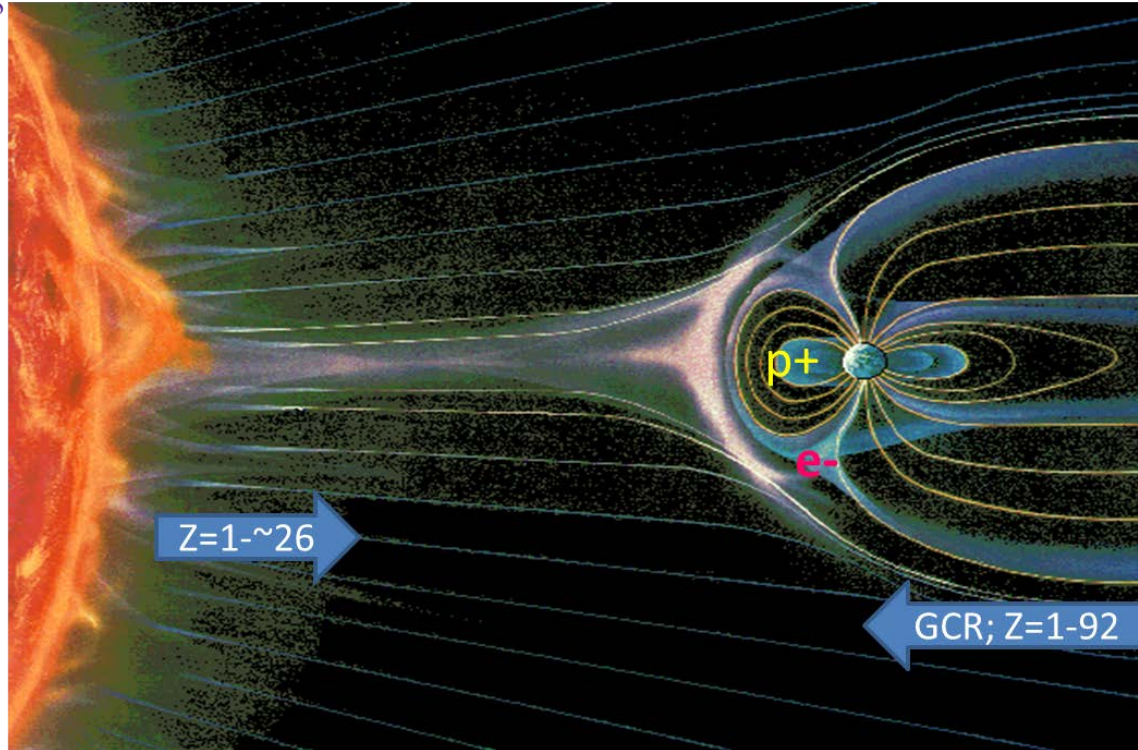
SEE Fundamentals: Cross Section and LET



- Ion energy loss rate (LET) vs. ion energy
 - Most energy loss due to ionization
 - SEE susceptibility increases w/ Q in SV

- SEE cross section, $\sigma = \# \text{ SEE} / \text{Fluence} (\# \text{ particles/cm}^2)$
- σ increases w/ Q
- If SV small and thin, LET ~ constant in SV, can replace σ vs. Q with σ vs. LET

SEE Radiation Environments

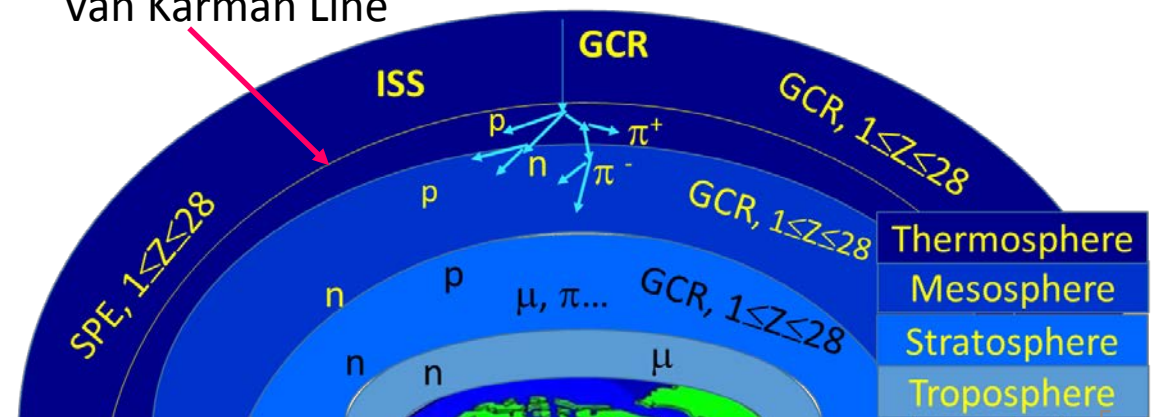


Adapted from K. Endo, Nikkei Science, Japan

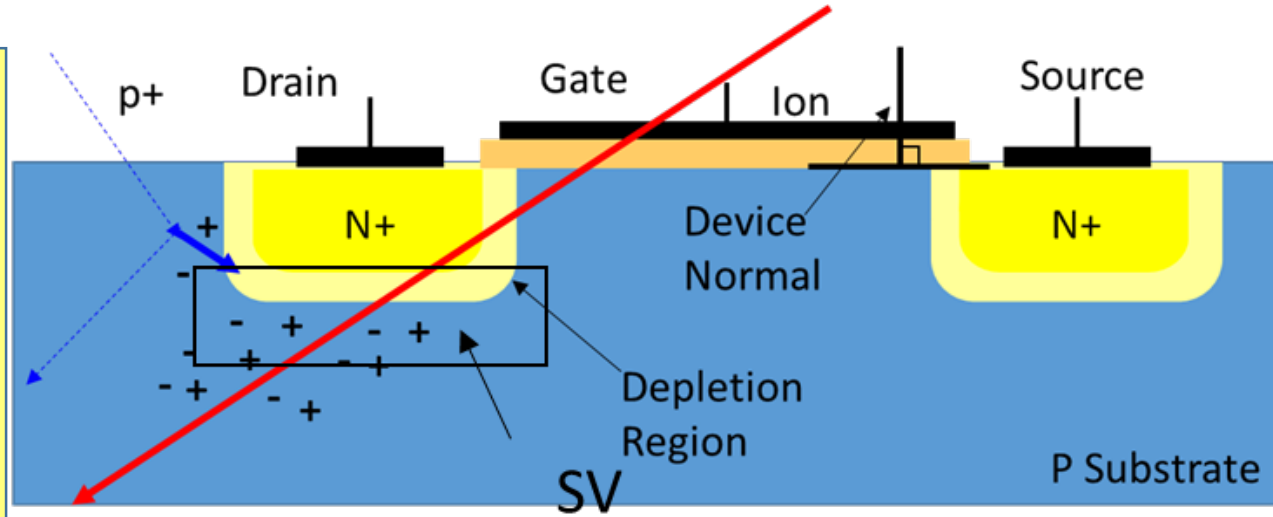
- Space radiation environment has 2 ion sources/types
 - Galactic Cosmic Rays (GCR) have Atomic # $1 \leq Z \leq 92$ and energies ~ 100 s of MeV/nucleon (shielding ineffective)
 - Solar Particle Events have $1 \leq Z \leq 26$ (mostly) and energies up to ~ 10 s of MeV/nucleon (shielding can be effective)
 - Solar protons/electrons trapped by planetary magnetic fields to form radiation belts

- Terrestrial radiation environment produced by interactions between GCR and SPE.
- Measurable GCR flux persists into the upper stratosphere
- In troposphere and at Earth's surface, mainly neutrons and muons (a few/cm²/s)
 - Flux worse near poles and at high altitude.
 - Neutrons cause SEE only by indirect ionization
 - Muons could cause SEE by indirect ionization, but low mass equates to low momentum transfer.
 - Not an issue yet at nominal supply voltages.

Van Karman Line



Single-Event Effects



- Single-Event Effect (SEE)—a change in state, stored data, output or functionality caused by passage of a single ionizing particle through a sensitive volume (SV) in the device.
 - Ionizing particle may be a primary heavy ion, secondary ion resulting from a scattering event, a primary proton (deep submicron CMOS)—or, in principle, a muon or even an electron

- SEE can occur any time w/ same probability
 - Follow Poisson statistics
 - $P(\#SEE = N) = \frac{\mu^N \exp(-\mu)}{N!}$, μ =expected #
 - Can dominate radiation risk for short-duration missions or benign radiation environments where TID failure risk minimal
- SEE consequences/mode depend on device technology and can be
 - Destructive (e.g. Single-Event Latchup—SEL)
 - Nondestructive and temporary (e.g. SET)
 - Nondestructive and recoverable (e.g. SEU)
 - Nondestructive, recoverable but disruptive (e.g. Single-Event Functional Interrupt--SEFI)
- **Affect only a single part/die**
 - Possible exceptions: overvoltage, bus contention, stacked parts

Single-Event Latchup (SEL) in CMOS

SEL: destructive SEE parasitic Silicon Controlled Rectifier (SCR = $pnpn$ structure)

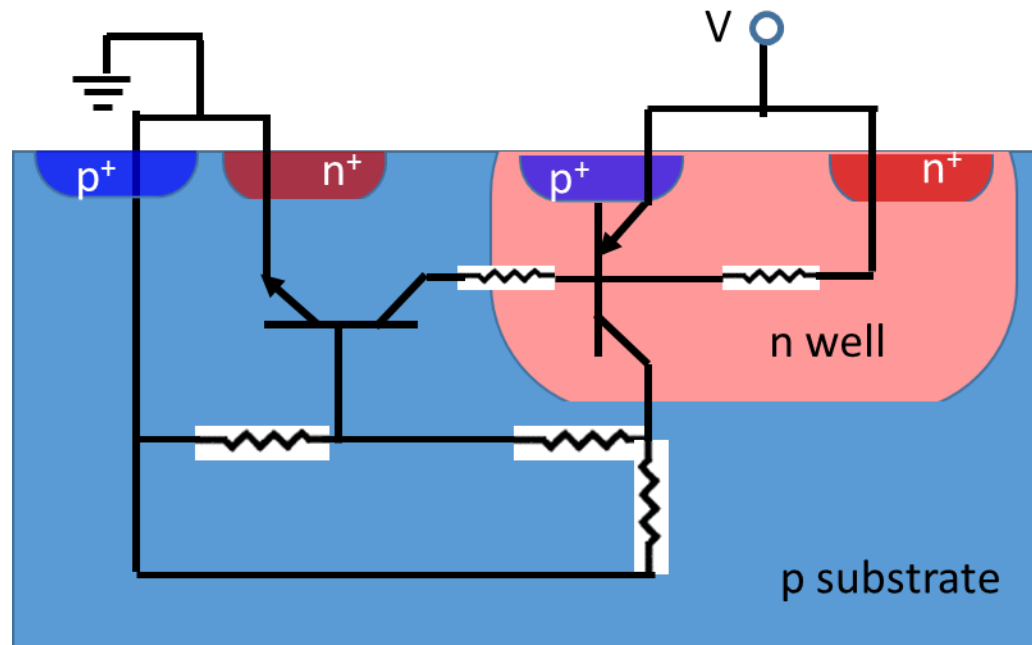
Mitigation

- 1) Cold Sparing
- 2) Replace susceptible parts
- 3) Current limit/Power cycle

SEL Consequences

- 1) Failure of Single die;
- 2) Latent damage
- 3) Loss of Functionality.

Short-range ions likely underestimate SEL risk.



Worst case: High T, V;
and ion range ~ 10s of μm

Cryogenic SEL occurs
due to carrier avalanching

Substrate involvement $\rightarrow$
SV depth $\gg 10 \mu\text{m}$;

“Similarity” value limited for SEL because SCR is parasitic

Single-Event Gate Rupture (SEGR) in Power MOSFETs

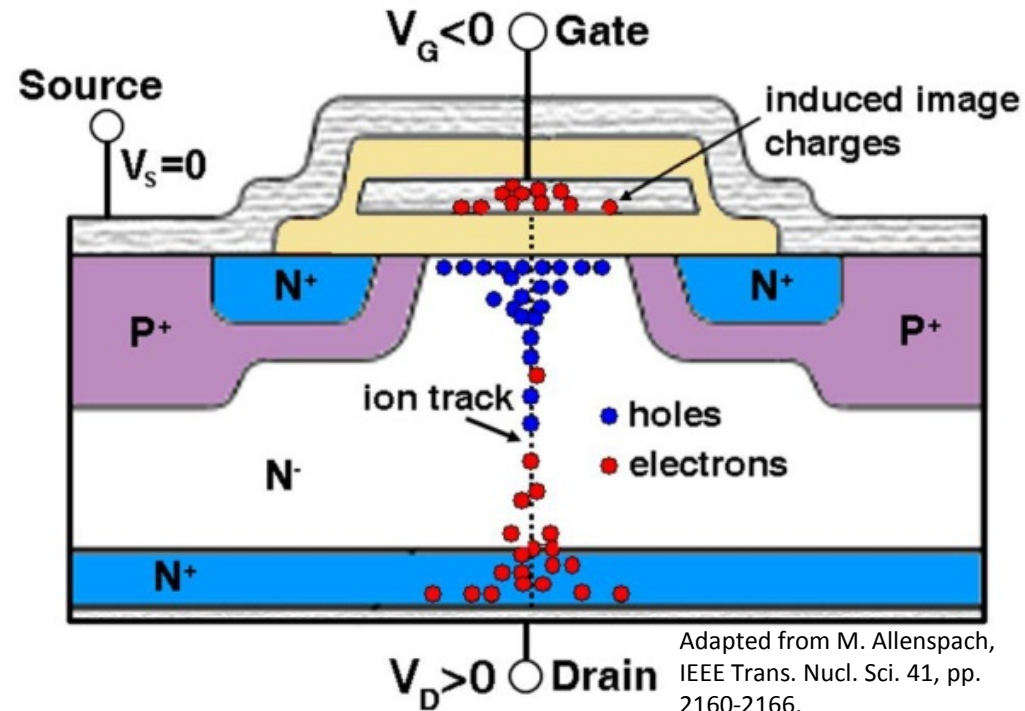
SEGR: inherently destructive failure of gate dielectric for MOSFET in OFF state

SEGR Mitigation

- 1) Derate to safe VDS, VGS
- 2) Replace susceptible part
- 3) Redundancy

Rate estimation impractical

SEGR test yields safe VDS/VGS



New technologies can introduce new vulnerabilities

Two-step process:

- 1) Ion strike weakens gate oxide,
- 2) Holes under gate rupture oxide

WC Conditions for SEGR

- 1) MOSFET OFF (nonconducting)
- 2) Higher $|V_{DS}|$ and $|V_{GS}|$.
- 3) Ions incident normal to gate
- 4) Ions having higher Z
- 5) Energy to reach below epi layer

Latent damage to gate possible

Single-Event Burnout (SEB)

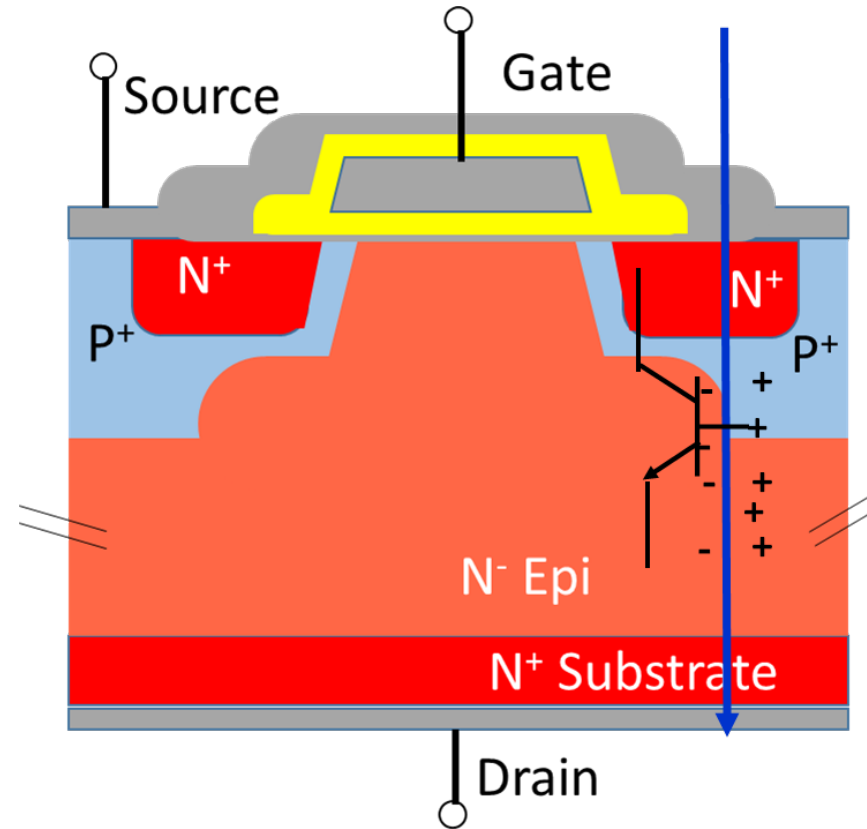
SEB: High-current parasitic BJT turned on in power MOSFET, JFET or BJT.

SEB Mitigation

- 1) Derate to safe VDS, VGS
- 2) Replace susceptible part
- 3) Redundancy

Complicated mechanism makes rate estimation impractical.
Testing gives VDS/VGS safe curve.

SEB dominates for COTS MOSFETs



WC Conditions for SEB

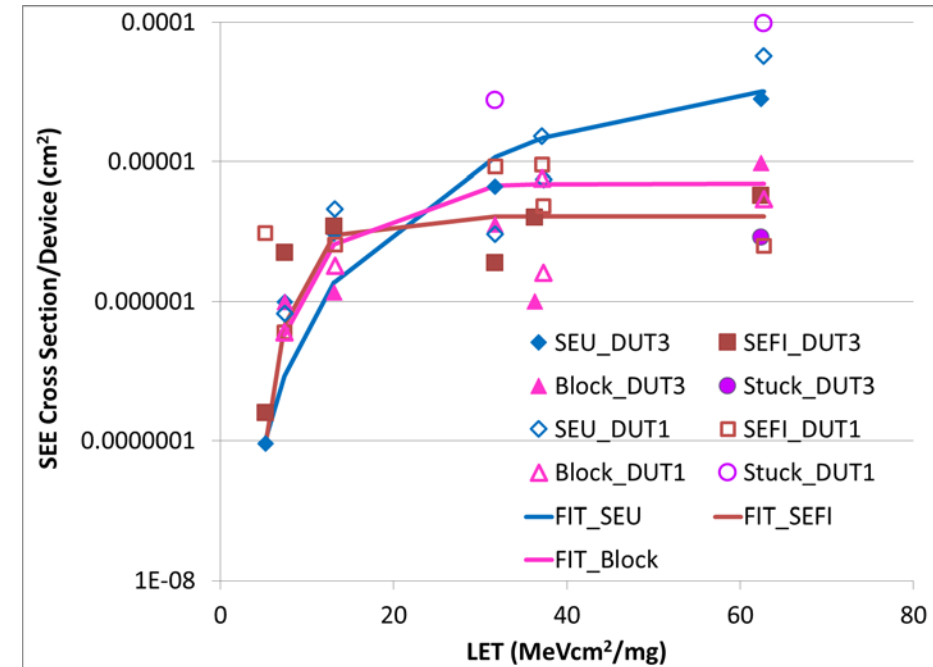
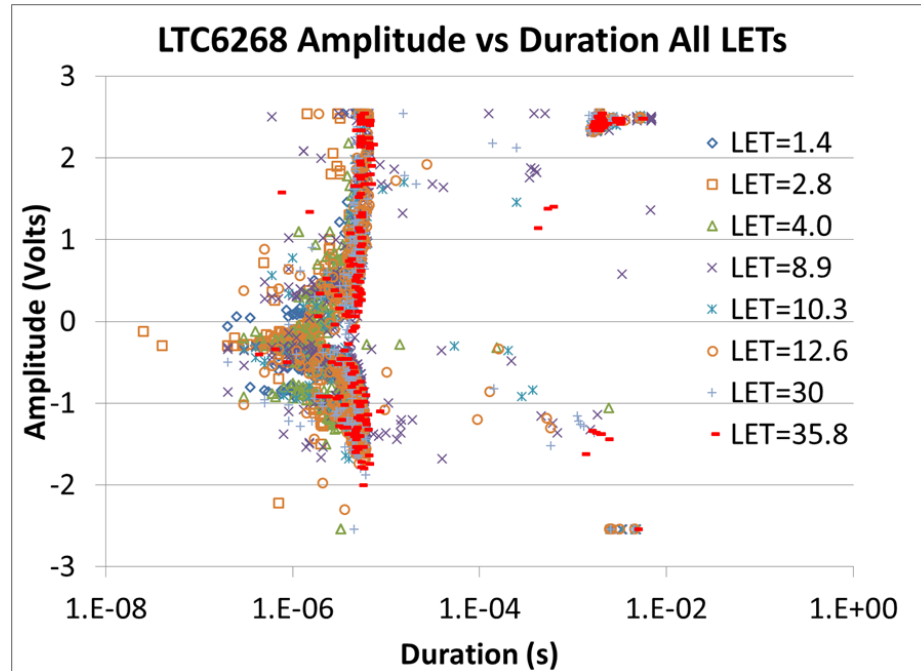
- 1) Part OFF (nonconducting)
- 2) Higher $|V_{DS}|$ and $|V_{GS}|$.
- 3) Ions incident normal to gate
- 4) Ions having higher Z
- 5) Range to reach below epi layer

Thermal latent damage possible.

σ vs. LET measurable with current limiting of SEB.

New technologies introduce new failure modes .

Nondestructive SEE



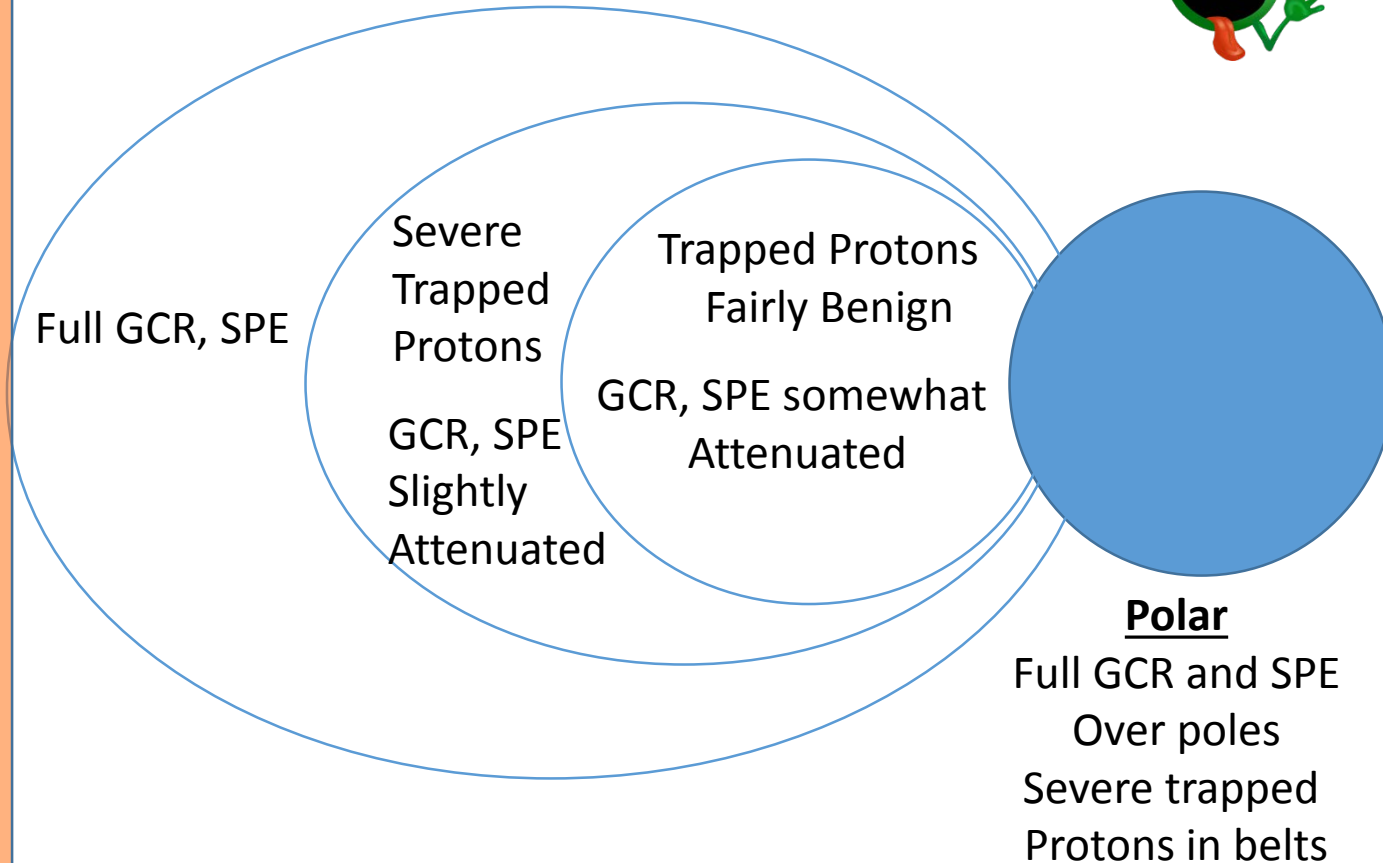
- Single-Event Transient (SET)—temporary disturbance of output of an analog or digital integrated circuit, gate, etc.
- Transient characterized amplitude and duration, as above
- Effect of transient depends on downstream circuitry
 - May be latched in downstream bistable elements
 - Could overstress sensitive devices downstream

- Single-Event Upset (SEU)—bit flip of a bistable memory cell, gate or register
- Multi-Cell and Multi-Bit Upset (MCU/MBU)—>1 bit upset by same ion is an MCU; MBU if bits in same word
- Single-Event Functional Interrupt (SEFI)—Interruption of normal device function, e.g. by upset in control logic
- Stuck Bits—permanent loss of programmability of single bit

Identifying SEE Threats: The Environment

Interplanetary

Full GCR and SPE



Polar

Full GCR and SPE
Over poles
Severe trapped
Protons in belts

- Galactic Cosmic Rays
 - Extremely high energies, so shielding has little effect, low flux
 - Cause SEE in both hardened and unhardened devices'
- Solar Particle Event Protons
 - Variable flux; Shielding has some effect
 - Main concern is for soft devices
- Solar Heavy Ions
 - Variable flux; shielding effective
 - Concern for both soft/hard devices
- Trapped Protons
 - Flux continual within belts, but worst for altitude >1000 km (0° inclination)
 - Shielding has some effect
 - Mainly a concern for soft devices

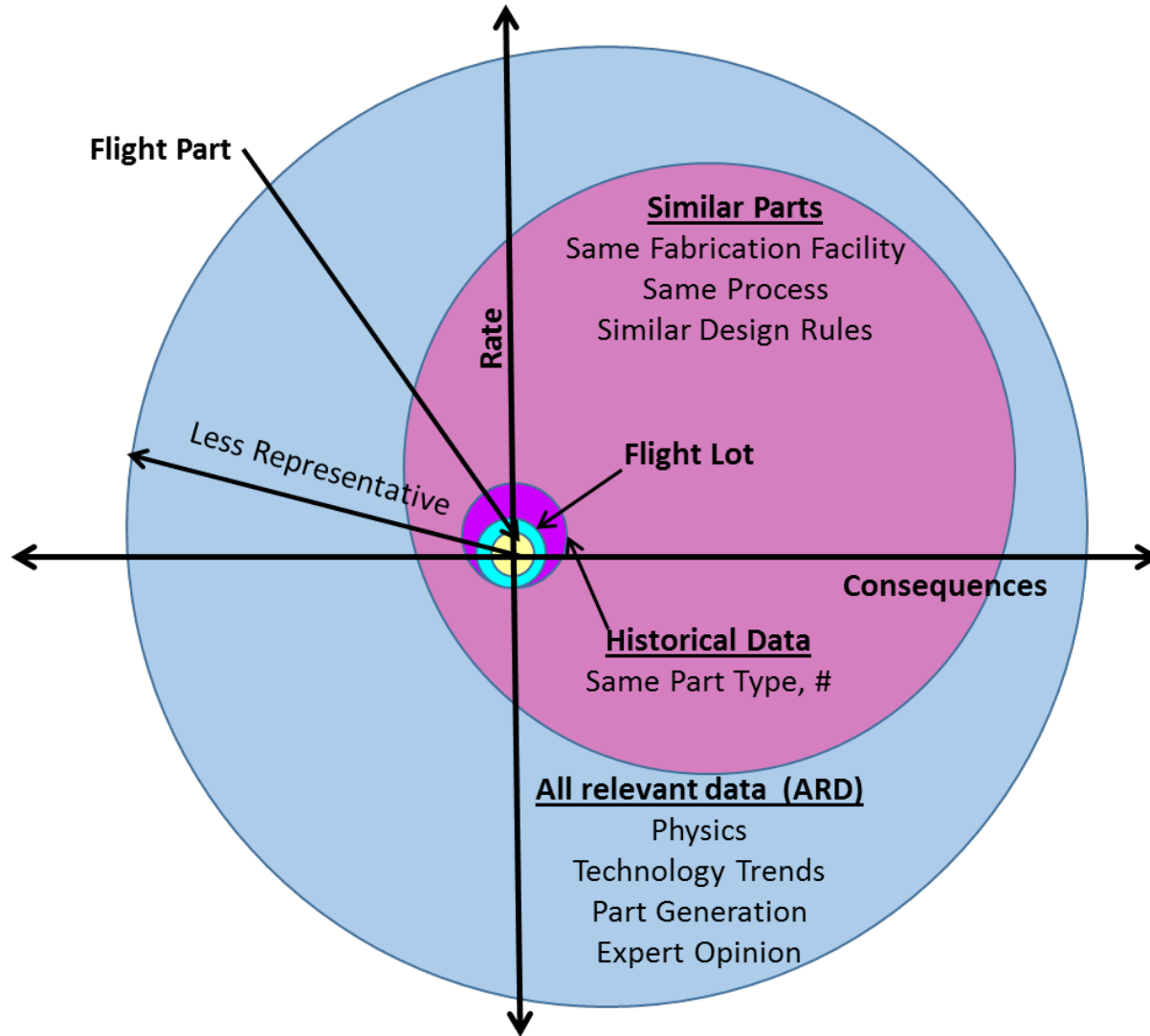
Identifying SEE Threats: Device Technologies

Common
High
Moderate
Not seen but possible

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

- Technology determines potential susceptibility
- Similar technologies often exhibit similar susceptibilities
 - GaNFETs, SiCFETs susceptible to SEGR; TrenchFETs usually susceptible to SEB
- New Technologies may exhibit new failure modes
 - SiC exhibits degradation (similar to Schottky diodes) as well as SEB and SEGR
- Commercial parts may exhibit different failure modes than rad hard counterparts
 - Commercial MOSFETs tend to fail via SEB, while rad hard MOSFETs fail due to SEGR
- Some failure modes exhibit trends with technology node, while some do not
 - Trends almost always have exceptions.

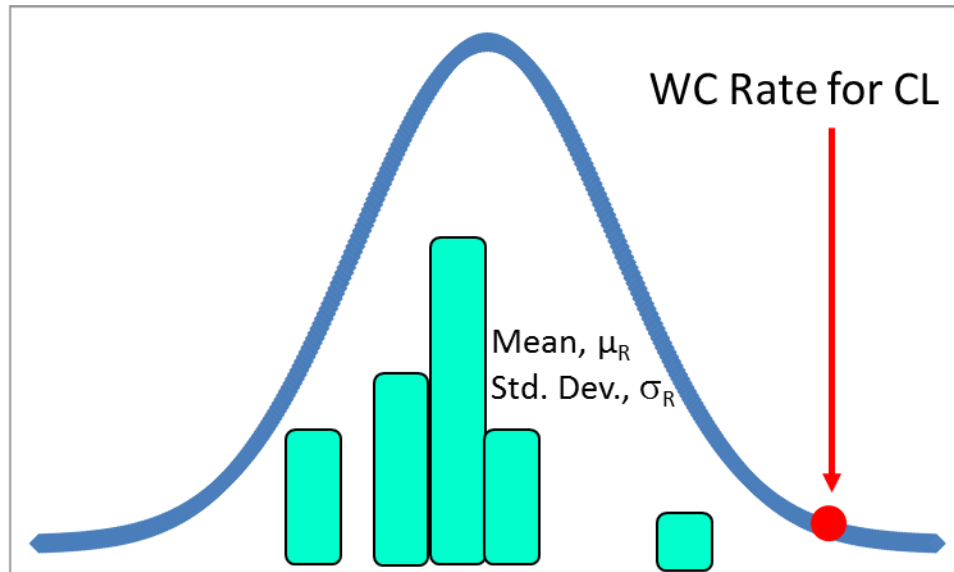
Evaluating SEE Threats: Sources of Data



- To bound SEE risk, need data constraining both SEE rates and SEE consequences.
- SEE testing destructive—cannot test flight parts
 - SEE data on sample from flight or other lot sufficiently representative
 - DSEE may vary more part-to-part and lot-to-lot
- Similarity data requires statistical model that converts data for other parts into bound on class of parts to which flight parts belong.
- Other data possibly valuable for constraining SEE risk
 - Physics (e.g. Process info and SEL susceptibility)
 - Heavy-ion data as proxy for proton SEE
 - Proton data as proxy for heavy-ion SEE
 - Technology, etc.
 - Need to have statistical/physical model to relate to flight-part SEE performance.

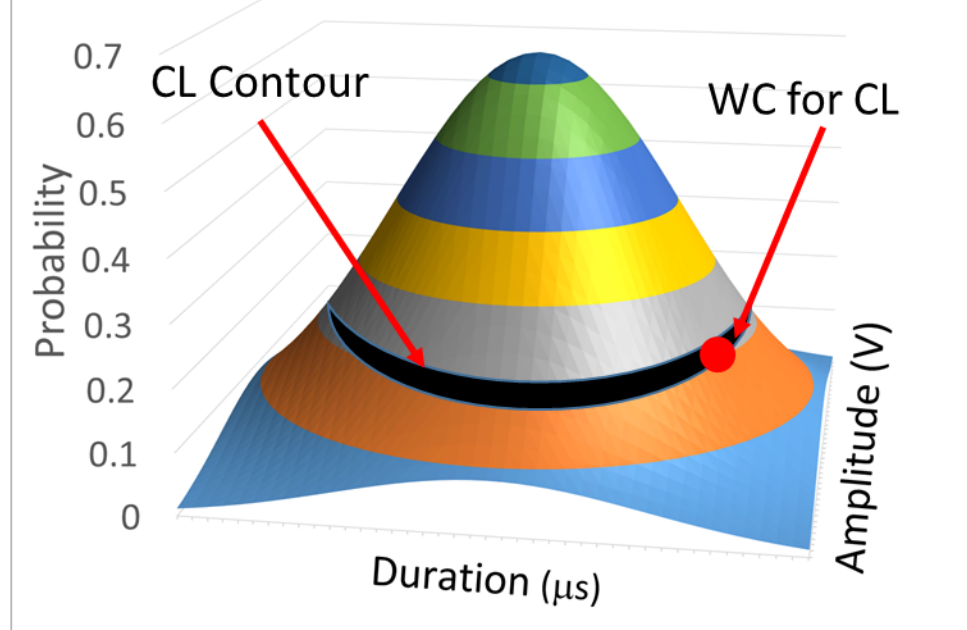
Proxy Example: SET Risk From Similarity Data

SET Rate Distribution for Parts in Process



**Lot-to-Lot Variation negligible
Part-to-Part Variation negligible
Select Rate at desired CL**

Amplitude/Duration Distribution for Process

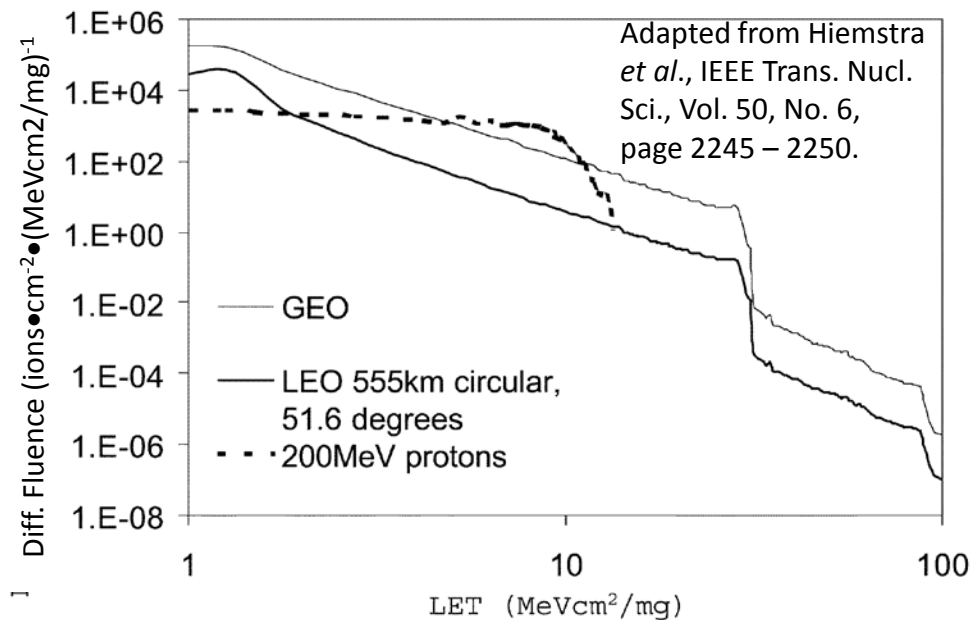


**Lot-to-Lot Variation negligible
Part-to-Part Variation negligible
Select Amplitude/Duration
at desired CL**

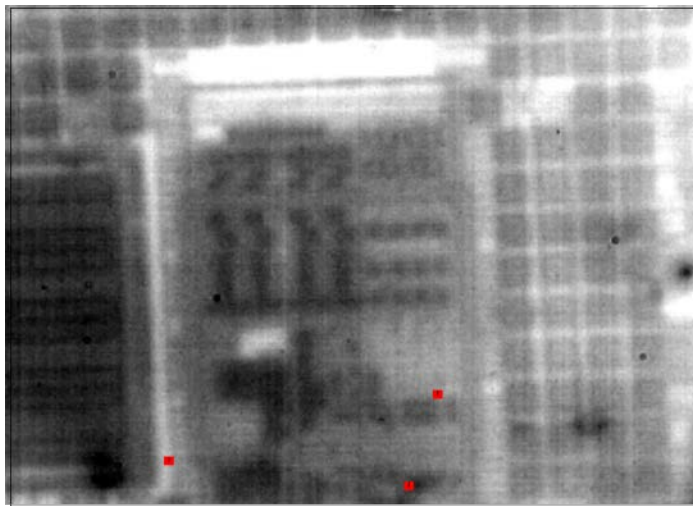
Risk of Failure due to SET

Proxy Example: Bounding Heavy-Ion SEE Risk w/ Protons

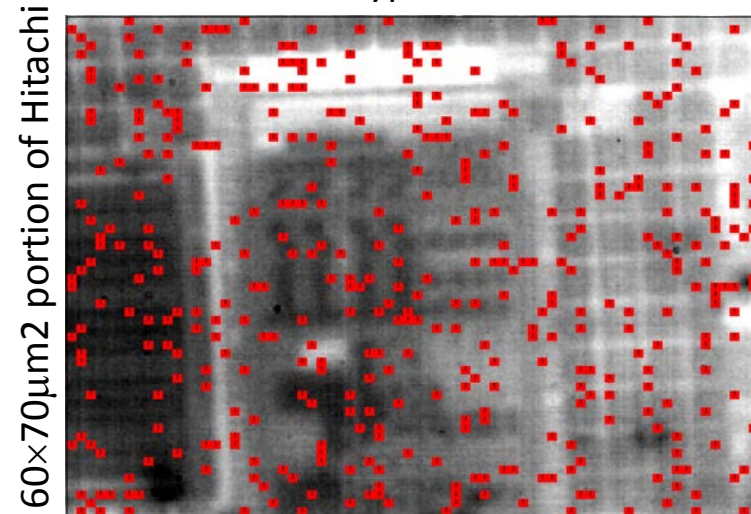
Ion Fluence: 2-yr LEO & GEO vs 10^{10} protons/cm²



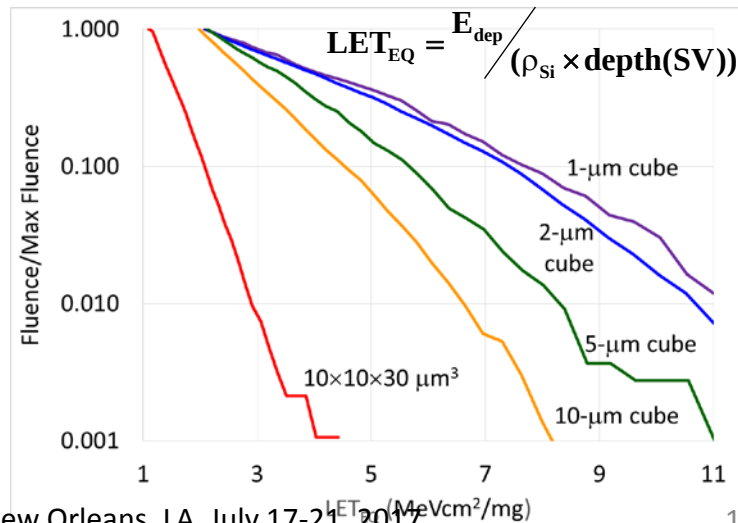
Recoil ions due to 10^{10} protons/cm²



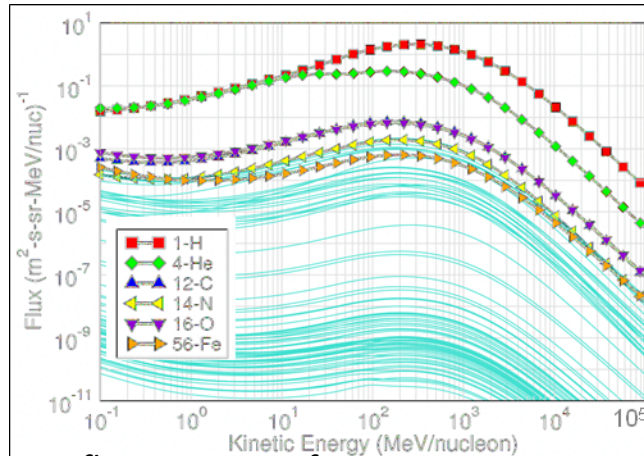
10^7 ions/cm² typical of HI SEE test



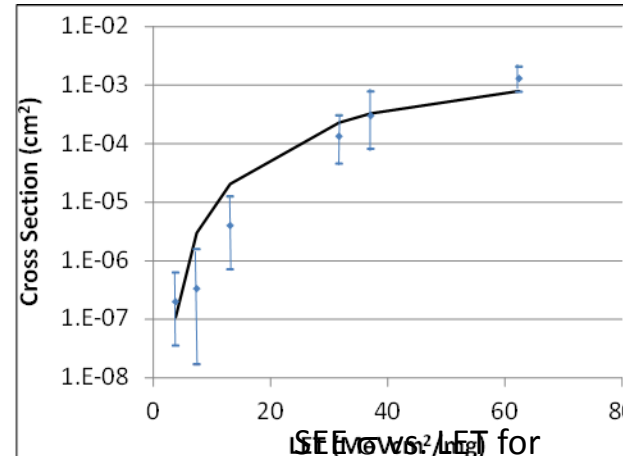
- Protons cause SEE by indirect ionization—recoil ion responsible for SEE
- Low space ion fluxes allow bounding ion fluence w/ LET < 10 MeVcm²/mg
- Testing possible without extensive modification of parts
- Caveats:
 - Only ~1/289000 protons generated recoil ion—coverage poor
 - For DSEE and other SEE w/ deep SV, charge limited by ion range, not LET



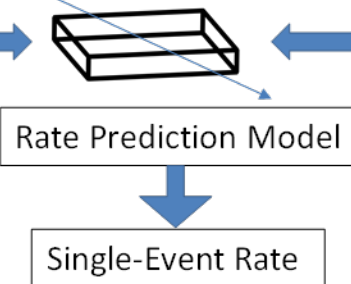
SEE Testing: Goals Differ for Different SEE modes



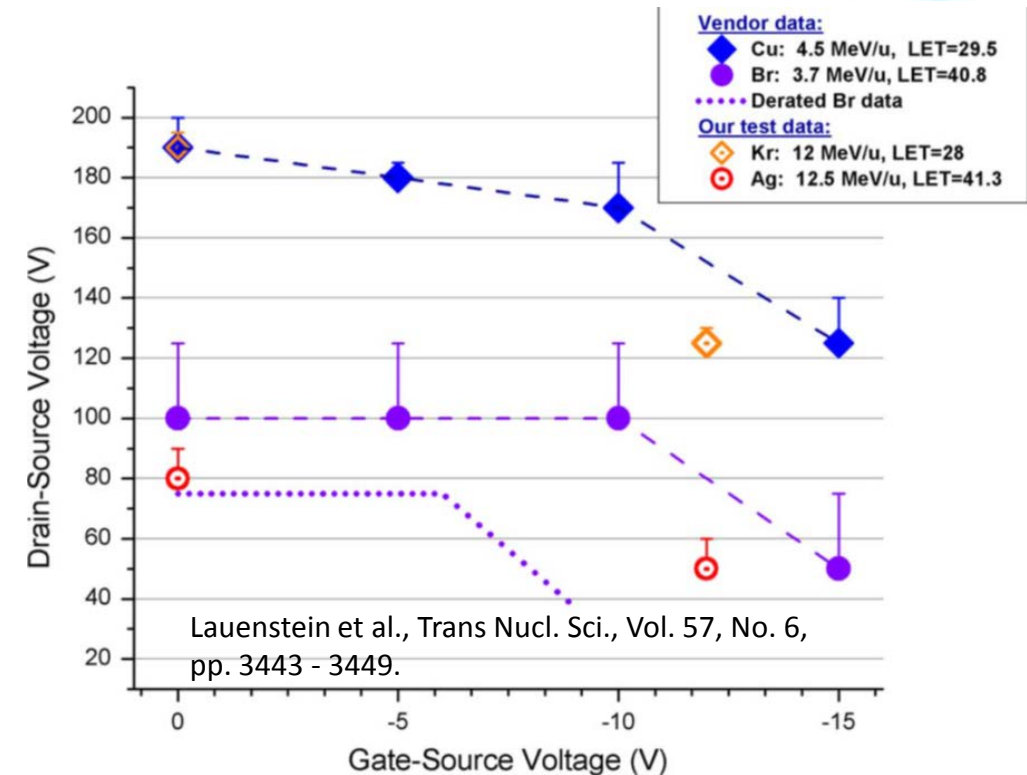
Ion flux vs. energy for
Z=1-92 from CREME96



SEE cross section for
heavy ions



- Most SEE tests seek to map device susceptibility (measured by SEE cross section σ) vs. LET
- σ vs. LET then combined with radiation model for mission environment to calculate mission specific rate

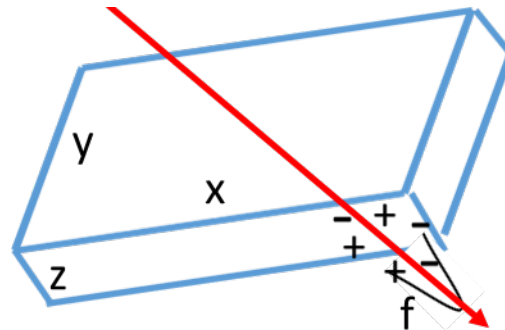


Lauenstein et al., Trans Nucl. Sci., Vol. 57, No. 6,
pp. 3443 - 3449.

- For SEB/SEGR, mechanism is too complicated to allow for rigorous rate estimation
- Need to avoid risk by mapping out application voltages where part susceptible
 - Result is Safe Operating Area

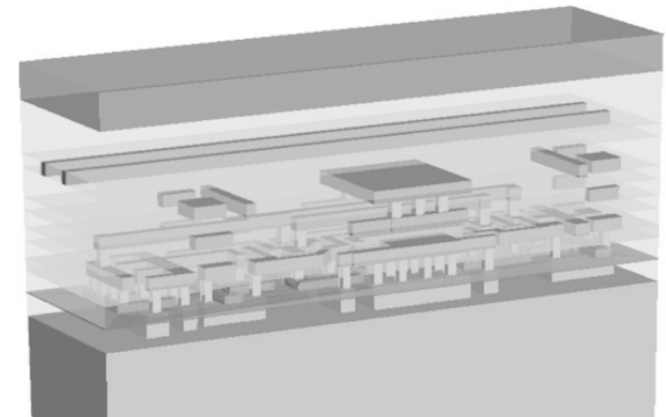
Goals of SEE Testing: Rate Estimation

- Buchner's Rule-Only 2 SEE rates matter: zero and nonzero
 - Can be accomplished with a single heavy-ion test run to high fluence ($>10^7$ ions/cm²) and high LET
 - Does not allow comparison beyond go/no-go
- Rectangular Parallelepiped (RPP) Model requires ≥ 4 parameters related to Weibull fit to σ vs. LET
 - LET₀—onset LET
 - σ_{sat} —saturated cross section for Weibull fit
 - w and s—Weibull width and shape parameters
 - Possible to predict rate to factor of 2x
 - Other parameters, x, y, z, f=funnel
- Assumes
 - simple slab SV geometry
 - LET constant along chord length



- Figure of Merit, $\text{FOM} = C(\text{Env}) * \sigma_{\text{sat}} / (\text{LET}_{0.25})^2$
 - C(Env) depends on radiation environment
 - Requires runs at a few LET values (>3)
 - Rates are ~order of magnitude, allowing comparison
 - Can be used for protons or heavy ions
- Monte Carlo Rate Estimation (e.g. CRÈME-MC)
 - Determines rate by propagating realistic ions through realistic model of device structures
 - Better device models yield better results
 - Usually used when device structure is complicated (e.g. multiple sensitive volumes) or when deviations from constant ion LET important

Adapted from Warren et al.,
," IEEE Trans.Nucl. Sci., vol. 54,
no. 6, pp. 2419–2425.



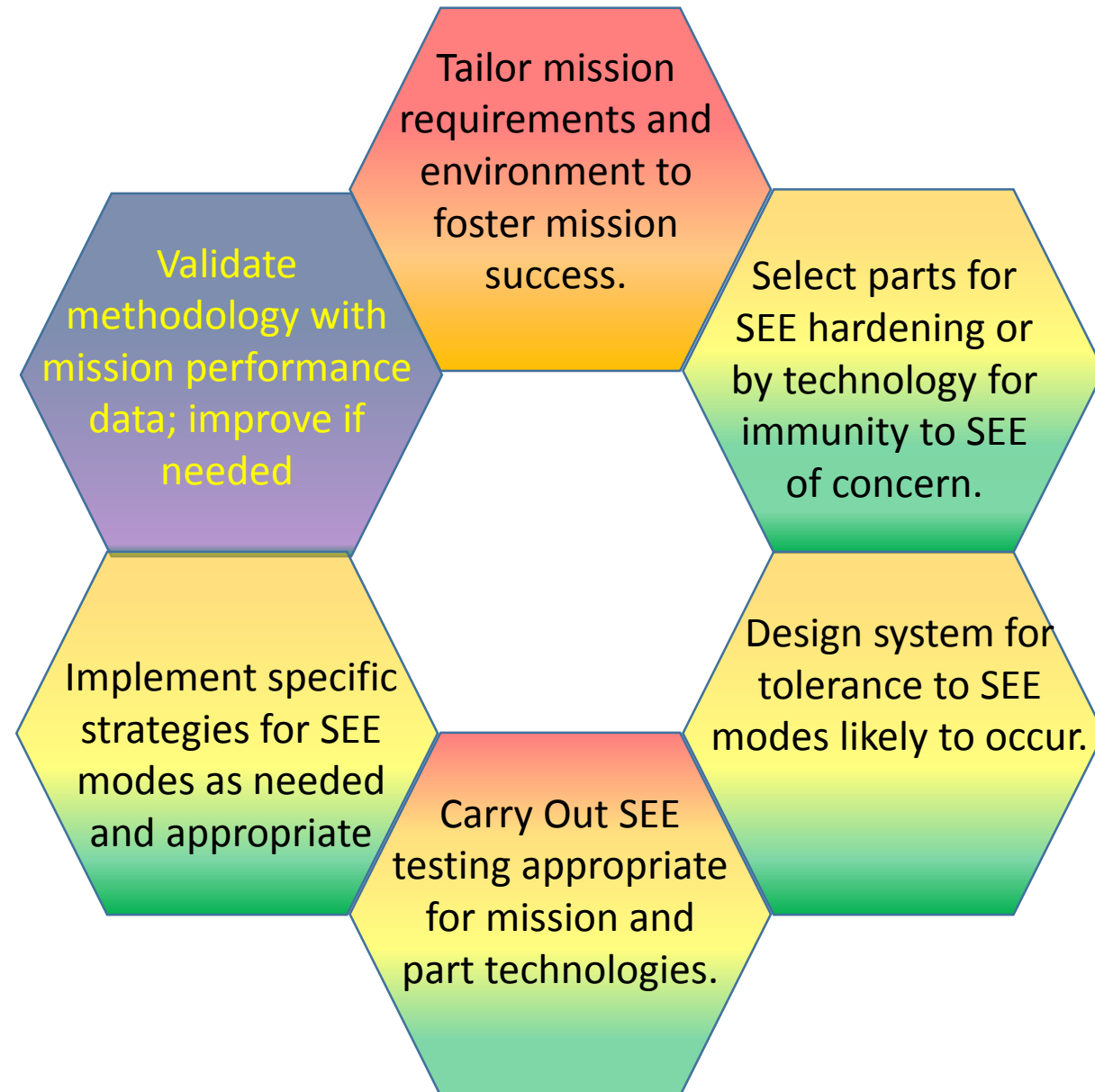
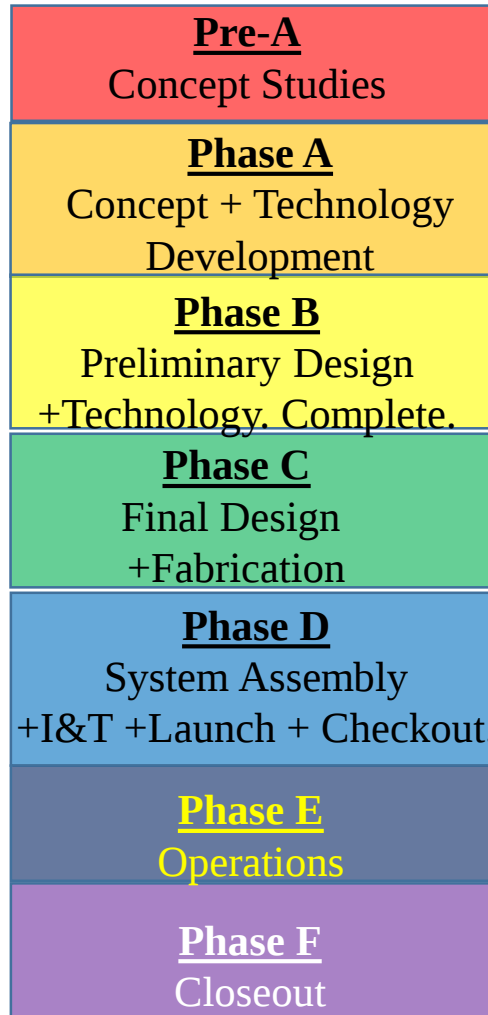
Carrying out the SEE test

- SEE Testing Standards

- JESD-57: Test Procedures for the Measurement of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation
 - Revision just completed
- ASTM-F1192: Standard Guide for the Measurement of Single Event Phenomena (SEP) Induced by Heavy Ion Irradiation of Semiconductor Devices
 - Revised in 2011
- MIL-STD-750, *Test Method 1080 Single Event Burnout and Single Event Gate Rupture*
 - Revised 2012
- ESCC 25100, *Single Event Effects Test Method and Guidelines* from European Space Components Coordination (ESCC)
 - Revised 2014
- Testing usually carried out for worst-case/bounding application conditions
 - Examples: SEL @ high temperature and voltage; SEGR: Ions at normal incidence, Z of ion > 28, VDS/VGS bounding
 - Ensures detection of susceptibility if present in device
- Observation: There is no *single* SEE test methodology
 - For each SEE test mode—method is optimized to ensure susceptibility detected if present in part
 - Ion characteristics, application conditions usually include worst-case for SEE mode.

Mitigation Can Happen at All Phases of Mission

NASA Mission Phases



Mitigating SEE Risk

Decrease SEE Risk

Decrease SEE Rate/Probability

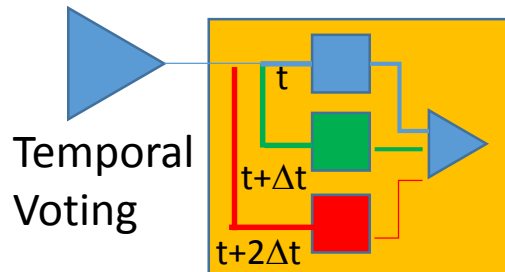
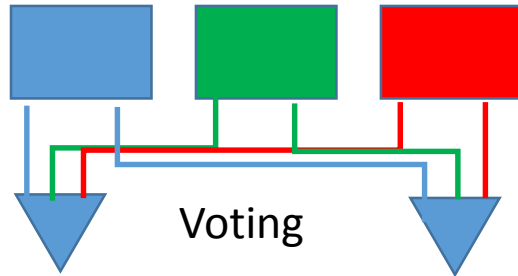
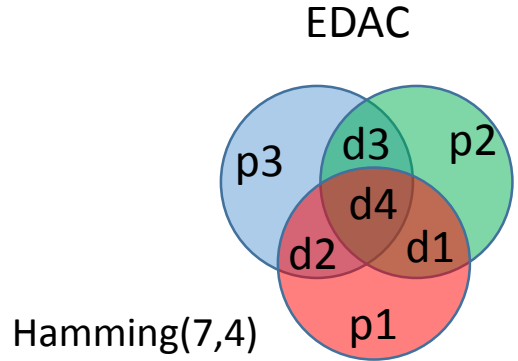
Strategy	Comments
Part Substitution	Need specific data; performance hit?
Select Application Conditions to Minimize Rate	Need specific data; performance hit?
Opportunistic Strategies	e.g. ΔV_{in} effect on LM139 SETs; bit interleaving; need specific test data
Limit performance to Requirements	e.g. RC filtering of SETs, limit frequency to reduce SETs

Decrease SEE Consequences

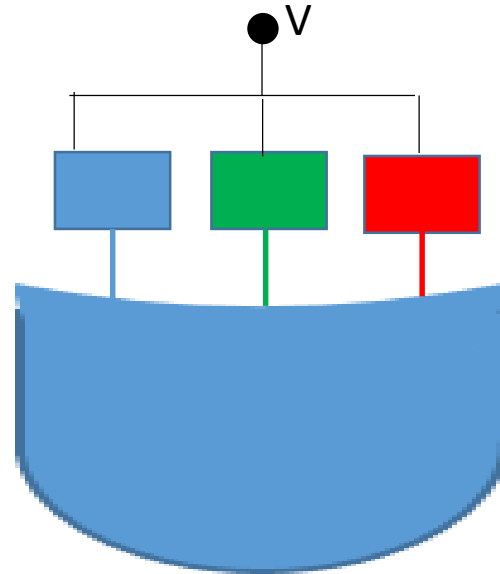
Strategy	Comments
Part Substitution	Need specific data; performance hit?
Select Application to minimize Consequences	Need specific data; performance hit?
Redundancy	e.g. EDAC, Voting, cold sparing. Can decrease reliability if done poorly.
Speed detection and recovery	e.g. Watchdog timers; error checking automated recovery

Redundancy—Must Pay In The Currency of The Realm

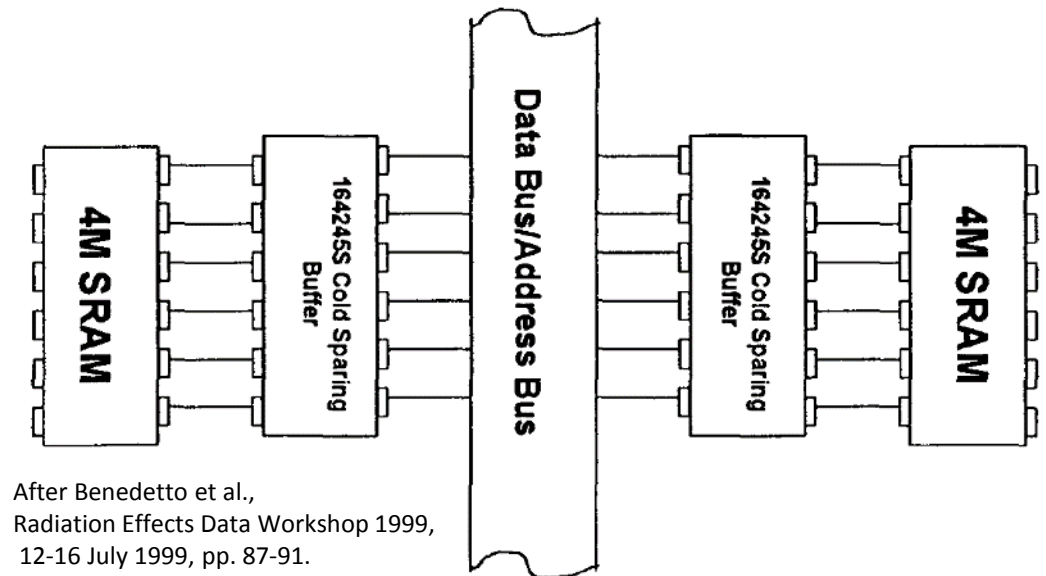
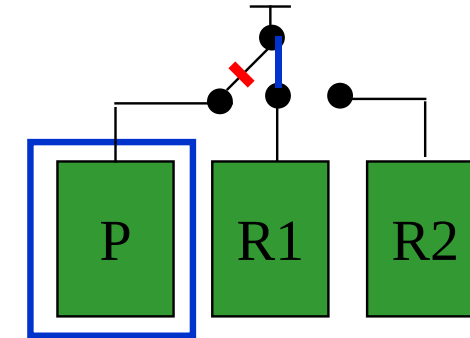
Data Accuracy



Availability



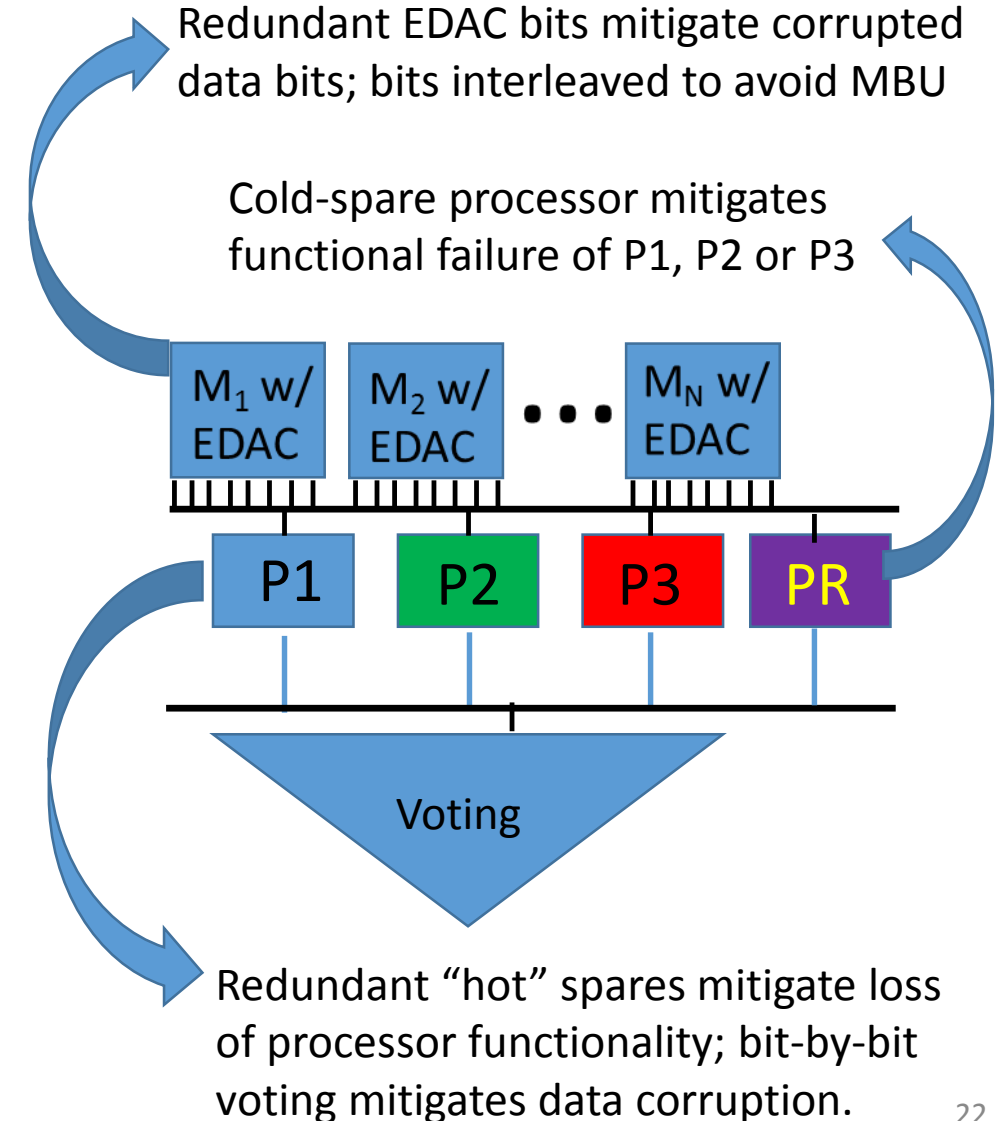
Survivability



After Benedetto et al.,
Radiation Effects Data Workshop 1999,
12-16 July 1999, pp. 87-91.

Multi-Tiered Mitigation

- Real systems often use multi-tiered SEE mitigation
- Example at right
 1. EDAC schemes can correct various #s of bits (e.g. Hamming code) or “nibbles” (e.g. Reed-Solomon 4 consecutive bits in a word)
 2. EDAC at right corrects j bits/nibble
 3. Memory architecture interleaves data across memory modules so j or fewer nibbles stored on each device
 4. Processors P1, P2, P3 vote output (propagating EDAC through entire processor algorithm usually too inefficient)
 5. PR is redundant processor—if unbiased, it is swapped in to replace failed (e.g. SEL) P1, P2 or P3; if biased, it replaces P1, P2 or P3 if unavailable (e.g. SEFI) at time of voting
 6. Memory provides data to P1, P2 and P3 (and PR if it is used to ensure availability)
 7. Capacitive filtering to mitigate transients (not shown)...
- Note that efficacy of all redundancy requires errors to be independent AND $P(\text{error/failure}) \ll 1$



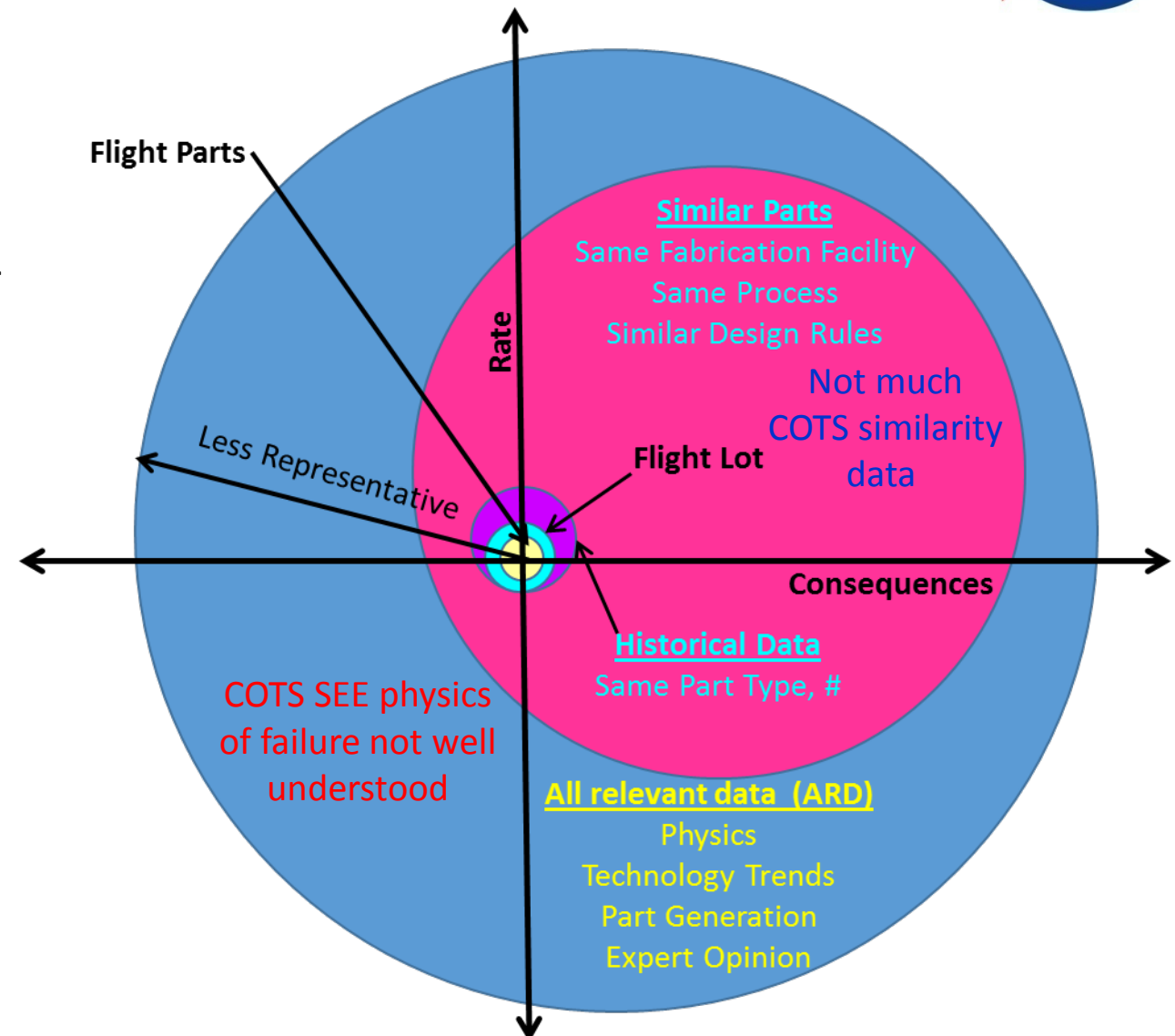
Why Harden SmallSats?

- Most SmallSats to date flown by educational institutions
 - Short turn-around time and short duration well suited to students
 - If mission fails, failure is a harsh but effective teacher
 - Consequences of failure usually not severe
 - Not a replacement for conventional missions
 - Make possible new types of missions and new players
- SmallSats could also be useful for science applications
 - Swarm missions well suited to geoscience, planetary exploration, etc.
 - Lower cost would allow “riskier” high-performance technologies
 - Single-instrument mission conceivable with a SmallSats
- Improved reliability and longer mission duration desirable
 - For important science data, stakes maybe higher
 - Longer satellite life means better time series data (fewer splices)
 - Cheaper launch costs mean more money for instruments

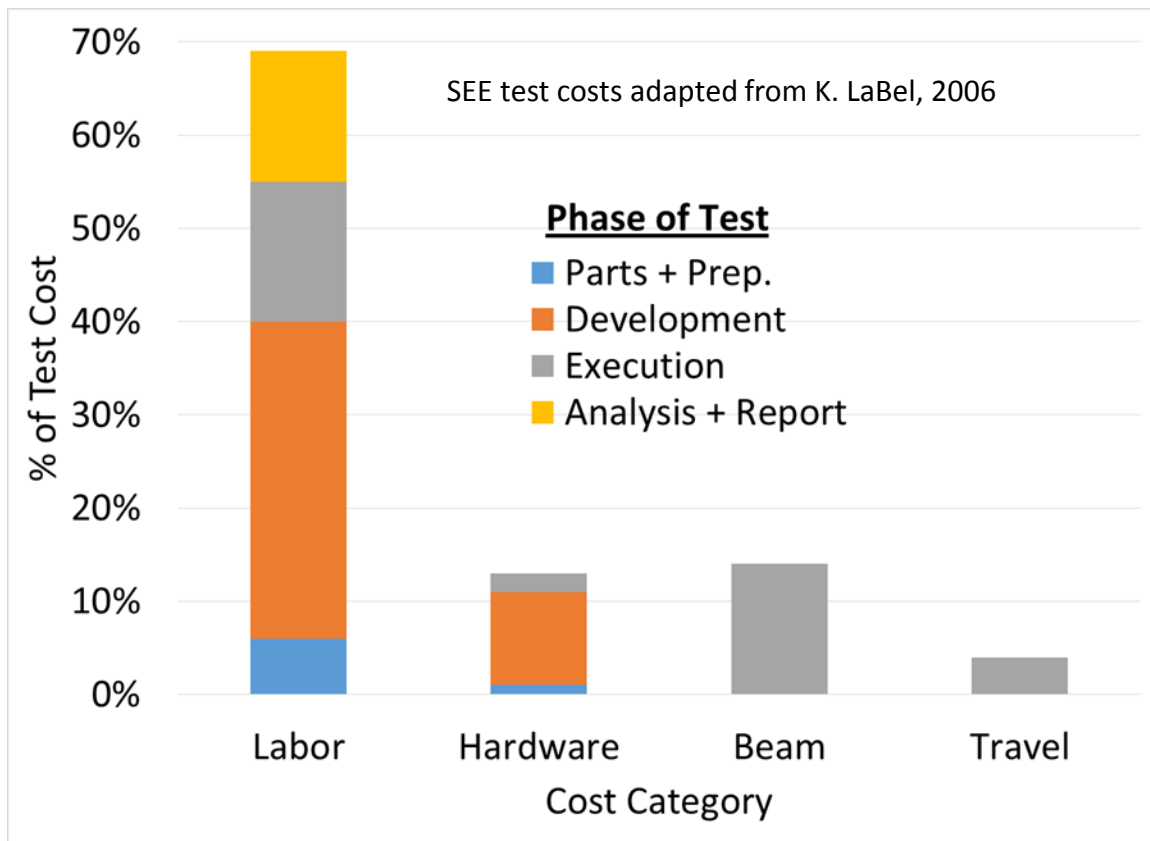
SEE Hardness Assurance for SmallSats: Challenges

SmallSats SEE HA Challenges

- Schedule critical for secondary payloads—
 - miss the date and stay on the ground
 - Delivery times for space/military parts may be longer than the mission schedule
- Budgets limited—secondary payload makes little sense if cost >> cost of launch as primary payload
- Size, Weight and Power limited
- Meeting performance likely requires parts COTS
 - Often little if any similarity or other data on COTS
- Higher risk tolerance $\neq$ lower qualification budget
- SEE test costs often dominated by part preparation and test equipment development
 - Testing less (fewer beam hours) may not save much



SEE Test Costs and Potential Savings



- SEE test costs front loaded
- Limited opportunities for savings, especially if rate estimation needed.

- Summary of 2006 Costs
 - Parts and Part Preparation~7%
 - Test development~4%
 - Tester development~40%
 - Manpower (test execution)~15%
 - Beam time~15%
 - Data analysis and Report~19%
- >50% of test cost is in development. Where are savings?
 - Less testing saves beam & manpower time, but increases risk
 - Protons save part prep and beam costs, but increase risk
 - Ultra-high energy heavy ions save prep costs , but \$\$\$\$
 - Laser saves beam costs, but may increase part prep costs
 - Very hard to reduce costs for conventional SEE testing
 - Development costs, analysis also dominated by manpower
- SmallSats COTS reliance also limits other data sources
 - Limited SEE data or physics of failure knowledge
- Conventional SEE Hardness Assurance likely beyond means of most low-budget programs.

SEE Hardness Assurance Options for SmallSats Teams

- Buy-it-and-Fly it
 - Viable if you can determine why missions fail and correct for next mission
- Board-level testing with protons or ultra-high energy heavy ions
 - “Test everything at once”
 - Can be done with protons or ultra-high energy heavy ions
- Rely on the kindness of strangers (partner w/ conventional satellite builder)
 - Left-over rad hard parts may be available
 - Larger group may provide more test and analysis capabilities
 - SmallSats may offer a test platform for new technologies of interest
- Risk-informed testing
 - Develop metric measuring consequences of possible error/failure modes
 - Use metric to prioritize testing decisions
- Strategies can be combined

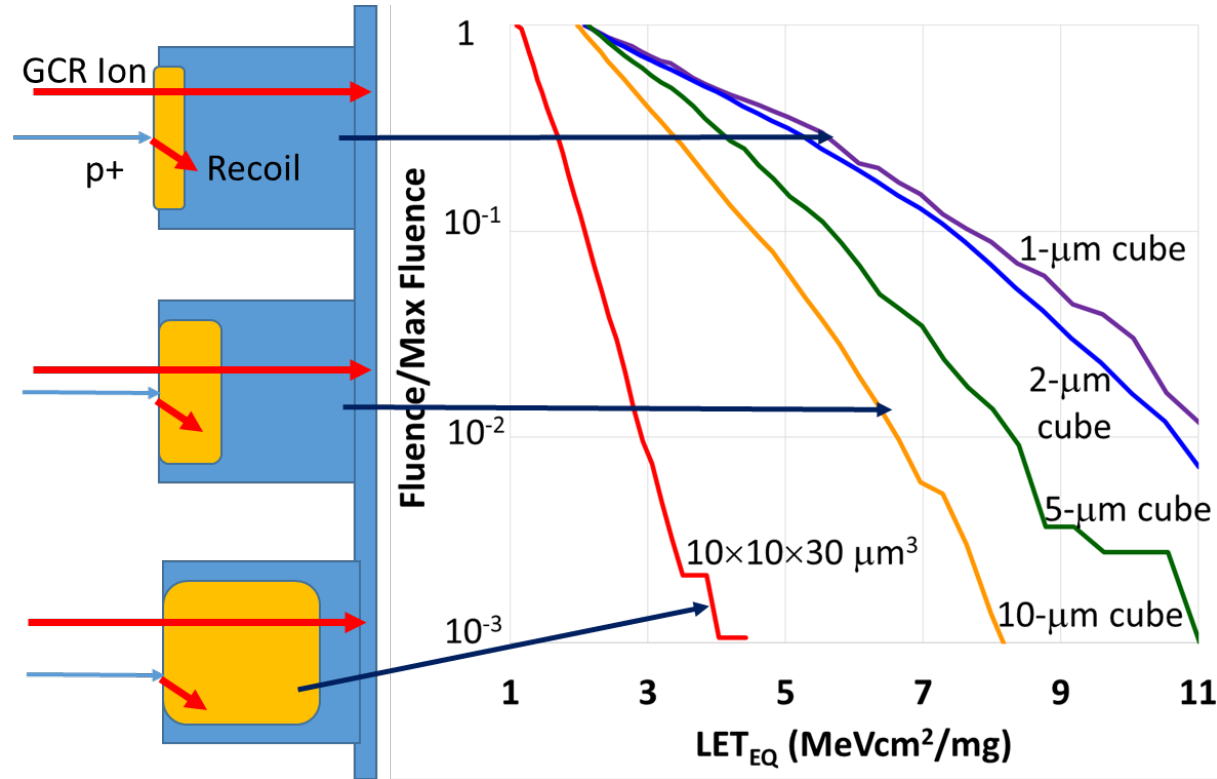
Buy-It-And-Fly-It

- COTS solutions exist for almost any satellite function
 - High performance and power achieved through use of state-of-the-art COTS parts
 - Usually no radiation data available
- Problem: If commercial system in a critical application, may never know what failed
 - Same flawed part could be used on next satellite, or good parts of design could be scrapped to avoid same failure
 - Unable to provide feedback to vendor for improvement of his product
- Diverse redundancy for critical systems could increase probability of mission success, but penalizes for SWAP and complexity
 - If the systems are commercial, how do you know the insides don't contain common-mode failures?



Gomspace FPGA-Based Software Defined Radio

Board-Level Proton Testing

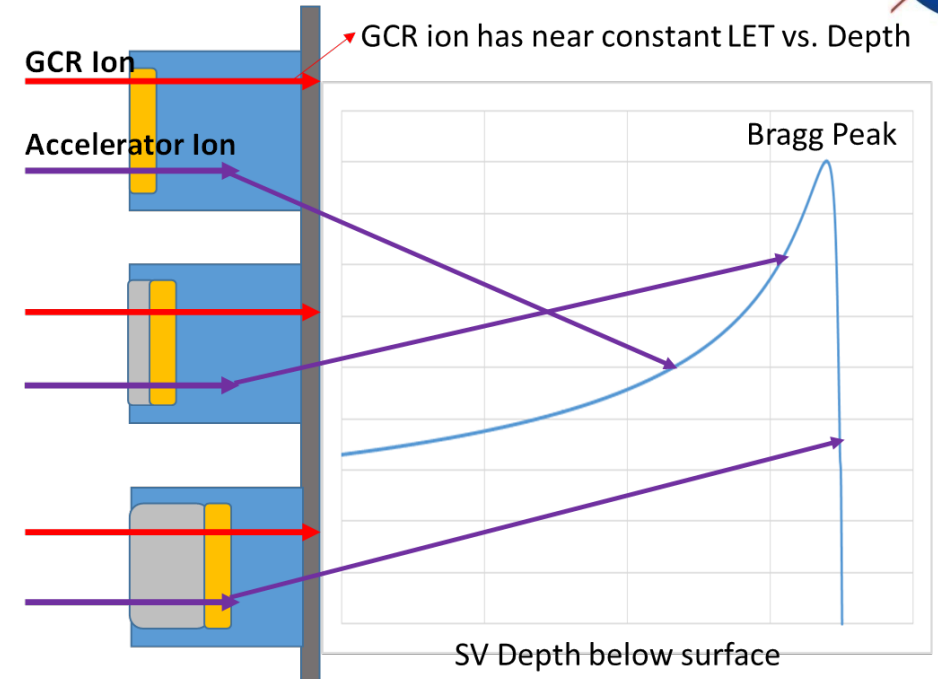


- Advantages
 - Board-level testing allows quick System SEE Assessment
 - No part preparation needed due to long proton range
 - Advanced test equipment not usually needed as diagnostic information limited to observed errors and functionality of system
- Disadvantages
 - Will mask some SEE that could affect operations
 - Not possible to test WC for every part type
 - Protons may not reveal destructive SEE modes
- Difficult to interpret results
 - If part-to-part variability significant for any parts in system, test unit performance may differ from flight performance

- In part-level proton testing, characteristics of ion that caused SEE unknown
- In board-level SEE testing, even the distribution of ion LETs responsible for SEE results unknown
- May be better able to decrypt results if device technologies (e.g. epi thickness) known

Board-Level Testing Also Possible with Ultra-High Energy Ions

- Heavy-ion board-level testing has similar advantages and disadvantages to proton board-level testing, except:
 - Advantages
 - Much more likely to reveal destructive SEE
 - Ion characteristics that cause a given SEE are known, allowing some understanding of mechanisms
 - Disadvantages with available ultra-high energy ion beams
 - Insufficient energy/range to test multiple boards
 - Insufficient energy/range to penetrate overburden on some parts
 - Beam time costly (~\$5000/hr.)
 - Selection of ions limited and retuning needed (~8 hr.) for change
- For ultra-high energy ion beams w/ limited ions, σ vs. LET curve constructed using variable-depth Bragg peak method
 - Ion beam energy degraded until cross section for SEE mode is saturated—if device overburden known, can calculate LET
 - If device overburden unknown, can further degrade ion beam until ion ranges out
 - Decrease degradation to get additional LET points
 - Not well suited for board-level testing

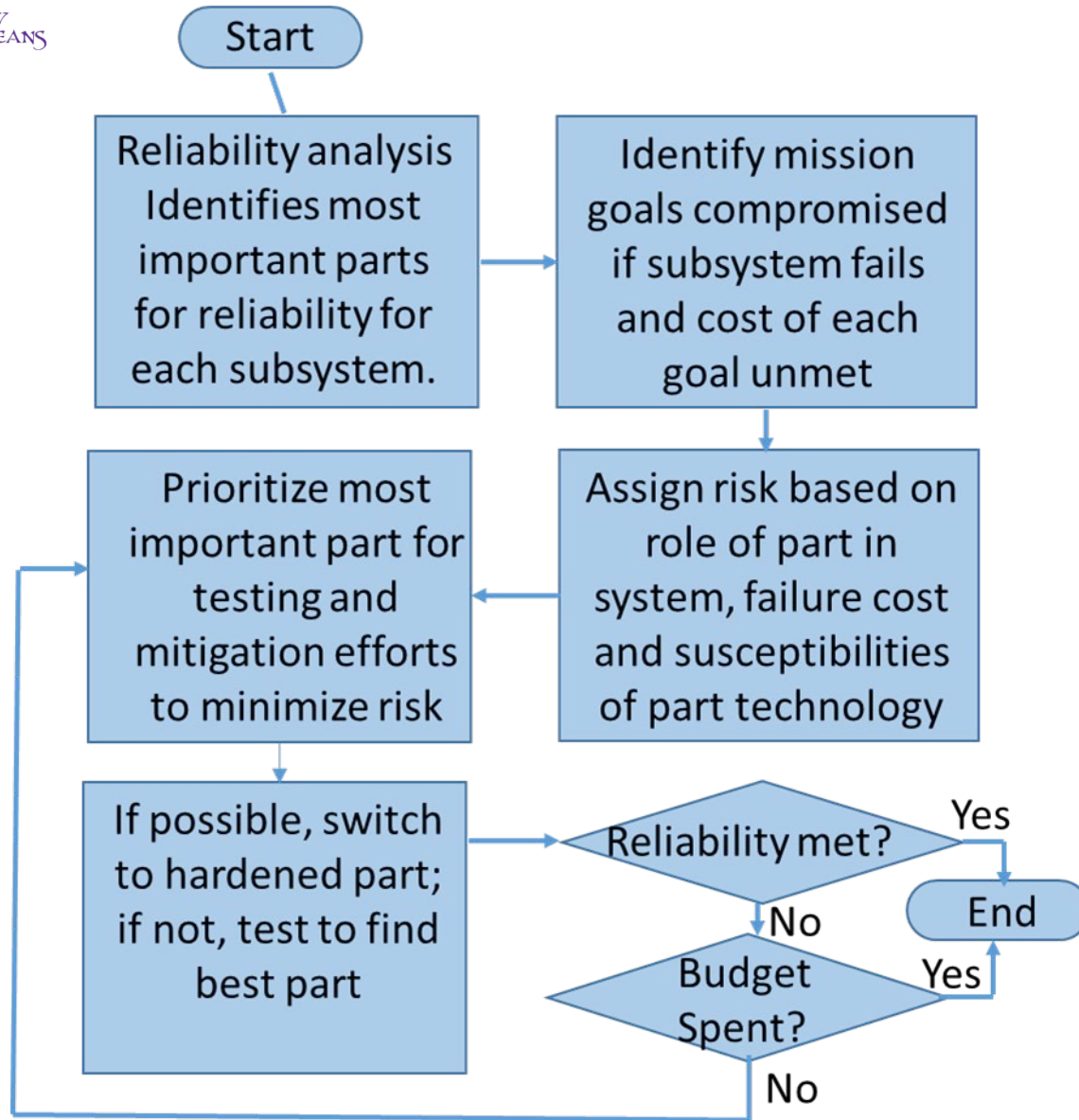


- Different devices on board may have different overburden
- Each device may see different LET
- Saturation for a part may mean range-out for others
- Detailed DPA and understanding of overburden for all parts needed to understand results

Partnering

- Advantages of partnering with high-reliability satellite manufacturers
 - Access to “left-over” space-grade parts
 - Access to lab and design facilities and expertise
- Disadvantages of partnering
 - Leftovers means you may not have access to everything on the menu
 - Unless rad hard parts are on the shelf, waiting on deliveries poses schedule risk
 - Testing by high-rel manufacturers may not be optimized
- Advantages for high-rel manufacturers
 - SmallSats can provide flight experience for technologies of mutual interest
 - More interesting if SmallSats can fly in a more severe environment
 - Flying more devices (e.g. in triplicate voting scheme) adds more confidence.

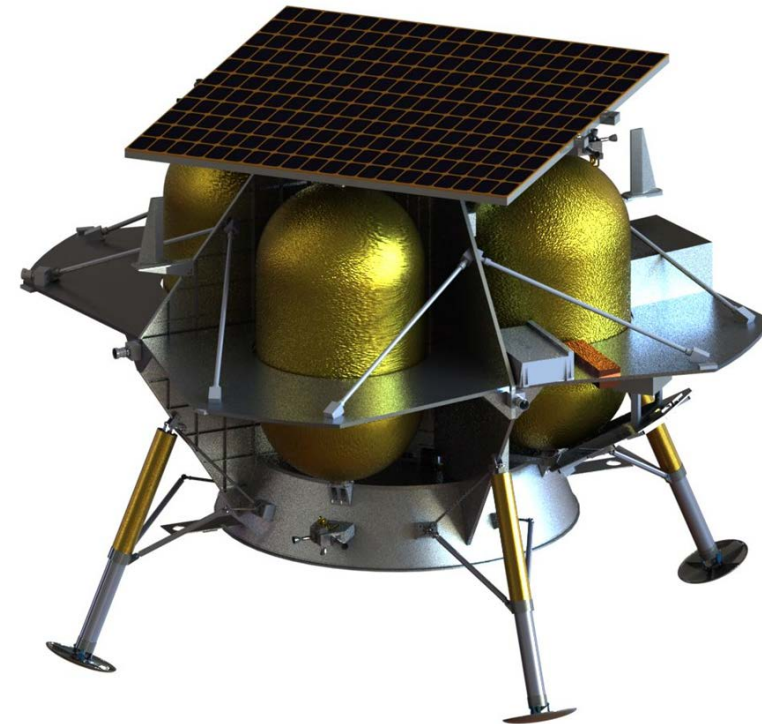
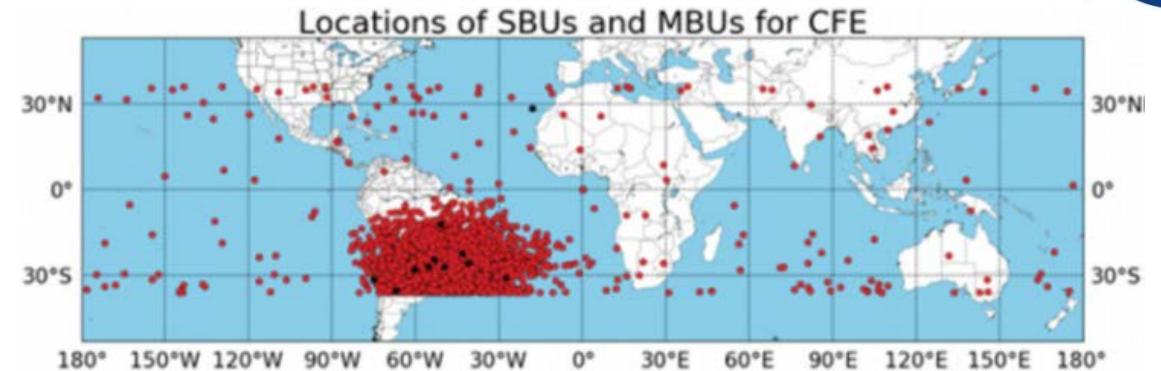
Risk Informed Hardness Assurance



- What does failure cost?
 - Each mission goal can be expressed as % of mission cost based on value to the mission
 - Sum of these costs for goals not met due to subsystem failure is cost of that failure
- Can failure exceed mission cost?
 - If failure is so complete that failure cause cannot be determined, subsequent failures due to same cause could contribute to total failure cost
- Risk metric
 - Normally Risk = Cost x Probability, but
 - Lacking test data, probability of failure unknown
 - Cost by itself can serve to prioritize test and mitigation efforts
 - Assumptions about failure probability based on technology (e.g. CMOS known to be SEL susceptible)

Some Examples

- Cibola Flight Experiment (CFE) designed to gather and process data for lightning and ionospheric studies
 - Main goal: assess RF antenna and related technology
 - Reconfigurable Computer was one of the first uses of reconfigurable FPGAs (Xilinx XQVR1000)
 - Partnership w/ Los Alamos National Laboratory afforded significant advantages for radiation testing/hardening
 - FPGAs triplicate voted, has watchdogs + error checking + diverse redundancy
 - Has already exceeded mission life goal by >2x
- Peregrine Lunar Lander from Astrobotic Technologies
 - 345 kg (dry weight) lander designed to deliver payloads to lunar surface for \$1.2 Million/kg.
 - Driven to make aggressive use of COTS due to schedule, cost, SWAP and performance
 - Redundancy not an optimal hardening strategy as it directly impacts payload that can be delivered
 - Receiving guidance from NASA's Lunar Cargo Transportation and Landing by Soft Touchdown (Lunar CATALYST) program
 - Radiation approach still a work in progress



Summary: SEE Hardness Assurance for SmallSats

- SmallSats pose unique challenges
 - Cost and Schedule force use of COTS, for which we have little radiation data
 - SEE hardness assurance methods not well suited to capitalize on risk tolerance
- SmallSats also pose unique potential
 - Well suited to collecting data for geoscience and planetary exploration
 - Spirit and Opportunity were consistent with SmallSats philosophy
 - Provide opportunity for risk-tolerant technology insertion
 - Swarm missions provide new approaches to reliability and survivability
- SmallSats also provide opportunities for radiation hardness assurance
 - Can we develop methodologies that capitalize on risk tolerance?
 - Can these methods be applied to conventional satellite platforms?
 - What additional risks would we run?
 - What assumptions can we make to reduce costs across the board?

A Visit From The Ghost of Short Courses Past

Rule of Thumb	Oops
SETs are recoverable	SET >1.8 V may damage RTAX-S FPGAs (Actel RTAX-S datasheet)
RF devices are SET immune	SOTA now CMOS responds to ps transients
MOSFETs SEB/SEGR immune if $V_{DS} < 30\%$ of rated V_{DS}	IRF640 commercial MOSFET fails to Ni w/ 22% of rated V_{DS} (O'Bryan, REDW 2003)
Bipolar ICs immune to destructive SEE	Failure in AD9048 (Koga et al., TNS 1994), AMP01 (O'Bryan et al., REDW 1999), Others (Lum et al., TNS 2000)
CMOS devices are ELDRS immune	Dose rate effects in CMOS (Witczak et al. TNS 2005)
CMOS devices immune to DD	Bulk damage in SDRAM cells (Shindou et al., TNS 2003, David et al., TNS 2006)
Indirect ionization negligible if $LET_{th} > 15$	SEU seen in hardened SRAM due to p+W scattering (Warren et al., TNS 2005)
If SEL leaves part functional, it's nondestructive	Latent damage due to SEL, (H. Becker et al., TNS 2005)
Others?	Stay tuned!

A catalogue of unpleasant surprises originally presented in 2007 short course. So what's new?

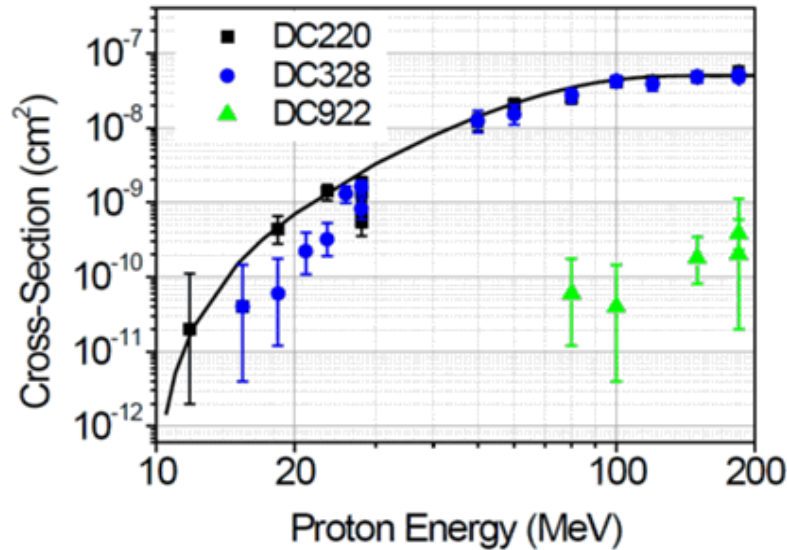
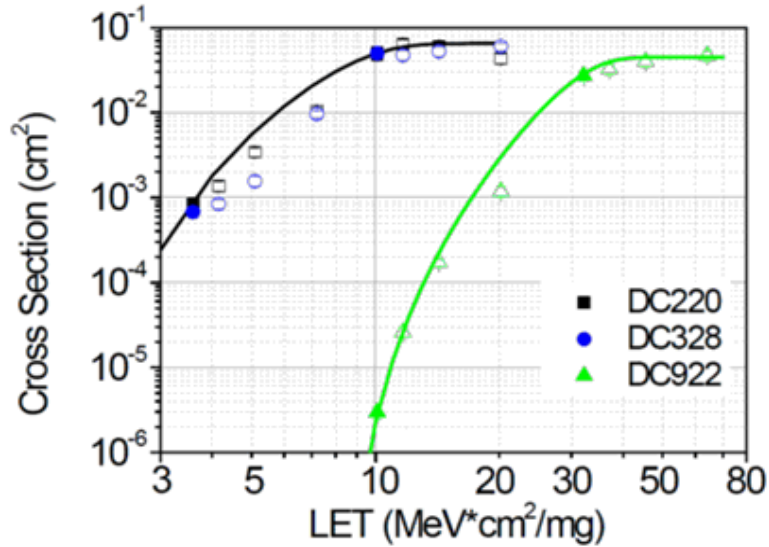
To be presented by Raymond L. Ladbury at the 2017 IEEE Nuclear and Space Radiation Effects Conference (NSREC 2017), New Orleans, LA, July 17-21, 2017.

Surprises since 2007

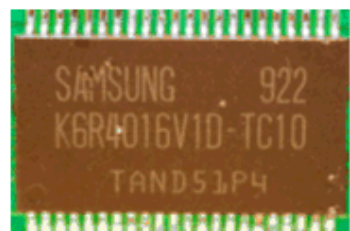
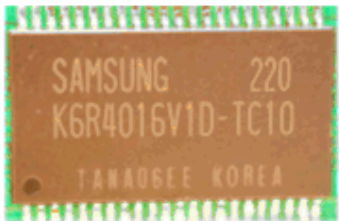
Rule of Thumb	Oops!
SEL gets better with decreasing temperature	SEL observed in Read-out IC at cryogenic temperatures <40 K (<i>C. Marshall et al., TNS 2010</i>)
SEE are not important for diodes	Schottky diodes observed to fail catastrophically due to previously unknown SEE mechanism. (<i>R. Gigliuto and M. Casey, NEPP ETW 2012</i>)
If part has no W plugs, no need to worry about proton destructive SEE if onset LET >20 MeVcm ² /mg.	p+Au fission in packages w/ Au plated lids produces ions w/ LET ~40 MeV•cm ² /mg (<i>T. Turflinger et al., TNS 2015</i>)
No need to worry about proton-induced fission if package has no high-Z materials	σ for p + Pd (Z=46) fission nearly as high as for p + Au (Z=79). Fission seen even for p + Ni (<i>T. Turflinger et al., TNS 2016</i>)

- Surprises found in testing about every 2 years or so
- If we rely too much on assumptions to save cost and schedule, we will discover them on orbit instead

And Last But Not Least: We Don't Have to Worry About Lot-to-Lot Variation for SEE... Do We?



- ESA: 3 Lots of SRAMs procured in same buy
- DC922 tested and found to have low SEL rate
- DC328 and DC220 SEL rates much higher



DC220 or DC328: ~ 1 SEL every 3 days on LEO polar orbit

Conclusions I

- SEE hardness assurance is a risk management tool
 - **Identify the threat** (based on device technologies and mission environment)
 - **Evaluate the threat** (based on testing device and analyzing other data)
 - **Mitigate the threat** (using redundancy, part substitution, circuit redesign, etc.)
- SEE mechanisms and space radiation environments mostly understood
 - Facilitates identification of threats
 - Allows tests to be designed for worst-case conditions to detect susceptibilities
- Use of proxy data to bound SEE rates remains challenging
 - Biggest Challenge: Not enough data!
 - Similarity data can constrain some SEE behavior (e.g. SET) but not others (e.g. SEL)
 - Proton data give an idea of low LET susceptibility for nondestructive SEE
 - Physics and engineering judgment can also help (e.g. SEL mainly a risk in CMOS)
- Mitigation strategies target probability, consequences or both

Conclusions II

- Extending SEE hardness assurance to SmallSats, etc. highly desirable
 - Longer missions mean better data sets
 - Small, inexpensive satellite swarms well suited to some missions
- SEE for small, inexpensive satellites poses significant challenges
 - Cost, schedule and SWAP all but necessitate wide use of COTS
 - Current HA methodology not well suited to consider risk tolerance to reduce costs
 - Many interesting strategies, but their effective use is still a work in progress.
- Developing SEE HA for SmallSats may also improve it for larger platforms
 - Risk tolerant SEE HA would be useful for any mission
 - SmallSats could provide platform for assessing new technologies
- SmallSats are not a replacement for conventional platforms
 - Not enough testing to detect new radiation threats
 - In a healthy space program SmallSats and conventional satellites will supplement rather than compete